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# Biomechanics and Utility of Shallow Soil Fixation by Sabina Valgaris Ant. Roots in Arid and Semiarid Soils

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**Abstract:** Aim: To investigate the biomechanical ability and utility of *Sabina valgaris* Ant. roots for soil fixation in arid and semiarid coal mining regions. Methods: Direct rapid shear and tensile strengths of shallow soil (~1.5 m) root samples were examined at 12.5 kPa, 25 kPa, 50 kPa, and 100 kPa. Results: Soil samples exhibited mean water content of 4.34 % and dry density of 1.35 g/cm$^3$, though saturated soil (46 %) water content was 17.2 %. Cohesion of *Sabina valgaris* root-soil composites gradually increased with root diameter ($P$<0.05), and friction did not change ($P$>0.05). Friction coefficients of soil-root and soil-soil interfaces were similar, obeying Mohr-Coulomb theory and exhibiting a sclerotic curve. Shear strength of *Sabina valgaris* Ant. roots were consistently higher than pure soil. In practical applications, the change in tensile forces of *Sabina valgaris* Ant. roots with plant growth stage are considerable, with lower tensile forces observed during the animated period than in early growth. Conclusion: Increasing root diameter improves tensile properties of shallow soils. These findings indicate that *Sabina valgaris* Ant. is an appropriate plant for achieving soil fixation and erosion prevention in arid and semiarid regions, though further study will be required to determine their wider applicability. 

**Keywords**: Friction validity, Root-soil composite, Shear strength, Tensile strength, Soil fixation, Revegetation.

## 1. Introduction

Recent systematic studies have indicated that plant root biomasses are key players in soil reinforcement, impacting soil erosion and sediment yield (Li P, et al., 2011). The highly variant shear and tensile strengths of single roots are important indicators soil fixation, preventing water contamination and potentially catastrophic land degradation (Genet M, et al., 2006). Though a variety of plant roots have been documented, *Sabina valgaris* Ant. is of particularly interest because it is widely available throughout arid and semiarid areas of Asia and Europe, where it is already employed in many soil fixation projects (Yao X. J., et al., 2009).

First explored in the mid-twentieth century, the shear and tensile strengths of single roots have been increasingly explored in recent decades, providing compelling evidence for consideration of these characteristics in soil conservation efforts

(Li P., et al., 2011). Using shear strength data, Endo *et al*. (1969) first demonstrated that root cross-section and biomass enhanced soil shear strength in 1969 (Yao X. J., et al., 2009). Jie *et al*. (1990) studied soil reinforcement by *Ulmspumla* roots, revealing that soil strength can be interpreted as a root-soil composite, generally yielding a much higher strength than pure soil. More recently, Wang *et al*. (2010) explored soil-soil and soil-root interface friction of *Sabina valgaris* and *Artemisia sphaerocephala*, indicating that the roots of these plants obey the Mohr-Coulomb theory but may have very different soil fixation abilities due to variant friction coefficients and cohesive strengths of their interfaces. Thus, *Sabina valgaris* Ant. Merits more consideration in terms of it mechanic effects on soil fixation.

In general, tensile strength studies of single roots describe either the relationship between plants with deep root systems using cross-sectional root diameter and ultimate stress or they describe plants with shallow root systems using various other mechanical models (Abushihe Y, 1992; Qingke Z, et al., 2002). For instance, Abushihe *et al*. (1992) studied the deep roots of *Cryptomeria japonica*, *Thuja occidentalis*, and Japanese red pine, revealing a positive correlation between root diameter and ultimate stress that can be expressed using the power function (Abushihe Y,1992).Similarly, Zhu *et al*. (2002) studied the roots of *Abiesfabri* and *Populus purdomii Rehd*, revealing that a positive correlation existed between tensile strength and root diameter. Due to the prevalence of land erosion, often leading to landslides and other soil failures, researchers have also investigated the biomechanical properties of the roots of a wide array of herbaceous plants with shallow root systems (Stokes A., et al., 2007; Stokes A, et al., 2009); however, reports investigating plants already widely employed in arid and semiarid areas are rare (Shi M, et al., 2008).

Using similar strategies as previous reports, the current study examines the biomechanical shear and tensile strengths associated with soil fixation in shallow soils by the root systems of *Sabina valgaris* Ant. Furthermore, the validity and biomechanical mechanism of soil fixation with *Sabina valgaris* Ant. were explored, providing an assessment of both current and potential applications of this plant for local soil preservation in arid and semiarid regions with many slopes, as occur in many landslide-prone regions of China (Stokes A., et al., 2007).

## 2. Materials and Methods

Root sample collection and preparation. Root samples were randomly collected from 30 four-year-old *Sabina valgaris* Ant. Plants from artificial field plots of 20 plants per plot (5 samples/plot) in the Ulam Mulun town of Yijinhuoluo, Ordos city, Autonomous Region of Inner Mongolia (P. R. China) at 109°45′~110°40′ E, 38°50′~39°50′ N. All samples were collected between February 20 2012 and March 15 2013. Whole, plants were collected to provide root samples. To avoid damaging roots, a test specimen was extracted from each plot to estimate root distribution and character (i.e., depth, width, number, and main root structure). Based on this data, a circular surface region with a radius of 25 cm centered on the plant base was excavated to a depth of 15 cm below the estimated root depth to ensure complete and undamaged sample collection. The perimeter of the excavation was made using a shovel, and various brushes were used to remove soil surrounding roots to avoid damage, thus allowing for recording of major physical property of root samples. For each sample, height, crown, and ground diameter of the sampled plant was recorded in the field, and values were reported as means ± standard deviations (SD) of 3 measurements of each plant. Shear properties of representative roots of *Sabina valgaris* Ant. were examined using representative roots, consisting of mode of root length and surface area of roots. These values correspond to a group of diameters represented by representative samples, as previously described (Xing H, et al., 2008). Briefly, diameter grades of 0-0.5 mm corresponded to test root diameters of 0.45, diameter grades of 0.5-1.0 mm (standard diameter) corresponded to test root diameters of 0.75, and diameter grades of 1.0-1.5 mm corresponded to test root diameters of 1.25 mm. Sample roots were then planted in soil similar to that of the excavation site and transported to the laboratory.

### 2.1. Soil Sample Collection, Water Content, and dry Density

Soil samples were sampled in the coal mining subsidence regions of Yijinhuole, Ordos (China) possessing aeolian loess soil textures. Three *Sabina valgaris* Ant. plants (root distribution = 80 %; 1.0-1.5 m depth) approximately 4 years of age were selected from each of one plots. Considering the estimated root distribution, as described in section 2.1 using test plant excavation, soil within a 1 m depth was excavated in 3 equal layers of shallow soil ( ≤ 2.0 m), and soil temperature and moisture were immediately analyzed. For the purposes of the current study, soil surface layer moisture content and density of all 3 layers were averaged, and means ± SD values were recorded for each sample and used to measure water content and dry density. Pure soil samples were prepared, as previously described.

To measure dry density, soil was sampled by quincunx sampling methods for bulk density analysis. Three equivalent ring-shaped samples were taken at depths of 0 - 30, 30 - 60, and 60 - 100 cm using cutting ring containers. Sampled soil was placed into an aluminum box, capped tightly, weighed, and then transported to a laboratory for oven drying with constant weight. Soil bulk density was calculated as follows:

$$\rho = w_b - /w_a \times V_r ,$$

where ρ is the soil bulk density (g/cm$^3$), $w_b$ is the weight of soil plus cutting rings before drying (g), $w_a$ is the weight of soil plus cutting rings after drying (g), and $V_r$ is the volume of cutting rings (cm$^3$).

To determine soil water content, ~20 g soil samples were placed in an aluminum box pre-heated to remove any moisture with a soil auger, and the total weight was determined with an analytical balance (0.01 g accuracy). Soil and box were dried at 105 ± 2 °C for eight hours. When weights were constant, the box was removed, covered, and cooled in a desiccator to room temperature. The final weight was then recorded. Soil moisture content θ was calculated, as follows:

$$\Theta = (w_b - w_a)/w_a \times 100\%,$$

where θ is the soil moisture content (%), $w_b$ is the weight of soil plus cutting rings before drying (g), and $w_a$ is the weight of soil plus cutting rings after drying (g).

In each sample, four root segments were collected with a minimum length of 100 mm. Each root sample was assigned a tagged identification number and marked at 15 mm intervals. Diameters were measured using electronic vernier calipers with 0.01 mm precision. Each diameter was measured 10 times in orthogonal directions at each mark and the means ± SD values were used as the experimental diameter. All roots were stored in sealed bags at constant temperature and humidity until testing, performed as soon as possible after sampling.

### 2.2. Shear Testing

Increasing soil water content cannot be readily discharged, producing measureable shear strength. Qualitative rapid shear tests were used to imitate natural precipitation conditions. An electric direct shear apparatus with four linked strain control (Nanjing Soil Instrument Factory Co., Ltd., Nanjing, P.R. China) was used to determine rapid shear (shear rate =0.8 mm/min) in samples of 3, 4, 5, and 7 root samples at 12.5 kPa, 25 kPa, 50 kPa, and 100 kPa. Results were expressed as the means ± SD of 3 parallel tests. A model YG (B) 026 H-250 electronic fabric strength tester (Wenzhou Darong Textile Instrument Co., Ltd., Wenzhou. P.R. China) was used to ascertain tensile force with a maximum loading speed of 'instantaneous'. Ultimate tension was determined as the point at which plant roots snapped under this simulated wind. Gravity stress, depth of soil conservation, and pressure of direct shear were determined.

### 2.3. Calculations

Shear displacement (Δu) and shearing strength (τ) were used in subsequent calculations. Friction properties of cohesion C and internal friction angle were calculated using rapid shear values, as previously described [13]. The vertical load was determined using the mean depth of root distributions. Shear strength and displacement curves were calculated for the soil-soil and soil-root surfaces.

### 2.4. Statistical Analysis

All values were expressed as means ± SD and analyzed with SPSS v.18.0 (IBM, USA). Changes in variables were assessed within and between groups. *P*-values of less than 0.05 were considered statistically significant.

## 3. Result and Analysis

### 3.1. Soil Properties

On average, the water content was 4.34 % and the dry density was 1.35 g/cm$^3$ in soil samples. Notably, for soil saturation of 46 %, the water content increased to 17.2 %. The gravity stress of the root distribution layer was found to be 12.5 kPa at 80 cm and 25 kPa at 1.5 m. The mean effect of soil conservation did not exceed 80 cm in any sample. Shear strength of *Sabina valgaris* Ant. root-soil composites.

Root diameter, cohesion, and the friction angle were each significantly different ($P < 0.05$). The cohesion of *Sabina valgaris* root-soil composites gradually increased with root diameter ($P < 0.05$), and the friction angle underwent no evident change ($P > 0.05$) (Fig. 1).

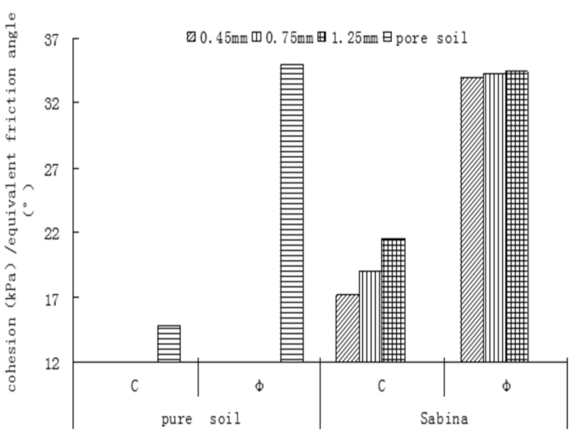


**Fig. 1.** Cohesion and the equivalent friction angle of pure soil and root-soil composite.

### 3.2. Friction Properties of Soil-root and Soil-soil Interfaces

The shearing strength relationship and shear displacement of the Sabina valgaris Ant. dry and wet soil-root interfaces were determined (Fig. 2). At the initiation of shear stress, the shearing strength (τ) increased rapidly, but the shear displacement (Δu) increased slowly. Shear displacement increased with increasing shear strength, and shearing strength reached a plateau with increasing length. Shear displacement increased continuously in a sclerotic manner, likely due to complex interfaces involved in the real root-soil interface. Notably, eliminating cohesive strength of this contact area creates frictional resistance and relative slip, which requires no less energy than destroying cohesive strength. The relational curves about the Δu/τ-Δu of Sabina valgaris Ant. root-soil surface were related by the coefficient R2>0.98 and the relationship $\Delta u/\tau = a\Delta u + b$ (Fig. 3). This formula demonstrates that the constitutive relationship of Sabina valgaris Ant. root-soil interfaces can be expressed as a hyperbolic function, consistent with previous studies of interfaces between reinforcement materials and soil by Clough et al. (Xing H, et al., 2008).

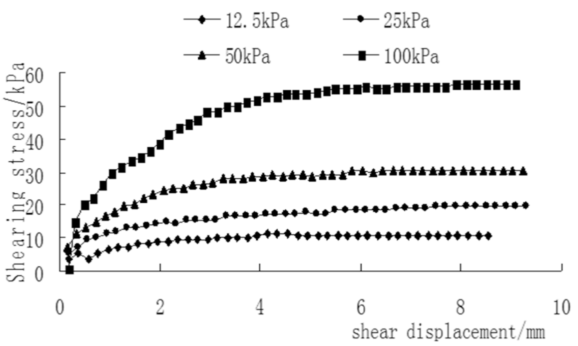


**Fig. 2.** Shear strength and displacement curves of Sabina valgaris Ant. root- soil interface.

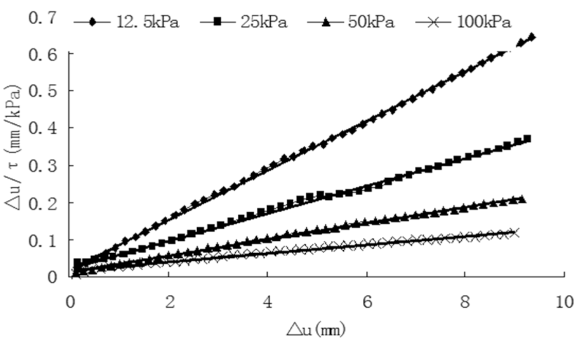


**Fig. 3.** Δu/τ-Δu relational curves of Sabina valgaris Ant. root-soil surface.

### 3.3 Single-root Tensile Strength

The relationship between tensile force and root diameter in single *Sabina vulgaris* Ant. roots was determined as a power function, a type of positive correlation that indicated increasing root diameter with increasing tensile force (Fig.4). The correlative coefficient between root diameter and tensile force, $R^2 \geq 0.91$, indicated high correlativity. Thus, as root diameter increases, differences in tensile force occur. As a result, variations in single-root tensile force occur in different growth period, resulting in a tensile force that is lower during the animated period than in the early growth period.

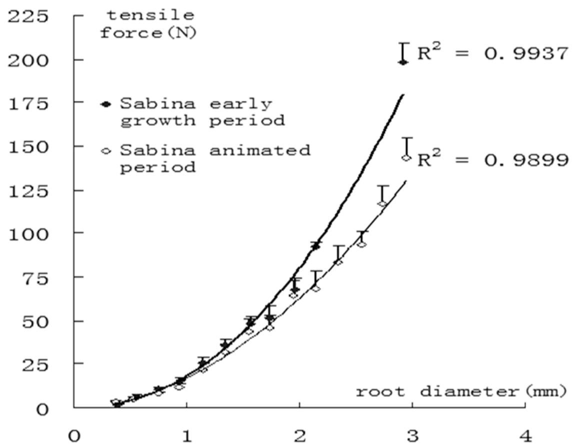


**Fig. 4.** Root diameter and tensile force *Early growth period 6.5 %, animated growth period 5.8 %.

## 4. Discussion

The current study analyzed the shallow soil composite soil-root interfaces of *Sabina valgaris* Ant. roots in terms of Coulomb's law, which utilizes shear strength composed of cohesion and internal friction angle (Thao TQ, et al., 2000), to demonstrate that the biomechanical properties of this plant have significant ability to deter erosion and fix soil. Notably, these properties were found to be dependent on growth phase, improving soil strength at variant levels. The soil-reinforcement ability of these roots was not only dependent on root characters and soil strength, but also varied based on the root-soil distribution, with root content per unit volume in surface soil positively correlated with soil cohesive force throughout the normal ranges of root growth and distribution for *Sabina valgaris* Ant. When root content per unit volume in surface soil was high, larger cohesive forces and subsequently larger shear forces better reinforce soil compared to many other shallow soil vegetation species. Thus, increasing root structures using *Sabina valgaris* Ant. has good utility for improving the shear load of shallow soils.

Unlike conventional composites used in civil engineering, such as concrete with steel rebar fibers, composites consisting of roots and soil generally lack relative displacement (Gartner W, 1989). This means that the mass of the soil does not decrease as root size increases, providing unique mechanical properties to the soil-root interface and resultant composite. Furthermore, the addition of rebar to concrete increases cohesion and internal friction angle (Gartner W., 1989); however, the progressive increase in root biomass and cross-section in soil causes no significant increase in the internal friction angle though cohesion still increases. Particularly in plants with high root percentages, nearing 80 % in *Sabina valgaris* Ant. in the examined soils, these results in a unique situation where residual stresses contribute to erosion prevention by preventing crack propagation along the soil-root interface, thus maximally retaining tightly compacted soil matric between root structures.

The improvements offered by different plants are varied. As described in current study, the biomechanical contributions of plant roots to soil fixation vary based on the water content of the soil, making erosion processes susceptible to precipitation. In a previous study, Wang *et al*. (2010) demonstrated that the shear strength of soil-roots was stronger than that provided by soil-soil cementation; furthermore, friction characteristics varied highly between plant species. Notably, this study highlighted that soil reinforcement properties of *Artemisia sphaerocephala* roots were superior to *Sabina valgaris* roots; however, this study did not take into account variations in soil type. A more recent study on improving shear characteristics specifically in coal mining regions reported that *Sabina valgaris* roots reliably improved root-soil composite shear strength to levels significantly greater than those of the prime soil, furthermore indicating the good survival of this plant species in these generally arid regions (Yao X., et al., 2009). Cumulatively, these findings indicate that *Sabina valgaris* Ant. may be a useful plant in improve soil fixation in arid and semiarid regions, though it may have lesser utility in other regions.

Compared to more costly engineering soil fixation methods, the use of *Sabina valgaris* Ant. roots for soil fixation and erosion prevention is environmentally safe and ecologically sound. Furthermore, revegetation techniques have been shown to have other practical benefits in arid and semiarid regions of sub-Saharan Africa, including low cost, ease of implementation by rural famers, and preservation of soil water and nutrient properties (Obalum S. E., et al., 2012), thereby benefiting both mechanical and ecological soil properties. On soils without vegetative cover in arid regions, precipitation runoff selectively detaches colloidal fragments at an appreciable rate, increasing surface roughness and infiltration, providing a poor growth environment for other plants due to lack of nutrients (Shi M. et al., 2008). This study demonstrates that *Sabina valgaris* Ant. can improve shallow soil fixation and prevent erosion due in many land-slide prone regions in China, and other arid and semiarid regions around the world that contain numerous sloping formations. Further investigation, however, should be conducted to determine variations in the biomechanical properties of *Sabina valgaris* Ant. roots in other soil types to determine if this species can be more widely employed as a revegetation soil fixation agent.

## 5. Conclusion

The current study demonstrates that the soil-soil and soil-root interfaces of *Sabina valgaris* roots obey the Mohr-Coulomb theory, exhibiting a curve with a sclerotic trend. Furthermore, in shallow soils, the shear strength of *Sabina valgaris* Ant. roots is higher than that of pure soil, suggesting that the plant will have good utility in achieving soil fixation and erosion prevention. Though adhesion of Sabina *valgaris* Ant. root-soil composites was higher than that of soil, the internal friction angles were notably consistent. For application of this plant species, it should be considered that the tensile forces of *Sabina valgaris* Ant. roots change dramatically with plant growth stage, with lower tensile forces observed during the animated period than during the early growth period. Thus, increasing root diameter can improve the tensile properties of shallow soils.

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