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STUDY ON SOIL REINFORCEMENT CHARACTERISTICS OF *ARTEMISIA NIGRA* AFTER ROOT DAMAGE IN CENTRAL AND WESTERN INNER MONGOLIA

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Keywords: Soil erosion, Cyclic load, Root-soil complex, Shear strength

Abstract

There was positive power function correlation between tensile strength and root diameter, and a negative power function correlation between tensile strength and root diameter after single, mild and severe cyclic loading. Cyclic load significantly increased the root tensile force and strength. Compared with single load, the tensile force increased by 22.61 and 47.61%, and the tensile strength increased by 20.38 and 43.85% after mild and severe cyclic load, respectively. The strength of the root-soil complex of *Artemisia nigra* were linearly positively correlated with the vertical load. The greater the depth of the burying root, the lower the soiling efficiency. The strength and cohesion of the root-soil composite under the condition of soil pore water pressure is less than that of the soil pore water. The internal friction angle are positive growth rates under different soil pore water pressure conditions. The strength characteristics of the root-soil composite increase with increasing root diameter. The shear rate has no significant effect on the strength characteristics of the root-soil composite.

Introduction

As one of the most serious ecological problems in our country, soil erosion has a large area, a wide distribution range and various types, which seriously restricts people's life production and economic development (Wang *et al*. 2001). The erosion types in the central and western regions of Inner Mongolia are complex and diverse, including various erosion forms mainly caused by hydraulic and wind erosion. It is a typical fragile ecological environment area with frequent natural disasters and rich coal resources. With the rapid economic development, the mining activities of coal resources will adversely affect the soil quality and aggravation the local ecological and environmental problems (Tang *et al.* 2016). Make soil erosion more serious. Plant (forest and grass) measures play an irreplaceable role in soil and water conservation, mainly from three aspects of soil ecology, hydrology ecology and mechanics, among which mechanics is mainly reflected in the root-soil complex formed by plant roots and soil (Yuan and Lei 2004, Zhang *et al.* 2015). As a kind of biological material, plant roots can be better combined with soil to form a root-soil complex, enhance the strength and stability of soil (Bordoni *et al*. 2016), and play the role of soil consolidation and erosion resistance. Among them, the mechanical properties of plant roots, which play a leading role, have gradually become the focus of research. At present, scholars at home and abroad have carried out a large number of experiments to study the mechanical properties of plant roots, mainly taking single plant roots as test materials to study their tensile characteristics (Tosi 2007, Jonasson and Callaghan 2010, Lv *et al.* 2011, Li *et al.* 2016) and shear characteristics (Zhu *et al*. 2008, Wang *et al*. 2012, Saifuddin *et al*. 2015).

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However, most scholars currently choose the taproot segment of plant roots as the research object, and there are few studies on the root segment containing lateral roots. Similar to taproot roots, root segments at branches containing lateral roots are not only channels for plant material transportation, but also play a role in connecting, supporting and consolidating, so that plant roots can better play their ecological functions and roles.

Materials and Methods

The research area is located at Yijin Horo Banner, Ordos City, in central and western Inner Mongolia, and the vegetation is found in *Artemisia nigra, Hippophae rhamnoides, Setaria viridis* and so on. It is located in the central mining subsidence management area of Shenfu Dongsheng Coalfield, one of the eight largest coalfields in the world. It is a semi-arid continental monsoon climate, with arid and windy spring and winter, concentrated rainfall in summer and autumn, frequent natural disasters and fragile ecological environment. The annual average temperature is 7.95°C, the highest temperature is 38.15°C, and the lowest temperature is -28.9°C. The average annual evaporation is 1790 mm, the average annual precipitation is 396 mm, and the average annual wind speed is 3.5 m/s. The average annual temperature is 8.9 ℃; The soil is mainly sandy: The common vegetation are *Artemisia nigra*, *Caragana microphylla*, *Hedysarum Scoparium* Fisch.et Mey., *Agriophyllum squarrosum* (Linn.) Moq, *Stipa bungeana*, *Sabina vulgaris* Ant.

Firstly, the selection criteria of standard plants were determined, and 30 plants were randomly selected in the typical plot of well-growing *Artemisia annularis,* and their plant height, crown width and ground diameter were measured. The selection criteria of standard plants were determined according to the average of each index: plant height (74.33 ± 13.11) cm, crown width (east and west: 91.33 ± 28.29 cm, north and south: 105.13 ± 32.16 cm), ground diameter (16.80 ± 5.34) mm. The root segment with lateral root branches of plant roots can be mainly divided into clumped-bone type and bifurcated type. In this experiment, all test roots were bifurcated, the Angle between the two lateral roots was about 50°~70°, the root length was 12 cm, the middle was 6 cm for the test root segment, and the clamping part of 3 cm was set apart at each end (Fig. 1). Electronic vernier caliper (0.01 mm) was used every 1cm to measure the root diameter of the point by cross crossing method, and marked with a red marker.

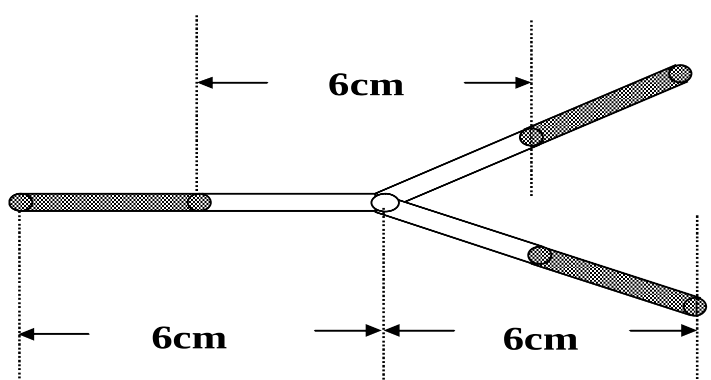

Fig. 1. Diagrammatic sketch of test root.

Then, root sampling was carried out for the standard plant, and the whole plant excavation method was used to dig out all the roots of *Artemsia nigrosa,* and the root segment with lateral root branches with sufficient length was selected. The test roots were put into the thermal insulation bag carried in time and covered with a certain amount of wet sandy soil to keep the test roots in an environment of about 4°C (rhizosphere soil temperature) and reduce water loss at the same time. After being brought back to the laboratory, they were stored in a low temperature incubator at 4°C. In order to ensure the activity of the test roots, each batch of roots was tested within 10 days.

The pre-test showed that when the diameter of the test root was more than 5 mm, its tensile force was larger, the required clamping force was larger, and the test root was prone to fracture at the clamp. In this test, *Artemisia nigra* were all born 4 to 5 years ago, and thicker roots with root diameter greater than 5 mm were less distributed. Therefore, this test determined 1~5 mm as the test root diameter range, and was divided into 8 diameter levels by 0.5 mm (1~1.5 mm, 1.5~2.0 mm, ... 4.5~5.0 mm). In tensile and tensile strength tests, 30 replicates were performed for each diameter stage; In the elastic-plastic test, 10 replicates were performed for each diameter stage. In the constitutive characteristic test, 20 replicates were performed for each diameter stage.

Artemisia melanorrhizae was randomly selected from the study area for 2-3 years, and its growth indicators such as plant height, crown width and base diameter were measured and the mean value was calculated as the basis for the selection of standard plants. The basic characteristics are shown in Table 1. The horizontal distribution range of *Artemisia annularis* root system was 50-100 cm, and the root system was densely distributed in 0-30 cm soil layer. The root system distribution was less under 40 cm soil layer, and the only root system was not fully developed and the root diameter was small. According to the size of standard plant, *Artemisia nigricola* was selected as the test plant. Take the base diameter of the test plant as the center of the circle, the radius is 1 m, and draw a circle on the surface. They divided the circle into four segments by making two perpendicular crossing lines. They selected a fan and dug down 0.5 m. The roots appearing in the excavation process are cut with branch shears. About 25% of the roots are artificially broken, which is considered as mild damage. After the roots are broken, the undisturbed soil is filled and compacted. Two segments were selected to dig and cut the roots, and about 50% of the roots were broken, which was considered as moderate damage. Three segments were selected to dig and cut the roots. About 75% of the roots were broken, which was considered as severe damage. At the same time, undamaged test strains were selected as controls. There were 20 plants with mild, moderate, severe injuries and control plants, and the total number of samples was 80. Healthy branches were selected and labeled before the experiment, and the growth index was measured.

Table 1. Growth state in standard strains of *Artemisia nigra*.

Index type	Standard strain of *Artemisia nigricans*					
Aboveground growth index	Density Plant/m^2	Coverage (%)	Plant height (m)	Crown width $(m)^2$	Base diameter (cm)	Branching number
	0.20	0.15	0.34 + / - 0.11	0.25 + / - 0.08	0.45 + / - 0.17	22 + 6
Root growth index	Root depth (cm)	Root moisture content (%)	Root surface area $(cm)^2$	Root volume $(cm)^3$	Cumulative root length (cm)	Root biomass (g)
	45 + 15	62.33 + / - 8.95	162.64 + / - 24.53	4.88 + / - 0.69	464.12 + / - 78.82	4.43 + / - 0.58

Several branches of the straight roots and lateral roots within the diameter range of 2~4 mm were selected, and cyclic loads were applied to the tested roots by TY8000 servo-controlled material testing machine. The test was divided into three groups. Group A was the ultimate root tensile test under a single load to determine the ultimate root tensile force. The preliminary experiments of our research group showed that the elastic limit point range of Artemisia minor root system within the diameter class range of 1-4 mm was 15 to 25% of the average limit force of the diameter class. Accordingly, the root system was set to withstand 30% limit tension, forming mild plastic deformation damage, and withstand 70% limit tension, which was close to the critical value of pulling the root system off, and was considered as severe plastic deformation damage. Group B is A mild cyclic load, and the applied force strength is 30% of the ultimate tensile force measured in group A. Before the first test, 30% of the ultimate force value is entered, so that the roots can stop stretching at a fixed tensile value. The cycle is carried out 50 times, and the loading speed is set at 20 mm·min-1. The complete cycle of a single root took 20 to 25 min, and the slip, epidermal rupture or fracture during the cycle were regarded as invalid data. 150 roots were tested repeatedly, and the test success rate was 55%. When 50 cycles were completed, the test root was stretched at the same loading speed until completely broken, and the tensile force value at breaking was recorded. Group C was A heavy cyclic load, and the applied force strength was 70% of the ultimate tensile force measured in group A. The cyclic operation method was the same as group B. A single complete cycle took 40 to 45 min, and 150 roots were tested repeatedly. The test success rate of this group was 25%. In the process of circulation, water is continuously sprayed on the test roots to ensure that the skin is moist and the mechanical characteristics caused by root water loss are eliminated. The root tensile strength is calculated as follows:

$$\delta = 4F / \pi D^2$$

Where: δ is the tensile strength (MPa); *F* is the tensile force *(N); D* is the average root diameter *(mm).* Choose a diameter range of 2 mm and a length of about 8 cm.

A blade was used to peel off the root skin along the root axis, and the complete portion was pasted. root skin on a circular wood chip with a diameter of 6.1cm and a thickness of 0.9cm with a decorative glue of Geolihao brand, so that each root skin is parallel to each other and the surface is smooth without convex and convex, as shown in Fig. 2a. In order to restore the natural state, the sample was covered with a slightly damp towel for later use. The depth of the upper and lower

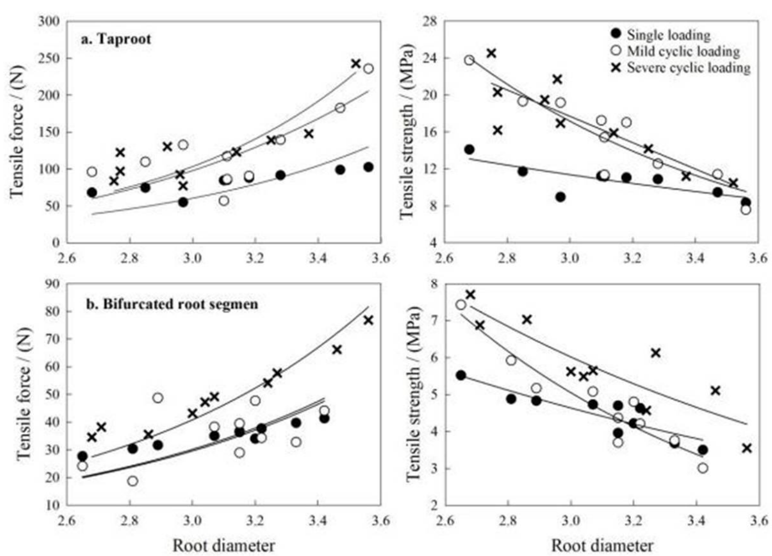

Fig. 2. Variation of tensile characteristics of *Artemisia nigricola* root after repeated drawing damage.

shear boxes is 2 cm, the lower box is put 1 cm thick pervious stone and test root sample, according to the dry density of soil and the set mass moisture content, weigh the appropriate amount of remodeled soil into the ring knife with a diameter of 61 mm and a height of 20 mm, and press the 1 cm thick pervious stone successively into the 1 cm thick soil sample, squeeze the pervious stone, and make the soil sample and pervious stone enter the upper shear box (Fig. 2b). The soil-soil interface sample is made similar to the root-soil interface sample, with a compacted thickness of 2 cm.

The direct shear resistance test of the root - soil interface was carried out by a ZJ type quadrupler strain controlled direct shear instrument in accordance with the requirements of Geotechnical Test Regulations SL237-1999. The prepared test block was placed into a shear box with the root axis parallel to the direction of shear force. 4 shear boxes should be filled in each test. The weights corresponding to the vertical loads of 12.5 kPa, 25 kPa, 50kPa and 100 kPa were added to the direct shear instrument. After installation, the shear test was started. The shear interface friction strength was recorded by software, and the test was repeated three times for each group. The internal friction Angle and cohesiveness of the root-soil interface were deduced by Moore Coulomb formula:

$$\tau = \tan\varphi \cdot p + c$$

Where, τ- shear strength of soil, kPa; φ- soil internal friction Angle; p- normal stress, kPa; c- soil cohesion, kPa.

Set the tangent value of the internal friction Angle $tan\varphi$ as the friction coefficient $\boldsymbol{f}$; $\boldsymbol{c}$ is the cohesiveness of the root-soil interface; $\boldsymbol{p}$ is the normal stress (vertical load) used to analyze the direct shear friction characteristics of the root-soil interface of Artemisia annua, and the formula obtained is as follows:

$$\tau = \tan\varphi \cdot p + c = f \cdot p + c$$

Results and Discussion

The tensile strength and tensile strength of a single root of a plant reflect the ability of the root system to resist the axial pulling damage of erosion forces. As shown in Fig. 3, within the range of 2~4 mm root diameter, the single load tensile force of For *Artemisia nigricans*, the tensile forces for straight roots, mild cyclic loading, and severe cyclic loading were measured to be 55.02-102.67 N, 57.08-195.96 N, and 77.40-242.89 N, respectively. A positive correlation was observed between tensile force and root diameter.There was a significant power function positive correlation (Table 2). There were significant differences in tensile strength among different treatments (P <0.05). Cyclic drawing significantly increased the tensile strength of straight roots. Compared with a single load, the tensile strength of mild and heavy cyclic loading increased by 37.64 and 50.71%, respectively. The tensile strength of straight roots The stress values under single load, mild cyclic load, and severe cyclic load were measured as 8.34 to 14.09 MPa, 7.57 to 23.76 MPa, and 10.49 to 24.53 MPa, respectively.The tensile strength is negatively correlated with root diameter as a power function. There were significant differences in the tensile strength among different treatments (P <0.05). Cyclic pulling could increase the tensile strength of *Artemisulva pedicularis,* and compared with a single load, the tensile strength of mild and heavy cyclic loading increased by 34.25 and 58.33%, respectively.

Within the range of 2~4 mm root diameter, the tensile force of lateral root branches under single, mild and severe cyclic load was significantly different (P <0.05), and the variation range was 27.67~41.33 N, 18.70~48.71 N and 34.54~76.82 N, respectively. The tensile force was significantly positively correlated with the root diameter (Table 2). Cyclic drawing can significantly increase the tensile force at lateral root branches, and the tensile force after mild and heavy cyclic loading increases by 7.59 and 44.50%, respectively, compared with a single load. The tensile strength of lateral root branches under single, mild and severe cyclic loads was significantly different (P <0.05), ranging from 3.50 to 5.52 MPa, 3.01 to 7.43 MPa and 3.55 to 7.71 MPa, respectively. The tensile strength was negatively correlated with root diameter as a power function. The tensile strength at the lateral root branch of Artemisia melanorrhizoea was increased by 6.51 and 29.37%, respectively, under mild and heavy cyclic loading compared with a single load.

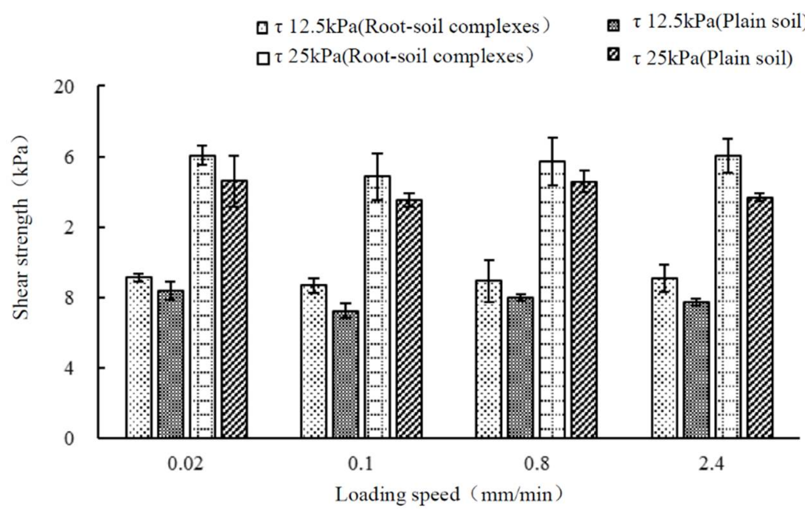

Fig. 3. The shear strength of root-soil composite under different shear rates.

Table 2. Pearson correlation between tensile characteristics and root diameter of *Artemisia ordosica*.

Root type	Mechanical index	Single load		Mild cyclic load		Heavy cyclic load	
		Regression equation	R^2	Regression equation	R^2	Regression equation	R^2
Taproot	Tensile strength	$F=11.546\ D^{1.724}$	0.626*	$F=5.165\ D^{2.733}$	0.634*	$F=4.361\ D^{2.982}$	0.646**
	Tensile strength	$\delta=48.104\ D^{-1.321}$	0.591*	$\delta=829.58\ D^{-3.542}$	0.796**	$Delta=358.47\ D^{-2.774}$	0.772**
Lateral root branch	Tensile strength	$F=6.493\ D^{1.487}$	0.937**	$F=3.141\ D^{2.118}$	0.609*	$F=2.365D^{2.691}$	0.950**
	Tensile strength	$\delta=25.537\ D^{-1.553}$	0.788**	$\delta=140.37\ D^{-3.028}$	0.902**	$\delta=55.932\ D^{-2.04}$	0.749**

**: P <0.01, *: P <0.05.

The shear rate was 0.025 mm/min, 0.11 mm/min, 0.85 mm/min, 2.41 mm/min, the dry density of soil was1.65 g/cm^3, and the soil moisture content was 7.95% (natural moisture content). The factors influencing the shear rate were tested at the shear rate of 0.9 mm/min and the root diameter of 1.7 mm.

The shear strength of the root-soil composite under different shear rates of 12.5 kPa and 25 kPa vertical loads (buried depth within 1.44 m) is shown in Fig. 3. It can be seen from the figure that the shear strength of the root-soil composite under two vertical loads decreases first and then increases with the increase of shear rates. The shear strength of the plain soil showed an irregular trend with the increase of the shear rate, and the shear strength of the root-soil complex under the four shear rates was greater than that of the plain soil. Under 12.5 kPa vertical load (buried depth 0.77 m), when the shear rate was 0.02 mm/min, the maximum shear strength of the root-soil complex was 9.13 kPa and 8.37 kPa, and when the shear rate was 0.1 mm/min, the minimum shear strength was 8.69 kPa and 7.23 kPa, respectively. When the shear rate was 0.02 mm/min under 25 kPa vertical load, the maximum shear strength of the root-soil complex and the plain soil value were 16.05 kPa and 14.61 kPa, respectively, and the minimum shear strength was 14.86 kPa and 13.53 kPa, respectively, when the shear rate was 0.1 mm/min.

The shear strength indexes of the root-soil complex and plain soil under different shear rates are shown in Fig. 4. It can be seen from the figure that under the four shear rates, the internal friction Angle of the root-soil complex is greater than that of the plain soil, and the internal friction Angle of the root-soil complex shows a trend of decreasing first and then increasing with the increase of the shear rate. When the shear rate was 2.4 mm/min, the maximum internal friction Angle was 23.02°, and when the shear rate was 0.1 mm/min, the minimum internal friction Angle was 22.20°. The internal friction Angle of plain soil showed an irregular change trend with the increase of shear rate. When the shear rate was 0.8 mm/min, the maximum internal friction Angle was 21.46°, and when the shear rate was 0.1 mm/min, the minimum internal friction Angle was 19.76°. Under the four shear rates, the cohesion of the root-soil complex was greater than that of the plain soil, and the cohesion of the root-soil complex and the plain soil showed a trend of decreasing first and then increasing with the increase of shear rate. When the shear rate was 0.02 mm/min, the maximum internal friction angles were 4.83 kPa and 4.25 kPa, respectively, and when the shear rate was 0.1 mm/min, the minimum internal friction angles were 4.13 kPa and 3.73 kPa, respectively. Duncan multiple mean test was performed on the shear strength indexes of root-soil complex and plain soil at different shear rates, and the results were shown in Table 3. When the significance level was 0.05, there was no significant difference between different shear rates and the internal friction Angle of the root-soil complex and plain soil.

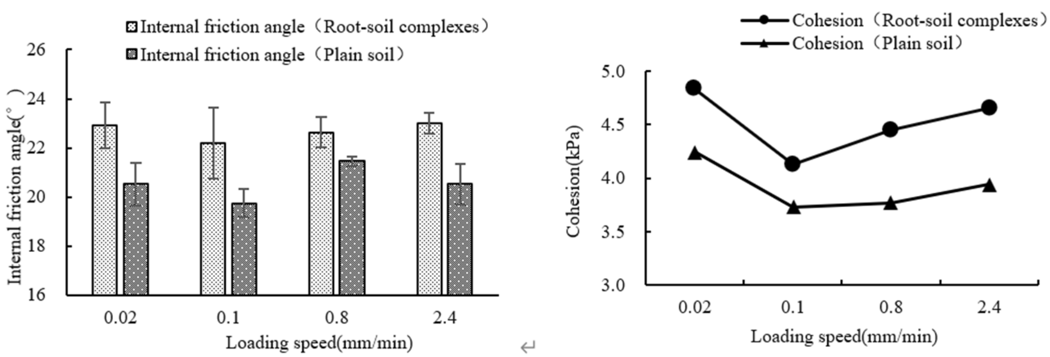

Fig. 4. The shear strength indexes of root-soil composite and soil with different shear rates.

The material mechanical properties of plant roots enable it to "reinforce" and "anchor" the soil, which can enhance the ability of soil to resist displacement and deformation during the process of erosion force. The mechanical indexes such as the tensile strength and tensile strength of the root system are the objective conditions to determine this "enhancement effect". In this study, the tensile strength of a single root of *Sagragon melanisia* was negatively correlated with the root diameter as a power function after a single or cyclic load, which was similar to the research results of many scholars, mainly because the cellulose microfilaments in the root cell wall had a tensile conduction function, which determined the mechanical strength of the cell wall, and the cellulose content generally decreased with the increase of the root diameter (Zhang *et al.* 2014, Li *et al.* 2016b). The tensile strength of the straight root was significantly higher than that of the lateral root branch, which was also prone to tear damage during the test, indicating that the branch node was the weak point of the root network.

Table 3. The result of multiple average which strength index of root-soil composite and soil with different shear rates.

Type	Duncan Grouping	Mean	N	Treat
Angle of internal friction in the root-soil complex	A	23.0227	3	2.4 mm/min
	A	22.9283	3	0.02 mm/min
	A	22.6425	3	0.8 mm/min
	A	22.1971	3	0.1 mm/min
Angle of friction inside the plain soil	A	21.4629	3	0.8 mm/min
	A	20.5363	3	2.4 mm/min
	A	20.5168	3	0.02 mm/min
	A	19.7570	3	0.1 mm/min
Cohesiveness of root-soil complex	A	4.8304	3	0.02 mm/min
	A	4.6525	3	2.4 mm/min
	A	4.4551	3	0.8 mm/min
	A	4.1282	3	0.1 mm/min
Cohesion of plain soil	A	4.2484	3	0.02 mm/min
	A	3.9368	3	2.4 mm/min
	A	3.7692	3	0.8 mm/min
	A	3.7251	3	0.1 mm/min

The cyclic pulling load simulates the repeated swaying effect of wind erosion forces on plants in nature, and the dynamic load is transmitted along the stem to the root system so that the plants are always in a state of fatigue and reciprocation. The research results showed that the tensile strength and tensile strength of a single root of Sagebrush were significantly increased after mild and heavy cyclic loads compared with a single load, and the effect of heavy cyclic loads was more obvious, which was consistent with the research results of Mu *et al.* 2019), Lv *et al.* (2013), indicating that under cyclic loads of erosion forces within the range that the root system could withstand (without breaking), the root system would be able to perform better. Its ability to resist axial pull-out damage will be improved, and its holding efficiency on soil will be enhanced. This may be because cyclic loading changes the arrangement of root cellulose microfibril. During the loading process, root cells will gradually lose water and squeeze the spatial structure, promoting the formation of microfibril aggregation, which will significantly improve the strength of fiber bundles against external forces (Genet *et al.* 2005). This characteristic of plant roots enables them to have better survival strategies when coping with erosion and destruction. Jaffe's research also shows that plants in stressed habitats are not easily damaged again after mechanical interference, and will enhance their resistance to adversity (Jaffe 1973).

Under natural conditions, the shear strength and shear strength indexes of the complex were higher than that of the plain soil, indicating that the existence of root system improved the shear strength of soi. The root system shifted from the original vertical direction to the direction of shear stress after shearing, indicating that with the increase of shear displacement in the shearing process, the shape of the root changes in the soil, and the shear force received by the root changes into the friction strength between the root and the soil, and the friction coefficient of the root-soil interface is greater than that of the plain soil. Under 12.5 kPa vertical load (buried root depth 0.77 m), the shear strength growth rate of the root-soil complex indicates that the soil consolidation effect of the root-soil complex in shallow soil layer is better than that in deep soil layer, which is the same as the results of Zhang (2011) and Zhou (2012).

The effects of different types of erosion forces on the root system of *Artemisia annua* in semi-arid mining area significantly changed its growth rate, photosynthetic physiological characteristics and mechanical properties of root soil consolidation. Root damage inhibited the growth of Artemisia melanorrhizoea, significantly reduced plant height, crown width and growth increment of branches and leaves, and even led to plant growth decline and death. The simulation of repeated pulling damage caused by wind loads of different strengths to root formation can significantly improve the axial tensile strength and tensile strength of root systems. Compared with a single load, the tensile strength after mild and heavy cyclic loads increases by 37.64 and 50.71%, respectively, and the tensile strength increases by 34.25 and 58.33%, respectively. It can be concluded that moderate wind load can enhance the soil consolidation ability of *Artemisia melanocephala* root system. The shear strength of the complex was positively correlated with the vertical load, and the higher the depth of embedment, the stronger the soil consolidation ability. The internal friction Angle of the root-soil complex is greater than that of plain soil, and the internal friction Angle of the root-soil complex decreases first and then increases with the increase of shear rate.

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References

Bordoni M, Meisina C, Vercesi A, Bischetti GB, Chiaradia EA, Vergani C, Chersich S, Valentino R, Bittelli M and Comolli R 2016. Quantifying the contribution of grapevine roots to soil mechanical reinforcement in an area susceptible to shallow landslides. Soil Till. Res. **163**: 195-206.

Genet M，Stokes A，Salin F，Mickovski SB，Fourcaud T，Dumail JF and RV Beek 2005. The influence of cellulose content on tensile strength of tree roots. Plant Soil **278**: 1-9.

Jaffe MJ 1973. Thigmomorphogenesis: The response of plant growth and development to mechanical stimulation. Planta **114**: 143-157.

Jonasson S and Callaghan TV 2010. Root mechanical properties related to disturbed and stressed habitats in the Arctic. New Phytol. **122**(1): 179-186.

Li PF, Lv RB, He HY, Cao W, Zhou X and Tian GX 2016a. Mechanical properties of plant roots in different types of highway slope along Xinyang-Nanyang. J. Northwest For. Univ. **31**(4): 73-80.

Li YF, Liu J and Zhang X 2016b. Study on the vulnerable root location of two kinds of plants by anti-fracture force. Proceedings of 2016 International Conference on New Energy and Sustainable Development, according to, Hunan, China.

Lv CJ, Chen LH, Zhao HH, Ji XD and Li YX 2013. Axial fatigue properties of Chinese pine roots. Tribology, **33**(06): 578-585.

Lv CJ, Chen LH, Zhou S, Wang PH, Ji XD and Zhang XP 2011. Root mechanical characteristics of different tree species. Tran. Chinese Soc. Agricul. Eng. **27**(S1): 329-335.

Mu F, Cheng ZM, Li YL, Xu XH and Li XG 2019. Study on the biomechanical and fatigue characteristics of single root soil consolidation in Taihang Mountain area. J. Northwest For. College **34**(02): 14-21.

Saifuddin M, Normaniza O, Rahman MM and Boyce AN 2015. Soil reinforcement capability of two legume species from plant morphological traits and mechanical properties. Curr. Sci. **108**(7): 1340-1347.

Tang J, Dang YH, Xue J, Wen YR, Xu N and Wu DF 2016. Effects of vegetation restoration on soil aggregate characteristics of an opencast coal mine dump in the loess area. Acta Ecol. Sin. **36**(16): 5067-5077.

Tosi M 2007. Root tensile strength relationships and their slope stability implications of three shrub species in the Northern Apennines (Italy). Geomorphol. **87**(4): 268-283.

Wang XK, Ouyang ZY, Xiao H, Miao H and FU BJ 2001. Distribution and division of sensitivity to water-caused soil loss in China. Acta Ecol. Sin. **21**(1): 14-19.

Wang YX, Sun HL, Luo LZ, Li SC, Luo S, Lu DQ, Long F and Liu C 2012. Study on characteristics of root shear of *Broussonetia papyrifera* L. on rocky-steep slope. Res. Soil Water Conser. **19**(3): 114-118.

Yuan XP and Lei TW 2004. Soil and water conservation measures and the ir benefits in runoff and sediment reductions. Tran. Chinese Soc. Agricul. Eng. **20**(2): 296-300.

Zhang CB 2015. Shuitu Baochi Zhiwu Cuoshi Yuan Li. 2015, Intellectual Property Publishing House, China.

Zhang CB, Chen LH and Jiang J 2014. Why fine tree roots are stronger than thicker roots: The role of cellulose and lignin in relation to slope stability. Geomorphol. **26**: 196-202.

Zhang YL 2011. Research on biomechanical characteristics of Sea buckthorn roots. Inner Mongolia Agricul. Univ.

Zhu HL, Hu XS, Mao XQ, Li GR and Sheng HY 2008. Study on mechanical characteristics of shrub roots for slope protection in loess area of Tibetan Plateau. Chinese J. Rock Mech. Eng. **27**(s2): 3445-3452.

Zhuo DD 2012. Study on improving the residual shear resistance of soil by single root of three plants. Inner Mongolia Agricultral University.

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