Time Effects on the Shear-Resistance Characteristics of Camelthorn Root-Soil Composites

Zhu Jianlin ^1,2, Li Qinglin ^1,2, Luo Xuanbing ^1,2, Wang Bowei ^1,2, Yu Shuailong ^1,2

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Abstract

Taking Alhagi sparsifolia, a typical desert vegetation species in Northwest China, as the research object, root-soil composite specimens were prepared by artificially cultivating Alhagi sparsifolia in PVC pipes. The aboveground biomass and root distribution characteristics of Alhagi sparsifolia were measured, and the shear strength indices of the root-soil composites were determined using large-scale direct shear tests. The effects of growth period and soil depth on the shear strength of the root-soil composites were analyzed. The results showed that, according to the growth indices of Alhagi sparsifolia, the growth period could be divided into the emergence stage (0~60 d), rapid growth stage (60~120 d), and seedling hardening stage (120~180 d). Root mass, average root diameter, and root tissue density were positively correlated with the growth period, whereas root water content and specific root length were negatively correlated with the growth period; the changes in all indices were most significant during the rapid growth stage. The influence of the time effect on the shear strength indices of the Alhagi sparsifolia root-soil composites was mainly reflected in the increase in cohesion. The cohesion values in different stages were 11.11 kPa, 17.32 kPa, and 19.14 kPa, respectively, representing increases of 44.9%, 125.8%, and 149.5% compared with bare soil, while the influence on the internal friction angle was relatively small. This study reveals the temporal variation law of the shear strength of Alhagi sparsifolia root-sandy soil composites and has important scientific significance for developing the theory of soil reinforcement and slope protection by desert vegetation in arid regions.

Full Text

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Zhu Jianlin ^1,2, Li Qinglin ^1,2, Luo Xuanbing ^1,2, Wang Bowei ^1,2, Yu Shuailong ^1,2

(1. College of Water Conservancy and Architectural Engineering, Shihezi University, Shihezi 832000, Xinjiang, China; 2. Key Laboratory of Ecological Water Conservancy Engineering of the Xinjiang Production and Construction Corps in Arid Areas, Shihezi 832000, Xinjiang, China)

Abstract: Taking camelthorn, a typical desert plant in Northwest China, as the research object, root–soil composite specimens were prepared by artificially planting camelthorn in PVC pipes. The aboveground biomass and root-distribution characteristics of camelthorn were measured, and large-scale direct shear tests were used to determine the shear-strength indices of the root–soil composites. The effects of growth period and soil depth on the shear strength of the root-soil composites were analyzed. The results show that, based on camelthorn growth indicators, the growth period can be divided into the emergence stage (0–60 d), rapid growth stage (60–120 d), and seedling hardening stage (120–180 d). Root mass, mean root diameter, and root tissue density were positively correlated with growth period, whereas root water content and specific root length were negatively correlated with growth period; all indicators changed most markedly during the rapid growth stage. The influence of time effects on the shear-strength indices of camelthorn root-soil composites was mainly reflected in increased cohesion. Cohesion at different stages was 11.11 kPa, 17.32 kPa, and 19.14 kPa, respectively, representing increases of 44.9%, 125.8%, and 149.5% compared with plain soil, whereas the effect on the internal friction angle was relatively small. This study reveals the temporal variation pattern of the shear strength of camelthorn root-sandy soil composites and has important scientific significance for the development of soil-fixation and slope-protection theory for desert vegetation in arid regions.

Keywords: root-soil composite; camelthorn; shear strength; time effect

Sandy soils are widely distributed in Northwest China [1]. They are characterized by low clay-particle content and a loose, easily disintegrated structure, and their shear strength is significantly lower than that of cohesive soils. Coupled with the arid natural environment of Northwest China, the insufficient shear strength of low-moisture soils is more likely to induce slope instability and wind-erosion damage, posing serious threats to the safe maintenance of engineering facilities and the sustainable development of the ecological environment [2]. Camelthorn is a perennial semi-shrub leguminous herb widely distributed in Northwest China. Its distribution area in Xinjiang reaches 1.73$×$10^6 hm^2, and it is the main constructive species along the southern margin of the Taklimakan Desert [3]. It grows in sandy land, along riverbanks, and beside farmland in desert regions, and is drought-resistant, salt- and alkali-tolerant, waterlogging-resistant, and highly adaptable. Its well-developed root system can effectively stabilize slopes and curb soil and water loss, and it also plays important roles in windbreak and sand fixation and in maintaining oasis ecological security [4].

Considerable progress has been made in research on soil reinforcement by vegetation roots. Early studies established simple calculation models for the increase in soil shear strength by root systems; subsequent scholars improved these models from different research perspectives [5] and used a variety of experimental methods to examine the intrinsic relationship between root systems and shear strength. Lin Dizhao et al. [6] conducted in-situ direct shear tests on trees under different cross-sectional area ratios and water-content conditions. Zhou Linhu et

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al. [7] evaluated differences in the mechanical strength of various herbaceous root systems through shear tests. Shen Ziyan et al. [8] investigated the physicochemical properties of soils and the shear-strength characteristics of root–soil composites at different depths in alpine grassland. Luo Buzhao et al. [9] and Zhong Caiyin et al. [10] further explored the effects of water content and root content on soil failure characteristics. Overall, shear testing has become a core method for quantitatively characterizing the soil-fixing effect of vegetation, while shear strength is a key indicator reflecting the contribution of root systems to slope stability. However, although the above studies have made important progress in revealing the effects of different vegetation types and key factors on the mechanical behavior of root–soil composites, their findings are generally based on root systems grown for fixed periods. In reality, the mechanical properties of root systems are driven by their growth processes. As root biomass accumulates, root diameter increases, lignification strengthens, and the contact mode at the root–soil interface continuously adjusts, root tensile performance, interfacial friction characteristics, and structural reinforcement effects all show stage-specific differences. As a result, the macroscopic shear strength of root–soil composites exhibits pronounced time dependence and nonlinear characteristics.

Based on the above understanding, attention to the "time effect of root mechanical properties" has gradually increased in China and abroad in recent years. Existing studies have shown that plant

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Author biography: Zhu Jianlin (2002-), male, master's student, mainly engaged in ecological slope-protection research. E-mail: zhujianlin@xjshzu.com
Corresponding author: Li Qinglin. E-mail: liql1150142@163.com

Plant growth stage significantly affects soil-fixing capacity[13]. Hao et al.[14], through numerical simulation, revealed the mechanical characteristics of alfalfa root–soil composites at different growth stages; the results showed that their compressive strength at 131 d of vegetation growth was 21% higher than that at 14 d. Other studies have further confirmed that growth stage is closely coupled with the mechanical properties of the root system itself. Zhang et al.[15] and Liu et al.[16] respectively investigated the pull-out characteristics of alfalfa and *Caragana* roots, and both results indicated that root pull-out force increases with growth stage according to a power function. Mao Zhengjun et al.[17–18], based on triaxial tests and in-situ pull-out tests, quantified the time-dependent

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mechanical behavior of an alfalfa–loess composite; its cohesion increased significantly with growth stage, and the pull-out strength likewise depended strongly on the degree of root development. Similar patterns are also widespread in other vegetation types. Lei Lei et al.[19] found that the shear strength of a black locust root–loess composite increased significantly with growth years. Wu Ruibin et al.[20] confirmed by triaxial tests that the reinforcement effect of a vetiver–red soil composite also continued to increase over time. These studies fully demonstrate that the soil-fixing effect of roots has a significant time effect and is a continuously evolving process driven by vegetation growth. However, these findings mainly focus on vegetation such as alfalfa, vetiver, and black locust, and mainly involve cohesive soil media such as loess and red soil. Systematic research is still lacking on the time-dependent mechanical effect of the typical desert plant *Alhagi sparsifolia* in sandy soil environments in the arid regions of Northwest China, and further exploration is needed.

In summary, this study focuses on the time effect of shear strength in the *Alhagi sparsifolia*–sandy soil composite of desert vegetation in the arid regions of Northwest China. Based on artificially controlled cultivation, undisturbed *Alhagi sparsifolia*–sandy soil composite specimens at 60 d, 120 d, and 180 d were obtained. Large-scale direct shear tests were carried out to determine the shear strength of the *Alhagi sparsifolia*–sandy soil composite, and the evolution of composite shear strength with the growth period of *Alhagi sparsifolia* was quantitatively characterized. The study can provide key parameters and a scientific basis for the theoretical construction of vegetation-based soil fixation and slope protection in arid regions, as well as for the optimization of soil and water conservation measures.

1 Materials and Methods

1.1 Test Materials

Alhagi sparsifolia was selected as the research object, and the seeds used came from the College of Agriculture, Shihezi University. The changes in the chemical components of the *Alhagi sparsifolia* root system with growth period are shown in Table 1. The sandy soil was taken from a riverbank slope in the Manas River basin on the northern slope of the Tianshan Mountains in Xinjiang. According to the *Standard for Geotechnical Testing Method* (GB/T50123—2019)[21], basic physical tests were carried out on the selected soil, and the results are shown in Table 2 and Fig. 1. The planting containers used in the experiment were PVC pipes. For the 60 d growth-period specimens, the pipe inner diameter was 300 mm and the height was 1000 mm; for the 120 d and 180 d growth-period specimens, the pipe inner diameter was 300 mm and the height was 3000 mm. The planting site was located

Table 1 Changes in chemical composition of the *Alhagi sparsifolia* root system over time

Tab. 1 Chemical composition of *Alhagi sparsifolia* root system at different growth stages

Growth period / d	Cellulose / %	Hemicellulose / %	Lignin / %
30	36.54	37.08	8.42
90	38.07	36.02	8.79
150	42.65	34.26	9.26
210	45.89	37.04	9.44

at No. 2 Company of the Shihezi University experimental field.

1.2 Test Scheme

The direct shear test used a ZJ large-scale direct shear apparatus produced by Nanjing Soil Instrument Factory. To obtain the shear-strength indices of the root-soil composite, and considering the depth-distribution characteristics of the *Alhagi sparsifolia* root system, three levels of normal stress—50 kPa, 100 kPa, and 200 kPa—were selected. Undisturbed specimens were subjected to layered direct shear with 15 cm as the layer thickness. In this paper, "depth" refers to the vertical measurement distance downward from the soil surface. According to experimental observations, the root system at the 60 d growth stage was mainly distributed within the 0-45 cm soil layer; below 45 cm, the number of roots was small, and they were highly prone to scattering during sampling and transport, making it impossible to guarantee undisturbed condition and test validity. Therefore, the 60 d specimens were divided into three depth layers: 0-15 cm, 15-30 cm, and 30-45 cm. For the 120 d and 180 d specimens, the roots extended deeper downward and were mainly distributed within the 0-90 cm range; specimens below 90 cm were likewise difficult to collect effectively and keep intact. Therefore, six depths were set: 0-15 cm, 15-30 cm, 30-45 cm, 45-60 cm, 60-75 cm, and 75-90 cm. With reference to the conditions for the quick shear test in the *Standard for Geotechnical Testing Method* (GB/T50123—2019)[21], the shear rate was selected as 1.2 $mm \cdot min^{-1}$, and the test was terminated when the horizontal shear strain reached 20%.

1.3 Specimen Preparation

(1) Vegetation planting. A test pit with dimensions of 3 m in length, 1 m in width, and 3 m in height was excavated at the Shihezi University experimental field. The soil was filled into PVC pipes in layers; the thickness of each soil layer was 50 cm. Preliminary compaction was carried out by manual water tamping, and the dry density was controlled at 1.58 $g \cdot cm^{-3}$. Ten *Alhagi sparsifolia* seeds were placed in each PVC pipe, with a planting depth of 2 cm. Thinning and final seedling selection were conducted during 0-30 d. Each pipe was watered once every 3 days, with 1000 mL

of water added each time, to ensure that the moisture contents of the specimens at the three different growth stages were consistent.

(2) Setting of the *Alhagi sparsifolia* growth periods. The growth periods of *Alhagi sparsifolia* were set as three time intervals: 60 d, 120 d, and 180 d.

(3) Preparation of direct shear test specimens. After the inner wall of a sampler with dimensions of 15 cm × 15 cm × 15 cm was coated with Vaseline, it was inserted into the soil. The pipe was cut off using a hand-held grinding wheel, and the roots on the lower side were cut off with a handsaw. Finally, the soil in the sampler was pushed into a shear box of the same size.

Table 2 Basic physical properties of tested soil

Soil type	Natural water content/%	Specific gravity	Natural dry density/$g \cdot cm^{-3}$	Maximum dry density/$g \cdot cm^{-3}$	Optimum water content/%	Cohesion/kPa	Internal friction angle/(°)
Silty sand	11.23	2.60	1.58	1.97	11.9	7.67	29.25

(a) Particle-size distribution curve
Vertical axis: soil content finer than a given particle size/%; horizontal axis: particle size/mm.

(b) Compaction curve
Vertical axis: dry density/$g \cdot cm^{-3}$; horizontal axis: water content/%.

Figure 1 Fundamental physical testing of soil

in [[unclear: continuation from preceding page]]. The direct shear test was carried out immediately after specimen preparation, so as to minimize changes in water content. In addition, a uniform watering regime was adopted to ensure consistency in the water contents of specimens from different growth periods.

(4) Determination of root-system parameters. After completion of the direct shear test, all roots in the shear box—that is, all roots in the sampler—were collected and used to determine indices such as root water content, mass, root diameter, and root volume. Among them, parameters such as root morphological characteristics, root diameter, and root volume were measured using a root scanner (Phantom 9980XL). The specimen-preparation process is shown in Figure 2.

2 Results and Analysis

2.1 Growth indicators of camelthorn root systems

The statistical results for root mass are shown in Figure 3. The distribution of roots differed among growth periods. Specifically, root mass tended to decrease as soil-layer depth increased. For the specimens at the 120 d growth period, root dry weight decreased with increasing soil-layer depth in a "concave-function" pattern, and roots in the deep layer (45-90 cm) accounted for 30.3% of total root mass. For the specimens at the 180 d growth period, root dry weight decreased with depth in a "convex-function" pattern, and the proportion of root mass in the deep layer (45–90 cm) increased to 42.4%. Root dry weight increased with growth period. The change in root dry weight was most pronounced between the 60 d and 120 d growth periods: at the same soil-layer depth, root dry weight differed by 3.83–10.15 g. During 60–120 d, camelthorn developed rapidly, the root system grew quickly, and root dry weight increased by 235.4%. The root dry weights of specimens from the 0–15 cm soil layer at the 120 d and 180 d growth periods were close, differing by only 0.17 g. As soil-layer depth increased, the difference in root dry weight first increased and then decreased, reaching a maximum of 5.65 g in the 45–60 cm soil layer and decreasing to 2.49 g in the 75–90 cm soil layer. Root fresh weight showed a similar pattern of variation with soil-layer depth. The average aboveground biomass values of camelthorn at growth periods of 60 d, 120 d, and 180 d were 72.3 g, 230.4 g, and 215.1 g, respectively. At the 180 d growth period, some camelthorn leaves had fallen off, manifested as a reduction in aboveground biomass.

Root water content is the ratio of the mass of water contained in the roots in each layer to the dry weight of the roots, and reflects the developmental status of the plant root system. As can be seen from Figure 4a, the root water content at the 60 d growth period was much greater than those at 120 d and 180 d, and increased with soil-layer depth, ranging from 338.64% to 549.57%. At growth periods of 120 d and 180 d, root water content generally tended to decrease with increasing soil-layer depth, with ranges of 133.50%–153.77% and 81.74%–147.74%, respectively. This difference indicates that, in the early stage, the root system was still in a rapid-growth state with high water content; as the growth period lengthened, root tissues gradually lignified and the cellular structure became denser, so the water content showed a decreasing trend with both depth and growth period.

Specific root length (SRL) is the ratio of the total length of roots in each layer to the total dry weight of the roots, and is an important indicator characterizing root resource-acquisition efficiency and growth strategy. As can be seen from Figure 4b, the SRL at the 60 d growth period was significantly higher than those at 120 d and 180 d. This was mainly because, during 60–120 d, camelthorn was in the developmental stage and its root water content was relatively high; after dehydration, the dry weight was relatively low, thereby yielding a higher SRL value. At the 60 d growth period, SRL showed an increasing trend with increasing soil-layer depth, rising from 170.5 $cm \cdot g^{-1}$ to 496.12 $cm \cdot g^{-1}$. In contrast, the SRL values at the 120 d and 180 d growth periods were generally lower, and the magnitude of their variation with depth

Fig. 2 Specimen preparation procedure

Visible labels in the figure: 60 d; 120 d; 180 d; outdoor planting; specimen excavation; undisturbed-soil direct shear; root collection.

Fig. 3 Root mass statistics

Legend: 60 d; 120 d; 180 d.

- **(a) Root dry weight**
  x-axis: soil-layer depth/cm; depth classes: 0–15, 15–30, 30–45, 45–60, 60–75, 75–90.
  y-axis: root dry weight/g.
- **(b) Root fresh weight**
  x-axis: soil-layer depth/cm; depth classes: 0–15, 15–30, 30–45, 45–60, 60–75, 75–90.
  y-axis: root fresh weight/g.

Fig. 4 Basic root system parameters

Legend: 60 d; 120 d; 180 d.

- **(a) Root water content**
  x-axis: water content/%; y-axis: soil-layer depth/cm.
- **(b) Specific root length**
  x-axis: specific root length/($\mathrm{cm \cdot g^{-1}}$); y-axis: soil-layer depth/cm.
- **(c) Root tissue density**
  x-axis: root tissue density/($\mathrm{g \cdot cm^{-3}}$); y-axis: soil-layer depth/cm.

smaller, with their ranges being 13.79-30.47 $\mathrm{cm \cdot g^{-1}}$ and 8.6-11.35 $\mathrm{cm \cdot g^{-1}}$, respectively, indicating that at the mature stage the root system of *Alhagi sparsifolia* tends toward thickening and structural stabilization.

Root tissue density (RTD) is the ratio of the total dry weight of roots in soil to the total root volume, and is a key indicator reflecting root construction strategies and physiological functions. As shown in Fig. 4c, the RTD of the *Alhagi sparsifolia* root system at the 60 d growth stage decreased with increasing soil depth, ranging from 0.2 to 0.43 $\mathrm{g \cdot cm^{-3}}$, indicating that the early-stage root tissue was still relatively loose and that the structure had not yet fully matured. As the growth period extended to 120 d and 180 d, RTD increased markedly overall, with the ranges rising to 0.64–0.97 $\mathrm{g \cdot cm^{-3}}$ and 0.54–1.23 $\mathrm{g \cdot cm^{-3}}$, respectively; compared with 60 d, these represented increases of 1.7–3.1 times and 1.2–4.3 times, respectively, reflecting intensified lignification and densification of the cellular structure in the middle and late stages. It is worth noting that the RTD of the 120 d specimens in the 0–30 cm surface soil layer was higher than that of the 180 d specimens, whereas in the 30-90 cm soil layer it was lower than that of the 180 d specimens. Under the same soil-layer conditions, the RTD of the 180 d specimens was 0.7-1.4 times that of the 120 d specimens, indicating that as the growth period entered the later stage, the developmental focus of the *Alhagi sparsifolia* root system gradually shifted from the surface layer to deeper layers.

As shown in Fig. 5a, the epidermis of the taproot of plants at the 60 d growth stage was relatively smooth, and several fibrous roots of different lengths were distributed on one side of the taproot, most of which were secondary roots. At the 120 d growth stage, as shown in Fig. 5b, the taproot diameter was significantly larger than at 60 d; the root system continued to grow and produced branches, and the surface roughness of the roots increased markedly. A rough surface plays a key role in increasing the friction angle between the root system and the soil mass. When the growth period reached 180 d, as shown in Fig. 5c, the taproot diameter further increased, and the number of fibrous roots also increased further. The densely distributed fibrous roots play a crucial role in enhancing the shear strength of the root-soil composite.

The average root diameters at different growth stages and different soil depths were measured using a root scanner, and the results are shown in Table 3. Overall, within the same growth period, root diameter tended to decrease as soil depth increased. For the 60 d specimens, the root diameters at different depths were relatively close; the average root diameters at 0-15 cm, 15-30 cm, and 30-45 cm were 1.35 mm, 1.27 mm, and 1.21 mm, respectively, with only small variation, indicating that no obvious spatial differentiation had yet formed in the early root structure. By contrast, for the 120 d and 180 d growth stages, the downward trend of average root diameter with depth was more pronounced. At 120 d, the average root diameters at 0-15 cm, 15-30 cm, and 30-45 cm reached 3.59 mm, 3.38 mm, and 3.00 mm, respectively; for the 180 d specimens, the average root diameters at the corresponding depths increased to 4.55 mm, 4.25 mm, and 3.96 mm, respectively. Under the same soil-depth conditions, the average root diameter increased significantly with growth period; for example, at the 15-30 cm soil depth, the average root diameter increased from 1.27 mm to 4.25 mm as the growth period extended.

2.2 Shear Stress and Shear Strain of the *Alhagi sparsifolia* Root-Soil Composite

Figure 6 presents the stress-strain curves of specimens from the 15-30 cm soil layer at three growth stages. During shearing, the specimens resisted shear deformation jointly through soil particles, the *Alhagi sparsifolia* root system, water, and air. Among these, the additional shear stress generated by tensile action in the roots was an important factor influencing the curve shape. As shear stress increased, the stress-strain curves showed small abrupt drops or rises, mainly reflecting two types of physical processes: first, stress redistribution caused by displacement of gravel within the specimen; and second, stress fluctuations induced by fracture of fibrous roots after they reached their ultimate tensile strength. With increasing normal stress, the peak shear strength of the specimens continuously increased. This was because an increase in normal stress enhanced the frictional force and bonding effect between the root system and soil particles, thereby improving the overall shear resistance of the composite [22] and reflecting the "pressure-hardening" behavior of the root-soil composite. Overall, the shear deformation patterns of specimens from different growth stages under different vertical stresses were similar, and the stress-strain relationship exhibited obvious nonlinearity; within the small-strain range

(a) 60 d (b) 120 d (c) 180 d

Fig. 5 Morphological characteristics of the root system

Tab. 3 Mean root diameter at different soil depths across growth stages

<table>
<tr><th>Soil depth/cm</th><th>Mean root diameter/mm, 60 d</th><th>Mean root diameter/mm, 120 d</th><th>Mean root diameter/mm, 180 d</th></tr>
<tr><td>0~15</td><td colspan="3">1.35$±0.18|3.59±0.29|4.55±0.12||15 30|1.27±0.25|3.38±0.30|4.25±0.05||30 45|1.21±0.17|3.</td></tr>
</table>

Note: The absence of data below 45 cm at 60 d is because the root system was mainly concentrated in the 0~45 cm soil layer.

At small strains of about 1% and below, the two were approximately linear. Thereafter, shear stress increased rapidly, the slope of the curve gradually decreased, and the shear stress entered a stable or continuously increasing stage. The shear responses of specimens at different growth stages differed to some extent. For the 60 d specimens, shear stress first increased with increasing displacement and then tended to stabilize, showing a strain- "stabilizing" type; whereas for the 120 d and 180 d specimens, shear stress continued to increase with increasing displacement, showing a strain- "hardening" type. This indicates that, as the growth stage was prolonged, the strengthening of the root structure and the enhancement of root-soil interface interactions enabled the composite to exhibit a stronger sustained load-bearing capacity under shear.

2.3 Shear strength of camelthorn root-soil composites

For stress-strain curves with peaks, the peak strength was taken; if no peak was present, the shear stress corresponding to an axial strain of 20% was taken as the shear strength. Figure 7 shows the shear strength of specimens at different growth stages. Under the low normal stress of 50 kPa, the stress state of the specimen was approximately equivalent to that of soil at a burial depth of 2.5 m. Because slope instability often occurs in the shallow layer at 1~2 m, the root system within this depth range usually penetrates the potential sliding surface. Therefore, analysis of shear strength under a normal stress of 50 kPa has clear practical engineering significance. Figure 7a shows the shear strength of specimens at different growth stages in each soil layer under a normal stress of 50 kPa. For the 60 d growth-stage specimens, the shear strength first increased and then decreased as soil depth increased, ranging from 33.33 to 39.56 kPa. The 180 d growth-stage specimens showed the same pattern of variation in shear strength, ranging from 44.44 to 64.44 kPa. The shear strength of the 120 d growth-stage specimens generally tended to decrease gradually with increasing soil depth, ranging from 44.44 to 50.22 kPa. Under the low-stress state of 50 kPa, the shear strength of specimens from the same soil layer generally increased with increasing growth stage.

Fig. 6 Stress–strain curves at different growth stages

Subfigures: (a) 60 d; (b) 120 d; (c) 180 d.
Legend: 50 kPa; 100 kPa; 200 kPa.
Axes: stress/kPa; strain/%.

Fig. 7 Shear strength at different growth stages

Subfigures: (a) 50 kPa; (b) 100 kPa; (c) 200 kPa.
Legend: 60 d; 120 d; 180 d.
Axes: shear strength/kPa; soil depth/cm.

trend. For the 0–45 cm specimens at growth stages of 120 d and 180 d, the mean shear strengths were 48.74 kPa and 56.44 kPa, respectively; compared with the shear strength of 36.74 kPa for the 60 d specimens, these values increased by 32.7% and 53.6%, respectively. Under medium and high stress states (100 kPa and 200 kPa), the shear strengths of the *Alhagi sparsifolia* specimens at growth stages of 120 d and 180 d were greater than those of the 60 d specimens; however, there was also a phenomenon in which the shear strength of the 120 d *Alhagi sparsifolia* specimens was greater than that of the 180 d specimens.

Figure 8 shows the variation in shear-strength parameters of the *Alhagi sparsifolia* root–soil composite with soil depth at different growth stages. Over the entire depth range, the internal friction angle of the 120 d specimens generally first increased and then decreased, varying from 31° to 35°. Cohesion showed the opposite trend, first decreasing and then increasing, with a range of 14.44–20.22 kPa. For the 180 d specimens, the internal friction angle exhibited a fluctuating upward trend with increasing depth, ranging from 29.7° to 35°; cohesion first increased and then decreased with soil depth, ranging from 9.79 to 29.55 kPa. For the 60 d specimens, cohesion changed with depth from 13.56 kPa to 13.78 kPa and then decreased to 6 kPa, while the internal friction angle gradually increased from 28.4° to 30.1°. These results reflect differences in strength response along the depth direction among different growth stages.

To systematically evaluate the influence of the *Alhagi sparsifolia* growth stage on shear-strength indices, all soil layers at the same growth stage were regarded as an integrated whole. Based on the mean shear strength of specimens at different depths under each vertical stress, fitting was performed to determine the strength parameters of the *Alhagi sparsifolia* root–soil composite at different growth stages. As shown in Fig. 9, the cohesion values of the specimens at the different growth stages were 11.11 kPa, 17.32 kPa, and 19.14 kPa, respectively, showing a significant increasing trend with growth stage; the internal friction angles were 29.24°, 32.62°, and 32.21°, respectively, indicating an initial increase followed by a slight decrease with growth stage. Compared with plain soil, the cohesion of the *Alhagi sparsifolia* root–soil composites at growth stages of 120 d and 180 d increased by 125.8% and 149.5%, respectively; compared with the 60 d growth stage, they increased by 55.9% and 72.3%, respectively. The internal friction angle differed little among growth stages, with a maximum difference of only 3.38° (between 60 d and 120 d), indicating that root growth and development had a limited effect on the internal friction angle, and that the enhancement of shear strength was mainly reflected in the increase in cohesion. In addition, the fitted shear-strength lines for the 120 d and 180 d stages nearly overlapped, indicating that the enhancement of soil shear performance by *Alhagi sparsifolia* roots mainly occurred during 0–120 d; after 120 d, the time effect in the soil was weakened. Thus, 0–120 d is the critical growth period during which *Alhagi sparsifolia* exerts its soil-reinforcement effect, which is similar to the conclusion of Mao Zhengjun et al. [23] in their study of the time effect of alfalfa.

Fig. 8 Shear strength parameters as a function of growth stage and soil depth

3 Discussion

The root system of *Alhagi sparsifolia* exhibits pronounced time-dependent evolutionary characteristics at different growth stages, with biomass accumulation, morphological structure, and water-content properties all showing stage-specific differences. This is similar to the conclusion of Mao et al. [24] that the root length density and root volume density of alfalfa vary significantly with growth stage. According to the experimental results, the growth process of *Alhagi sparsifolia* can be divided into three stages: the emergence stage (0–60 d), the rapid growth stage (60–120 d), and the seedling hardening stage (120–180 d). Root dry weight increased significantly with growth stage, and the root dry weights at 120 d and 180 d were both significantly greater than that at 60 d, indicating that *Alhagi sparsifolia* entered a stage of rapid underground biomass accumulation during 60–120 d. This characteristic is consistent with the pattern by which xerophytic shrubs rapidly expand their root systems at early stages to improve resource acquisition capacity [25]. The increment during 120–180 d gradually slowed, reflecting a gradual transition of the *Alhagi sparsifolia* root system from "quantitative expansion" to "structural reinforcement." Notably, the aboveground biomass of the 180 d specimens was slightly lower than that of the 120 d specimens, whereas the underground root system continued to grow. This resource-allocation pattern of "reduced aboveground biomass and continued underground root development" is a typical adaptive strategy by which deep-rooted desert vegetation maintains survival during overwintering and drought conditions. With the arrival of winter (November), plants allocate more resources underground, promoting root lignification (manifested as increased root tissue density) and extending roots into deeper soil layers. Together with the changes in root cellulose, hemicellulose, and lignin with growth stage shown in Table 1, this further indicates an increase in the degree of root lignification. Root morphological indices likewise exhibited systematic changes with growth stage. Specific root length was significantly higher at 60 d than at 120 d and 180 d, preliminarily indicating a transformation of the root system from a fine, absorption-oriented type to a coarse, support-oriented type. Compared with the emergence stage, the seedling hardening stage showed increased root diameter, higher root tissue density, and correspondingly improved mechanical properties [26]. Root water content increased with growth stage.

Fig. 9. Shear strength of specimens at different growth periods (a) Fitted straight lines
Legend: 60 d; 120 d; 180 d
Vertical axis: Shear strength/kPa
Horizontal axis: Normal stress/kPa

$$y = 11.11 + 0.56x, \quad R^2 = 0.99$$

$$y = 17.32 + 0.64x, \quad R^2 = 1.00$$

$$y = 19.14 + 0.63x, \quad R^2 = 0.97$$

(b) Shear-strength indices
Left vertical axis: Cohesion/kPa
Right vertical axis: Internal friction angle/(°)
Horizontal axis: Growth period/d
Legend: Cohesion; internal friction angle

Fig. 9. Shear strength during growth

shows a significant decreasing trend. This is related to the increase in root diameter and enhanced tissue lignification, which make the cellular arrangement more compact; this structural transformation also helps improve the ability of the root system to resist deformation[^27].

Fig. 10 shows the marked differences between the shear failure planes of shallow and deep camelthorn root-soil composites. As shown in Fig. 10a, the shallow root system has a high density. During shearing, the taproot undergoes obvious deflection along the shear direction, and a prominent zone of soil aggregation forms around the roots. The failure plane is relatively rough and contains localized concave structures, indicating that, under loading, the roots compress and constrain the surrounding soil[^28], causing the soil to undergo compression or restricted deformation along the shear direction. In contrast, the number of roots in the deep specimens is significantly reduced. As shown in Fig. 10b, the shear failure plane is smoother, and the soil-aggregation phenomenon is markedly weakened, indicating that differences in the spatial distribution of roots directly affect the shear failure mode. As shear displacement increases, the shear stress increases accordingly (Fig. 6). During this process, the root deflection angle also increases, leading to an increase in the tangential component of root tensile force, thereby enhancing the normal force and friction at the root–soil interface. This mechanism is consistent with the findings of Qi et al.[^29], namely that plant roots can alter the movement pattern of soil particles in the root–soil interface region by restricting the motion of local soil particles, thereby enhancing the overall stability of the composite system. Consequently, the shear stress increases with the development of shear displacement. In addition, the more numerous the root branches and the more complex the structure, the larger the effective contact area with the soil; thus, the interfacial frictional resistance and interlocking effect become more pronounced, further strengthening the shear resistance of the composite[^18]. This mechanism leads to the differences in the shear failure planes of shallow and deep specimens.

From the perspective of strength parameters, the enhancement effect of camelthorn roots on cohesion is significant and increases with the growth period, whereas their influence on the internal friction angle is relatively limited, increasing first with the growth period and then decreasing slightly. This pattern is consistent with the findings of Zonghua et al.[^30] and Wang et al.[^31] for root–soil composites of black locust and vetiver grass: that is, the reinforcing effect of roots is mainly reflected in a significant increase in cohesion, while the variation in internal friction angle is relatively small. Compared with plants such as black locust and vetiver grass, camelthorn, as a desert semi-shrub, has a root system characterized by "deep penetration and high lignification" ; in

(a) Shallow layer **(b) Deep layer**

Fig. 10. Shear failure planes of root–soil composites Fig. 10. Shear failure planes of root-soil composites

During the rapid growth stage (60–120 d), an effective deep reinforcement can already form, and the key period for soil fixation (60–120 d) is markedly earlier than that of alfalfa (150 d)[23]. This indicates that camelthorn can rapidly adapt to arid environments and form a stable soil-fixing structure, giving it outstanding application advantages in desert ecological restoration.

Across different growth stages of camelthorn (Fig. 5), root-surface roughness and branching structure changed over time. Specifically, at the emergence stage (60 d), the roots were relatively fine and their surfaces comparatively smooth; after entering the rapid growth and seedling hardening stages (120 d and 180 d), the roots gradually thickened and their surfaces became rougher. These changes may, to a certain extent, enhance friction at the root-soil interface. However, for sandy soil, because the soil particles are relatively large and the structure is loose, local contact gaps may exist between roots and soil, potentially limiting the improvement in the internal friction angle caused by increased roughness. Meanwhile, the differences in root-surface roughness and branching structure between the rapid growth stage and the seedling hardening stage weakened, causing the influence of prolonged growth duration on the internal friction angle to gradually decrease. Under low-stress conditions, shear strength generally increased with growth duration, but a local anomaly appeared in the surface layer, where the shear strength of the 120 d sample was slightly higher than that of the 180 d sample (Fig. 7). Possible causes of this phenomenon include differences in the spatial distribution of roots, the influence of root growth angle on interfacial friction[32], and the evolution of root mechanical properties with growth stage. During 60–120 d, the roots were in a vigorous growth period, with more fibrous roots and greater flexibility, making the root-soil interlocking effect more pronounced; by 180 d, however, root lignification had increased and flexibility decreased, making roots more prone to brittle fracture during shearing and thereby weakening their contribution to cohesion. In addition, experimental operation may also have caused local deviations. For example, in surface-layer samples, the harder 180 d root-stem structure may have produced a "supporting" effect when vertical stress was applied, thereby affecting the transmission of effective stress. Under medium- and high-stress conditions, the phenomenon that the shear strength of the 120 d sample exceeded that of the 180 d sample also occurred, indicating that under medium- and high-stress states, growth duration was no longer the dominant factor affecting shear strength. At this time, under relatively high loading, the root-soil composite was significantly compacted, and roots were more likely to deform or fracture during shearing, causing damage to the composite structure. The soil-fixing capacity of the roots was thus markedly weakened, and shear strength was mainly controlled by the soil's own structure[33]. In addition, under the same growth duration, the fluctuation of cohesion with depth (Fig. 8) reflects the spatial heterogeneity of root distribution and root-soil interfacial interaction. Among them, the 180 d sample showed the most pronounced fluctuation, which may have been jointly caused by uneven deep-root distribution and differences in water content among soil layers[11]. Overall, these local fluctuations are reasonable variations during root development and do not affect the dominant pattern of shear strength changes with growth duration.

From the perspective of the mechanism of root-soil interaction, its mechanical behavior is influenced not only by root geometry and distribution characteristics, but also by the synergistic effects of multiple microstructural and biochemical processes. In addition to being governed by root morphology and tensile-fracture performance, soil shear strength is also related to root bending, branching structure, root-hair distribution, biological secretions, and soil water content; together, these factors promote the formation of more stable aggregate structures among soil particles[34]. Among them, the degree of root bending, branch growth, and the amount of secretions are all regulated by root growth stage; therefore, root-soil interaction is essentially characterized by significant time dependence. Moreover, as root diameter gradually increases and penetrates the soil, radial expansion is imposed on the surrounding soil mass, making the root-soil interface more compact. This process not only enhances interfacial friction, but also increases electrostatic forces and van der Waals forces among soil particles[17], thereby jointly improving the macroscopic shear strength of the root-soil composite. During growth, camelthorn roots may enhance soil cohesion by improving soil pore structure and secreting organic cementing substances, thereby increasing the shear strength of the soil mass[35-36]. In this study, large-scale direct shear tests were conducted on undisturbed camelthorn root-soil composites. Compared with the common experimental method of artificially inserting roots into remolded soil, this approach can preserve the natural contact state of the root-soil interface to the greatest extent and more realistically reflect the mechanical behavior of root-based soil reinforcement. Nevertheless, the method used in this study still has certain limitations. On the one hand, camelthorn of the same growth duration was used in the experiments, which minimized differences in spatial root distribution as much as possible; however, the spatial variability of naturally grown roots and the resulting discreteness of experimental data are unavoidable. Subsequent experiments could reduce data dispersion by increasing the number of parallel samples. On the other hand, in order to reproduce the real growth environment of camelthorn, water content in different soil layers was not controlled during the experiment. Future studies could design control groups, with water-supplementation treatments and controlled water content, to investigate the influence of different water contents at the same growth duration on the shear strength of camelthorn root-soil composites.

4 Conclusions

(1) Within the scope of this study, camelthorn roots exhibited significant time-sequential developmental patterns at different growth stages, and their biomass, morphological structure, and water-content characteristics all showed staged evolutionary features. The growth process was divided into three stages: emergence stage (0-60 d), rapid growth stage (60-120 d), and seedling hardening stage (120-180 d). With increasing growth duration, root diameter increased, root tissue density rose, and water content decreased, reflecting functional transformation of the root system and embodying the ecological strategy by which camelthorn adapts to drought and overwintering environments through resource reallocation and structural optimization.

(2) Under low-stress conditions, the shear strength of the camelthorn root-soil composite increased with increasing growth duration, and camelthorn roots in silty sand could still effectively exert a reinforcement effect at a burial depth of about 2.5 m. Under medium- and high-stress conditions,

the soil-fixing effect exerted by the root system was weakened [[unclear: continuation below page not visible]].

weakened, and the dominant role of the matrix was enhanced.

(3) Cohesion increased with the extension of the growth period, whereas the internal friction angle showed a trend of increasing first and then decreasing as the growth period was extended. Compared with plain soil, the cohesion of the camelthorn root-soil composite at growth periods of 120 d and 180 d increased by 125.8% and 149.5%, respectively; compared with the 60 d growth period, it increased by 55.9% and 72.3%, respectively. The increase in internal friction angle was relatively small. The shear-strength indices at 120 d and 180 d were close to each other and greater than those at 60 d. Within the growth period, 60–120 d is the key growth stage during which camelthorn exerts its soil-reinforcement effect.

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Shear strength of the *Alhagi sparsifolia* root-soil composite over time

ZHU Jianlin1,2, LI Qinglin1,2, LUO Xuanbing1,2, WANG Bowei1,2, YU Shuailong1,2

(1. School of Water Conservancy and Architecture, Shihezi University, Shihezi 832000, Xinjiang, China;
2. Key Laboratory of Ecological and Hydraulic Engineering Corps in Cold and Arid Areas,
Shihezi 832000, Xinjiang, China)

Abstract: This study aimed to investigate the typical desert vegetation *Alhagi sparsifolia* in northwestern China. Samples of root-soil composite were prepared by artificially cultivating *Alhagi sparsifolia* in PVC pipes. The aboveground biomass and root distribution characteristics of *Alhagi sparsifolia* were measured, and the shear strength parameters of the root-soil composite were determined using large-scale direct shear tests. The effects of growth stage and soil layer depth on the shear strength of the root-soil composite were analyzed. Based on the growth indicators of *Alhagi sparsifolia*, the growth period can be divided into three stages: emergence (0–60 d), rapid growth (60–120 d), and seedling hardening (120–180 d). Root biomass, average root diameter, and root tissue density were positively correlated with growth stage, whereas root water content and specific root length were negatively correlated with growth stage. The most significant changes were observed during the rapid growth stage. The effect of time on the shear strength parameters of the *Alhagi sparsifolia* root-soil composite was primarily reflected by an increase in cohesion. The cohesion values during the different stages were 11.11 kPa, 17.32 kPa, and 19.14 kPa, representing increases of 44.9%, 125.8%, and 149.5%, respectively, compared with cohesion of plain soil. The internal friction angle was less affected. These results describe the temporal variation in the shear strength of the *Alhagi sparsifolia* root-sandy soil composite, providing important scientific insights for the future characterization of soil stabilization and slope protection by desert vegetation in arid regions.

Keywords: root-soil composite; *Alhagi sparsifolia*; shear strength; time effect

Note: Figure translations are in progress. See original paper for figures.