GROWTH-DEPENDENT DRAINED MECHANICAL BEHAVIOR OF ALFALFA-REINFORCED LOESS

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Abstract: This study investigates the influence of vegetation growth period on the drained mechanical behaviour of loess reinforced with Medicago sativa L (Alfalfa). Loess specimens were cultivated for 30, 60, and 90 days and tested using consolidated drained triaxial compression under effective confining pressures of 50, 75, and 100 kPa. Results show that progressive root development significantly enhances shear strength and reduces volumetric contraction. At σ_3' = 50 kPa, peak deviatoric stress increased from 103.29 kPa (unreinforced) to 164.57 kPa at 90 days, corresponding to a strength gain of approximately 60%, while volumetric contraction decreased by about 31%. The results demonstrate that vegetation-induced stabilization of loess evolves progressively with root development and must be incorporated into engineering evaluations as a growth-period- and stress-dependent reinforcement mechanism.

Keywords: loess; root reinforcement; triaxial test; vegetation growth period; soil-root interaction

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1.Introduction

Loess deposits cover large areas of northern China and form the foundation of many natural and engineered slopes. Due to their Aeolian origin, loess soils are characterized by an open structure, high porosity, and weak interparticle bonding, which result in low resistance to deformation under shallow stress conditions [1-3]. These features make loess particularly sensitive to environmental disturbances, such as rainfall infiltration and surface erosion, which commonly trigger shallow slope failures [4]. Field investigations across the Chinese Loess Plateau, including surveys in Shanxi Province, have reported thousands of loess-related slope failures that have caused widespread damage to infrastructure and agricultural land [5]. The frequent occurrence of shallow instability highlights the need for stabilization approaches that are effective within near-surface soil layers.

Conventional stabilization methods, such as rigid retaining structures and ground reinforcement systems, are often applied to mitigate loess slope failures. However, these methods can be costly, environmentally intrusive, and poorly suited to shallow failures governed by surface processes. As an alternative, vegetation-based stabilization has been increasingly promoted for loess slopes because it combines mechanical reinforcement with ecological benefits [6-8]. From a mechanical perspective, plant roots can improve soil stability by increasing shear resistance and restricting deformation within the root-permeated zone[9, 10].

Experimental studies have demonstrated that roots enhance soil shear strength primarily by mobilizing tensile resistance and increasing soil–root interfacial friction. Early investigations using direct shear tests showed that shear strength increases with root tensile capacity and root density within the failure zone [11-13]. Later studies confirmed that root reinforcement depends on both root characteristics and soil properties [9, 14-16]. Despite their usefulness, direct shear tests impose a predefined failure plane and do not adequately represent stress redistribution and deformation processes in naturally rooted soils [17].

To address these limitations, triaxial testing has been increasingly adopted to study the mechanical behavior of root-reinforced soils under controlled stress conditions [9, 10, 18-20]. Triaxial tests allow independent control of confining pressure and drainage, enabling more realistic evaluation of soil–root interaction. Previous triaxial studies have shown that increasing root content leads to higher shear strength and reduced volumetric contraction during drained shearing [9, 10, 20]. However, many of these studies rely on specimens prepared by artificially mixing roots into the soil, which does not represent the progressive development of root systems that occurs in vegetated slopes.

In natural conditions, root reinforcement develops gradually as plants grow. The growth period controls root biomass accumulation, root geometry, and network continuity, which together govern the magnitude of soil–root interaction. Experimental evidence indicates that increasing plant age results in higher peak shear strength and improved volumetric stability, as more developed root systems provide greater tensile resistance and internal restraint [10, 21-23]. Root mechanical efficiency is further influenced by architectural traits such as root diameter and branching pattern [24-28]. Nevertheless, the growth-period-dependent mechanical behavior of naturally rooted loess under low confining pressures remains insufficiently quantified.

This study investigates the effect of vegetation growth period on the drained mechanical behavior of loess reinforced with Medicago sativa L (Alfalfa). M. sativa L was selected due to its widespread application in loess slope restoration and its ability to develop an effective root system within short growth periods. Loess specimens were cultivated for 30, 60, and 90 days and tested using consolidated drained triaxial compression under effective confining pressures of 50, 75, and 100 kPa. The mechanical response was evaluated through stress–strain behaviour, volumetric deformation to clarify how progressive root development influences loess strength and deformation. The results provide experimental insight into the time-dependent contribution of root reinforcement to shallow loess stability.

2.Materials and experimental program

2.1 Soil Properties and Plant Species Selection

The soil used in this study was a natural loess collected from a slope near Taiyuan City (Lat =37°57'29.25", Long. 112°37'48.83") in Shanxi Province, China. This area lies within the eastern Chinese Loess Plateau, where loess deposits are thick, weakly bonded, and prone to collapse under shallow stress conditions [29]. Sampling was carried out at locations with negligible surface vegetation to avoid the influence of pre-existing roots. The surface layer was removed, and soil was obtained from depths of 0.2–0.6 m. The collected material was sealed immediately after excavation and transported to the laboratory. The resulting gradation curve is shown in Fig. 1, indicating that the soil is dominated by silt-sized particles with minor sand contents, consistent with typical Aeolian loess [30]. Compaction characteristics were determined using modified Proctor tests (ASTM D1557), yielding an optimum water content of 12.5% and a maximum dry density of 1.56 g cm^{-3}. Scanning electron microscopy images (Fig. 2) reveal a loose and porous fabric composed of angular particles and inter-aggregate voids, reflecting the metastable nature of natural loess.

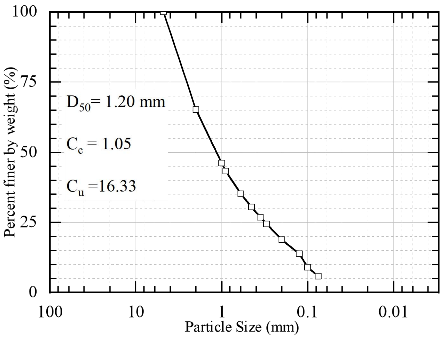

Fig. 1 Grain-size distribution of the tested loess

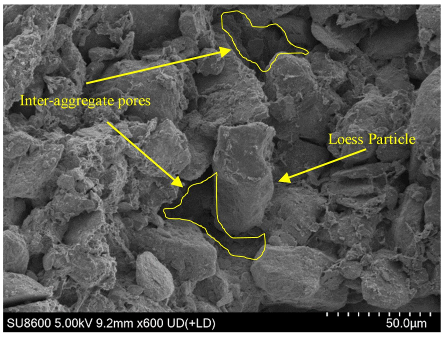

Fig. 2 Scanning Electron Microscope (SEM) of the tested loess

Medicago sativa L (Alfalfa) was adopted as the reinforcing vegetation to examine the growth-period-dependent mechanical response of root-reinforced loess. M. sativa L is commonly implemented in loess slope rehabilitation and erosion control projects, providing practical relevance to the present study [31, 32]. Its root system is dominated by a distinct taproot accompanied by branching lateral roots, which enables effective soil anchorage and the development of measurable soil–root interaction within short cultivation periods [31].

2.2 Specimen Preparation and Growth Procedure

Prior to specimen preparation, the loess was oven-dried at 105 °C for 24 h and then mixed with distilled water to reach the target moisture content corresponding to optimum compaction. The conditioned soil was statically compacted into cylindrical PVC molds with an internal diameter of 75 mm and a height of 200 mm. After compaction, the soil surface was lightly roughened and seeded uniformly with M. sativa L. seeds at a rate of 20–27.5 g m^{-2}, following standard practice for controlled vegetation experiments [33]. The planted specimens were placed outdoors under natural environmental conditions inside a transparent shelter that prevented direct rainfall while allowing air circulation (Fig. 3a). Seed germination occurred within 2–4 days, and specimens were cultivated for growth periods of 30, 60, and 90 days (Fig. 3b). These growth durations represent early developmental stages during which root systems undergo rapid expansion and biomass accumulation [34]. Throughout the cultivation period, all specimens were watered regularly and subjected to identical environmental conditions.

At the end of each growth period, the PVC molds were carefully split and removed to extract intact root–soil columns (Fig. 3c). The central portion of each column was trimmed to standard triaxial dimensions of 50 mm in diameter and 100 mm in height using a thin-walled cutting sleeve (Fig. 3d). Unreinforced loess specimens were prepared using the same compaction and trimming procedures to provide a consistent reference condition.

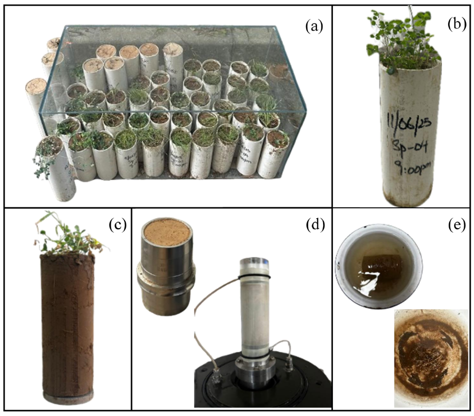

Fig. 3 Experimental workflow for M. sativa L-reinforced loess: (a) vegetated columns during cultivation; (b) representative column at selected growth age; (c) intact root–soil core extraction; (d) trimming and triaxial specimen setup; (e) post-test root washing and recovery for root biomass measurement.

3.Results

The mechanical behavior of loess under low confinement is significantly modified by progressive root development. The drained responses at $\sigma_3' = 50$ kPa are shown in Fig. 4 ($q - \varepsilon_a$) and ($\varepsilon_v - \varepsilon_a$), where the unreinforced soil provides the baseline for assessing the influence of M. sativa L growth at 30, 60, and 90 days.

As shown in Fig. 4, the unreinforced loess exhibits typical strain-hardening behavior under drained loading, reaching a deviatoric stress of approximately 103 kPa at 15% axial strain. The stress increase gradually stabilizes at moderate strains, reflecting the weak bonding and contractive nature of the soil structure. In contrast, all vegetated specimens demonstrate consistently higher stress levels throughout shearing, and the magnitude of this increase becomes more pronounced with longer growth duration.

At 30 days, the reinforced specimen mobilizes approximately 126 kPa at 15% axial strain, representing an increase of about 22% relative to the unreinforced soil. At 60 days, the stress level increases further to roughly 144 kPa (≈39% increase), while the 90-day specimen reaches approximately 165 kPa, corresponding to an overall strength enhancement of nearly 60% compared with the plain loess. In addition to higher peak stress, the initial tangent stiffness increases systematically with growth period, indicating improved resistance to deformation at small strains. The progressive upward shift of the stress–strain curves confirms that shear resistance is increasingly mobilized as root biomass develops.

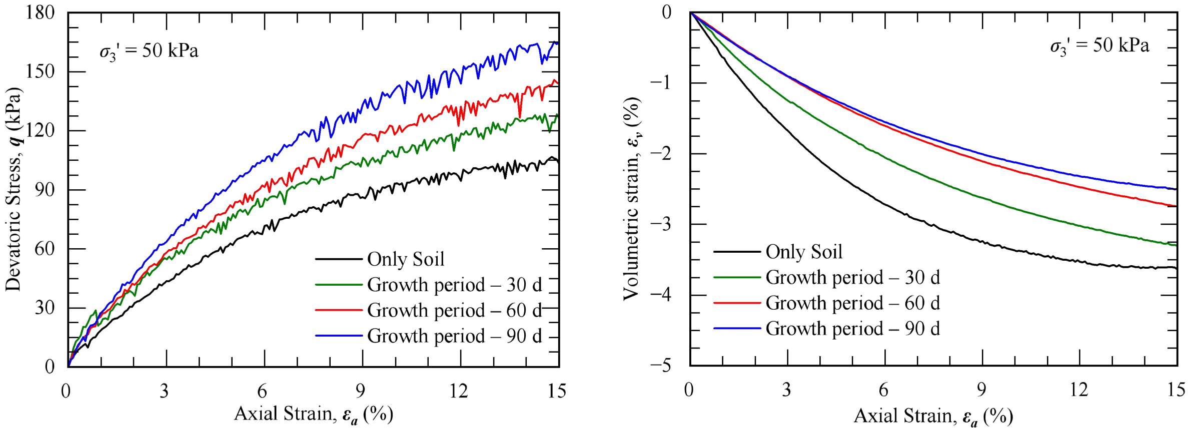

Fig. 4 Stress–strain and volumetric behavior of M. sativa L -reinforced loess at different vegetation growth periods under σ_3' = 50 kPa

The volumetric responses in Fig. 4 reveal that all specimens undergo contractive deformation during drained shearing; however, the magnitude of contraction decreases with vegetation growth period. The unreinforced soil exhibits a volumetric strain of approximately −3.6% at 15% axial strain. Reinforcement at 30 days reduces contraction to about −3.3%, while further reductions to approximately −2.7% and −2.5% are observed at 60 and 90 days, respectively. The total reduction in volumetric contraction between unreinforced soil and the 90-day specimen is therefore on the order of 28–30%. Moreover, the rate of volumetric contraction diminishes more rapidly for longer growth periods, indicating improved internal restraint against particle rearrangement.

Taken together, the stress–strain and volumetric results demonstrate that vegetation growth period exerts a systematic control on the mechanical behavior of loess. Increasing root development leads to higher deviatoric stress mobilization, greater stiffness, and reduced contractive tendency under identical stress conditions. The most significant enhancement occurs between 60 and 90 days, corresponding to accelerated root biomass accumulation. These findings confirm that progressive root development substantially strengthens and stabilizes the soil–root composite under low confining pressure.

4.Conclusions

Based on consolidated drained triaxial testing of M. sativa L-reinforced loess cultivated for 30, 60, and 90 days under effective confining pressures of 50–100 kPa, the following conclusions are drawn:

Vegetation growth period systematically controls both shear strength mobilization and volumetric response. At σ_3' = 50 kPa, peak deviatoric stress increased from 103.29 kPa (unreinforced) to 126.29 kPa, 143.88 kPa, and 164.57 kPa at 30, 60, and 90 days, corresponding to strength increases of approximately 22%, 39%, and 60%, respectively. Over the same growth interval, volumetric strain at 15% axial strain decreased from −3.63% to −3.30%, −2.74%, and −2.49%, representing a maximum contraction reduction of approximately 31%. These results indicate that progressive root biomass accumulation increases both load-carrying capacity and resistance to contractive deformation, with the most significant improvement occurring between 60 and 90 days.

Confining pressure directly influences the absolute strength level and enhances reinforcement mobilization. For 90-day specimens, peak deviatoric stress increased from 164.57 kPa at 50 kPa to 248.48 kPa at 75 kPa and 307.76 kPa at 100 kPa. Across all growth periods, increasing σ_3' produced higher stiffness and greater shear resistance. The interaction between confinement and root development was most evident at 75–100 kPa, where both strength enhancement and volumetric stabilization were amplified, indicating improved soil–root interfacial stress transfer under higher normal stress.

Overall, M. sativa L (Alfalfa) reinforcement modifies the drained mechanical behavior of loess through a growth-dependent increase in apparent cohesion accompanied by reduced volumetric contraction. The reinforcement effect evolves progressively with root development and is amplified under higher effective confinement, emphasizing that vegetation-induced stabilization of shallow loess slopes must be evaluated with explicit consideration of both growth stage and stress conditions.

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