ChinaRxiv

AI translation · View original & related papers at
chinarxiv.org/items/chinaxiv-202412.00225

Combined effects of polymer SH and ryegrass on the water-holding characteristics of loess (Postprint)

Authors: YING Chunye

Date: 2024-12-17T00:00:00+00:00

Abstract

The Chinese Loess Plateau has long been plagued by severe soil erosion and water scarcity. In this study, we proposed a technique involving the combined use of polymer SH and ryegrass and evaluated its effectiveness in modifying the water-holding characteristics of loess on the Chinese Loess Plateau (Chinese loess). We analysed the volumetric water content and water potential of untreated loess, treated loess with single polymer SH, treated loess with single ryegrass, and treated loess with both polymer SH and ryegrass using the loess samples collected from the Chinese Loess Plateau in July 2023. Moreover, fractal theory was used to analyse the fractal characteristics of the soil structure, and wet disintegration tests were conducted to assess the structural stability of both untreated and treated loess samples. The results showed that the loess samples treated with both polymer SH and ryegrass presented much higher volumetric water content and water potential than the untreated loess samples and those treated only with ryegrass or polymer SH. Moreover, the planting density of ryegrass affected the combined technique, since a relatively low planting density (20 g/m2) was conducive to enhancing the water-holding capacity of Chinese loess. The fractal dimension was directly correlated with both volumetric water content and water potential of Chinese loess. Specifically, since loess treated with both polymer SH and ryegrass was more saturated with moisture, its water potential increased, thus improving its water-holding capacity and fractal dimension. The combined technique better resisted disintegration than ryegrass alone but had slightly less resistance than polymer SH alone. This study provides insight into soil reinforcement and soil water management using polymetric materials and vegetation on the Chinese Loess Plateau.

Full Text

Preamble

Journal of Arid Land (2024) 16(12): 1686–1700
doi: 10.1007/s40333-024-0089-9; CSTR: 32276.14.JAL.02400899
Science Press Springer-Verlag

Combined Effects of Polymer SH and Ryegrass on the Water-Holding Characteristics of Loess

YING Chunye[1], LI Chenglong[2], LI Lanxing[3]*, ZHOU Chang[4]

[1] School of Geological Engineering, Qinghai University, Xining 810016, China
[2] Petroleum Engineering Technology Research Institute of Shengli Oilfield, SINOPEC, Dongying 257000, China
[3] Army Engineering University of PLA, Xuzhou 221000, China
[4] School of Resources and Geosciences, China University of Mining and Technology, Xuzhou 221116, China

Abstract: The Chinese Loess Plateau has long been plagued by severe soil erosion and water scarcity. In this study, we proposed a technique involving the combined use of polymer SH and ryegrass and evaluated its effectiveness in modifying the water-holding characteristics of loess on the Chinese Loess Plateau. We analyzed the volumetric water content and water potential of untreated loess, loess treated with polymer SH alone, loess treated with ryegrass alone, and loess treated with both polymer SH and ryegrass using samples collected from the Chinese Loess Plateau in July 2023. Moreover, fractal theory was used to analyze the fractal characteristics of soil structure, and wet disintegration tests were conducted to assess the structural stability of both untreated and treated loess samples. The results showed that loess samples treated with both polymer SH and ryegrass exhibited much higher volumetric water content and water potential than untreated samples and those treated only with ryegrass or polymer SH. Moreover, the planting density of ryegrass affected the combined technique, as a relatively low planting density (20 g/m^2) was conducive to enhancing the water-holding capacity of Chinese loess. The fractal dimension was directly correlated with both volumetric water content and water potential of Chinese loess. Specifically, since loess treated with both polymer SH and ryegrass was more saturated with moisture, its water potential increased, thus improving its water-holding capacity and fractal dimension. The combined technique better resisted disintegration than ryegrass alone but had slightly less resistance than polymer SH alone. This study provides insight into soil reinforcement and water management using polymeric materials and vegetation on the Chinese Loess Plateau.

Keywords: loess; ryegrass; polymer SH; water-holding characteristics; fractal theory; Chinese Loess Plateau

Citation: YING Chunye, LI Chenglong, LI Lanxing, ZHOU Chang.

2024. Combined effects of polymer SH and ryegrass on the water-holding characteristics of loess. *Journal of Arid Land*, 16(12): 1686–1700. https://doi.org/10.1007/s40333-024-0089-9; https://cstr.cn/32276.14.JAL.02400899

Introduction

The Chinese Loess Plateau, one of the most well-known regions, hosts the largest loess deposit in the world in terms of both depth and area (Huang and Shao, 2019). It is characterized by severe soil erosion and water scarcity. Soil water-holding characteristics refer to the soil' s ability to retain water and describe the relationship between soil suction and humidity (degree of saturation, gravimetric water content, or volumetric water content). These characteristics are closely related to the deformation, strength, and permeability of unsaturated soil (Vanapalli et al., 1996; Fredlund, 2006). The water-holding characteristics of loess on the Chinese Loess Plateau have significant direct impacts on food security, human health, and the overall functioning of ecosystems (Gomiero, 2016; Chen et al., 2024). Current efforts concentrate on modifying the water-holding characteristics of Chinese loess by implementing various measures such as vegetation cover (Zhang et al., 2021c; Qiu et al., 2024), chemical materials (Zhang et al., 2021b; Zhang et al., 2023), and biogeochemical improvements (Xue et al., 2022; Yang et al., 2022).

Among chemical materials, polymer SH—an organic polymer curing material developed by Lanzhou University, China (Chen et al., 2017)—offers numerous advantages, including low viscosity, non-toxic composition, cost efficiency, ease of application, adjustable gelation time, complete water solubility, and exceptional homogeneity when blended with soil (Wang et al., 2005). Consequently, it has broad application prospects in ecological modification. Currently, its application has been extended from initial loess improvement to granite residual soil (Yuan et al., 2023) and coarse-grained soil at earthen ruins (Zhang et al., 2020). Extensive studies have demonstrated that polymer SH treatment significantly improves various loess properties, including liquid limit, plastic limit, stability, unconfined compressive strength, low-temperature resistance, and ability to withstand dry-wet and freeze-thaw cycles (Qin et al., 2008; Chen et al., 2017; Zhang et al., 2021a). Moreover, a notable decrease in accumulative sediment yield and collapsibility has been observed in polymer SH-treated soil (Ying et al., 2024). Due to these positive effects, polymer SH can protect loess slopes by forming protective layers that maintain good water-holding capacity and increase erosion resistance (Li et al., 2016).

Vegetation is an important measure for modifying soil water-holding characteristics (Shi and Shao, 2000; Haruna et al., 2020). In general, plants contribute to increasing soil water-holding capacity through various mechanisms, including water absorption by roots (Leenaars et al., 2018), shading to reduce evaporation (Williams et al., 1993), increasing soil cohesion (Suzuki et al., 2007), providing plant litter coverage (Xie and Su, 2020), improving soil structure (Suzuki et al., 2007), enhancing microbial activities (Zheng et al., 2018), and increasing organic matter content (Lal, 2020). These functions are interrelated and interdependent, collectively sustaining the stability and sustainability of the soil ecosystem. As typical vegetation for soil and water conservation, ryegrass has been successfully used in America (Malik et al., 2000), Brazil (Ramos et al., 2014), Portugal (Trindade et al., 2009), and China (Zhou and Shangguan, 2008), among other countries. Ryegrass can increase the organic matter content of loess, adjust soil temperature, decrease wind speed and relative light intensity, and improve water-holding capacity (Li et al., 2009). Additionally, ryegrass planting can effectively control soil erosion and reduce sediment yield and runoff (Zhou and Shangguan, 2007; Zhou and Shangguan, 2008; Dong et al., 2015), thus affecting soil water-holding characteristics. The ability of ryegrass to enhance soil water-holding characteristics is directly associated with changes in soil physicochemical properties during its growth process. Specifically, as ryegrass grows, root activities and organic matter decomposition modify soil structure, increase soil porosity, and consequently enhance water-holding capacity (Angers and Caron, 1998; Koudahe et al., 2022). An experiment on ryegrass with growth periods of 4–16 weeks revealed that with prolonged growth in loess, soil bulk density gradually decreased, whereas water-stable aggregates and organic matter contents progressively increased (Qin, 2016). However, herbaceous vegetation growth is a long-term process, and long-term monitoring is necessary to accurately reflect vegetation impacts on soil properties.

Both polymer SH and ryegrass alone can effectively modify the water-holding characteristics of loess. Ryegrass can penetrate deeply into loess with its well-developed root system, stabilizing loess particles to reduce soil erosion, absorbing water from the ground through transpiration, and consequently increasing water-holding capacity (Ying et al., 2024). Meanwhile, polymer SH can form stable aggregate structures in loess due to its unique three-dimensional network structure, which enhances porosity, permeability, and water-holding capacity (Qin et al., 2008; Zhang et al., 2021a). During its degradation process, polymer SH can provide nutrients for ryegrass and promote its growth (Ying et al., 2024). However, current research into the combined effects of polymer SH and ryegrass on loess water-holding characteristics remains inadequate.

Understanding the intricate relationship between soil structure and water-holding capacity is crucial, necessitating advanced methods to accurately model and interpret these dynamics. To facilitate this, experimental data obtained from soil-water characteristic curve tests, which tend to be discrete, are typically fitted using mathematical models. Commonly used models include the Campbell model (Jabro et al., 2009; Pittaki-Chrysodonta et al., 2018) and van Genuchten model (Ghanbarian-Alavijeh et al., 2010; Wei et al., 2019). However, the physical meanings of parameters in these models are often unclear, and accurately determining these parameters can be challenging. In contrast, the fractal method, which uses fractal theory to determine the soil-water characteristic curve, provides parameters directly related to soil structure properties with clear physical meanings (Comegna et al., 1998; Yang et al., 2023). This renders the fractal method an ideal approach for fitting the soil-water characteristic curve and providing insights into soil structure and its relationship with water-holding capacity.

The primary objectives of this study are to: (1) evaluate the combined effects of polymer SH and ryegrass on the water-holding characteristics of Chinese loess; and (2) investigate the relationship between soil structure and water-holding capacity using fractal theory. To achieve these objectives, we designed an experiment including six groups of loess samples and monitored the volumetric water content and water potential during ryegrass growth to quantify changes in water-holding capacity. Furthermore, fractal theory was applied to analyze soil structure and offer deeper insights into the underlying mechanisms of observed changes. The outcomes of this study are anticipated to clarify the synergistic effects of polymeric materials and vegetation and help formulate efficient soil stabilization and water management strategies for the Chinese Loess Plateau.

Materials and Methods

2.1.1 Loess

The loess used in this study was collected in July 2023 from a gentle slope in Zichang County, Shaanxi Province, located on the Chinese Loess Plateau [Figure 1: see original paper]. The sampling depth was 20.0 cm below the surface. According to Zeng and Huang (2010), loess from this region exhibits a meta-stable structure characterized by high porosity, low foundation bearing pressure, and remarkable collapsibility.

Particle size distribution was determined through sieve analysis and hydrometer testing. Grading criteria followed the Standard for Engineering Classification of Soil (Ministry of Housing and Urban-Rural Development of the People' s Republic of China, 2008), revealing that samples comprised 11.09% clay (particle size $d \leq 0.005$ mm), 87.39% silt ($0.005 \text{ mm} < d \leq 0.075$ mm), and 1.52% sand ($0.075 \text{ mm} < d \leq 2.000$ mm). In accordance with the Standard for Geotechnical Testing Method (Ministry of Housing and Urban-Rural Development of the People' s Republic of China, 2019), fundamental tests were conducted to assess physical properties, with results presented in Table 1 . Based on the Unified Soil Classification System (USCS) outlined by ASTM (2011), the loess samples were categorized as low-liquid-limit clay.

2.1.2 Polymer SH

Polymer SH is an organic curing material developed by Lanzhou University, consisting primarily of a hydrophobic macromolecular chain connected by C-C bonds with hydroxyl (-OH) and carboxyl (-COOH) hydrophilic groups interspersed throughout. This polymer has a density of 1.09 g/cm^3 and an approximate molecular weight of 20,000.

As reported by Wang (2016), optimal conditions for treating loess with polymer SH were determined through comprehensive analysis of the impact of polymer

SH concentration and curing time on various physical and mechanical properties, including compressive strength, shear strength, compressibility, and permeability. Previous mechanical tests revealed that a curing period of 28 days and an application rate of 3.00% polymer SH constituted optimal treatment conditions. Consequently, this study sprayed loess samples with a 3.00% polymer SH solution and required a 28-day curing period.

2.1.3 Ryegrass

Perennial ryegrass (*Lolium perenne* L.) has been extensively used to manage soil and water loss in loess regions. This species boasts a high germination rate, rapid growth, and relatively low seed price, making it easily accessible (Young et al., 1975). Considering sowing expertise at the sampling site and specific test conditions, ryegrass planting densities were established at 20 and 40 g/m^2 for comparative purposes. Since ryegrass requires more than two weeks to establish its root system, a 28-day curing period was determined for ryegrass-treated loess. Additionally, a 22-day data collection period was used to reveal the influence pattern of ryegrass growth duration on soil water-holding capacity.

Six groups of untreated and treated loess samples were established for testing water-holding characteristics and disintegration abilities (Table 2). Each group contained three parallel samples; in the analysis, the average value of measurements from three parallel samples was adopted as the final result.

2.2.1 Monitoring Volumetric Water Content and Water Potential

In experiments monitoring soil volumetric water content and water potential, each set of parallel loess samples had uniform dimensions of 30.0 cm × 40.0 cm × 20.0 cm. The preparation process comprised several crucial steps. First, thoroughly air-dried and sieved loess was prepared. Second, a 3.00% polymer SH solution was sprayed onto the loess surface to ensure uniform mixing according to the preset maximum dry density (MDD) and optimal moisture content (OMC) of 1.50 g/cm^3 and 16.86%, respectively. Third, loess samples were shaped to the specified dimensions. Fourth, ryegrass seeds were sown onto the surface, followed by application of a 0.5-1.0 cm thick layer of nutrient soil (peat blended with perlite) to promote growth. Fifth, samples were transferred to a plastic greenhouse and cured for 28 days.

A comprehensive setup monitored volumetric water content and water potential during curing. As depicted in Figure 2 [Figure 2: see original paper], since ryegrass root depth is 4.0-9.0 cm, water content sensors (EC-5, Beijing Haohan Technology Co., Ltd.) with a measurement range of 0.00%-100.00% and water potential sensors (TEROS 21, Shenzhen Jiuzhou Industrial Products Co., Ltd.) with a range from -9 to -100,000 kPa were buried 10.0 cm below the top surface. These sensors were integrated with a data collector (Em50, Beijing Dorgean Electronic Technology Co., Ltd.) for efficient data retrieval. Flora detectors were inserted to monitor the ryegrass growing environment and ensure optimal conditions, including suitable temperature and adequate illumination. Due to the immature root system during the first week after planting, volumetric water content and water potential were not measured. Data collection commenced one week after planting.

The irrigation method was based on plant growth status. Before initiating the formal experiment, extensive preliminary tests determined the optimal irrigation volume. Insights from these studies led to implementation of a consistent spraying regime of 200 mL of water at noon each day during the initial week after planting to increase seed germination and ensure adequate soil moisture. After ryegrass sprouted, the irrigation schedule was adjusted. Factors such as branch and leaf growth rate, wilting of tender leaves, and color changes in stems and leaves were considered, resulting in a decision to water plants with 200 mL once weekly. Once ryegrass completed its growth cycle, watering was discontinued to mimic an arid environment. The experiment was conducted from August to December 2023.

2.2.2 Fractal Pore Theory

The fractal method involves establishing a soil-water characteristic curve parameterized by clearly defined physical meanings (Tyler and Wheatcraft, 1990; Huang and Zhang, 2005). Using fractal theory, fractal dimensions can be straightforwardly derived from measured soil-water characteristic curve data. The fractal dimension has a direct correlation with soil pore structure, where a higher fractal dimension corresponds to lower soil porosity (Tao et al., 2014).

The fractal model reflecting soil volumetric water content and soil matrix suction in this study was introduced and validated by Tao et al. (2014). This expression is as follows:

$$\theta_w = \phi - \left(\frac{h_{\max}}{h}\right)^{3-D}$$

where θ_w is the soil volumetric water content (%); ϕ is the total soil porosity (%); $h_{\max}$ is the soil matrix suction corresponding to the maximum pore diameter (kPa); h is the soil matrix suction (kPa); and D is the fractal dimension.

The total energy of soil can be expressed as (Li et al., 2006):

$$E = m_w g z + \frac{m_w g}{\rho_w}$$

where E is the total energy of soil (J); m_w is the mass of water in the soil body (kg); g is gravitational acceleration (m/s^2); z is the relative height (m); and ρ_w is the water density in the soil body (kg/m^3).

The water potential (E_w; kPa), which is the water energy per unit soil volume, can be expressed in conjunction with Equation 2 as:

$$E_w = \rho_w g z + h$$

Assuming a constant water density of 1000 kg/m^3 and since measurements from the apparatuses were uniform in height, the relative height can effectively be considered zero. Consequently, soil matrix suction is equivalent to the absolute value of soil water potential. Based on Equation 1, the relationship between soil volumetric water content and soil water potential can be expressed as:

$$\theta_w = \phi - \left(\frac{E_{w\max}}{E_w}\right)^{3-D}$$

where $E_{w\max}$ is the soil water potential for the maximum pore diameter (kPa).

The relationships among total soil porosity, soil dry density, and specific gravity can be expressed as follows:

$$\phi = 1 - \frac{\rho_d}{\rho_w G_s}$$

where ρ_d is the soil dry density (kg/m^3), controlled at 1500 kg/m^3 in this study; and G_s is the specific gravity, set as 2.70 in this study.

We substituted Equation 5 into Equation 4 and took the logarithm of both sides of Equation 4. The correlation between soil volumetric water content and soil water potential can be derived as follows:

$$\ln\left(\theta_w + \frac{\rho_d}{G_s}\right) = (D-3)\ln(-E_w) + \ln\left(\frac{\rho_d}{G_s}\right) + (3-D)\ln(-E_{w\max})$$

After establishing the characteristic curve defined by soil volumetric water content and soil water potential (the negative value of soil matrix suction), one can construct a scatter plot using $-\ln(-E_w)$ as the abscissa and $\ln(\theta_w + \rho_d/G_s)$ as the ordinate. If points on this plot exhibit a linear relationship and assuming the slope of the line is k, then the fractal dimension (calculated using $3-k$) can be used to demonstrate the fractal nature of soil pore distribution. Fractal dimension can effectively represent changes in soil pore structure.

2.2.3 Disintegration Test

Disintegration tests were conducted using a self-designed instrument to assess the disintegration characteristics of loess samples in October 2023. Figure 3 [Figure 3: see original paper] shows that a cylindrical loess sample measuring 61.800 mm × 40.000 mm (diameter × height) was submerged in water. A metal plate with uniformly distributed mesh was used to position the test sample. The dimensions of the metal plate and mesh were 10.0 cm × 10.0 cm and 10.000 mm ×

10.000 mm, respectively. A digital dynamometer directly attached to the metal plate documented mass changes during disintegration. Dynamometer readings were automatically transmitted to a computer via USB to quantitatively analyze mass changes over time. The test was completed when the sample completely disintegrated or when duration reached 24 hours.

Data obtained from the digital dynamometer were used to compute the disintegration ratio of loess samples, expressed as:

$$A_t = \frac{R_1 - R_t}{R_1 - R_0} \times 100\%$$

where A_t is the disintegration ratio of the test loess sample (%); R_1 is the floating weight of an unbroken loess sample determined through parallel tests on wax-sealed samples (N); R_t is the dynamometer reading at specific time t (N); and R_0 is an apparatus constant reflecting the combined weight of the metal wire and plate when the test sample is absent (N).

Results

3.1 Variations in Volumetric Water Content Under Different Treatments

Figure 4 [Figure 4: see original paper] shows fluctuations in volumetric water content across various curing durations. Considering distinct initial impacts from sample preparation and ryegrass planting, initial volumetric water content varied across the six groups. Volumetric water content consistently decreased across all groups at a gradually declining rate over time. Following watering on days 12 and 17, samples experienced a transient increase in the subsequent 24 hours. When watered 200 mL weekly, the surge in volumetric water content was generally more pronounced following initial watering due to initial arid conditions. Overall, during the experimental period, the ranking of volumetric water content among groups on any given day was: Group E > Group F > Group D > Group B > Group C > Group A. When calculating the decline rate by comparing the first and last day of the experiment, the following descending order of decline rates was observed: Group E (25.27%) < Group F (33.49%) < Group D (36.90%) < Group B (37.63%) < Group C (39.01%) < Group A (42.31%).

Loess treated with polymer SH (Groups D, E, and F) presented higher volumetric water content than loess without polymer SH treatment (Groups A, B, and C) on the same experimental day. When the same amount of polymer SH was added, ryegrass-treated loess had higher volumetric water content than loess without ryegrass treatment. For example, volumetric water content from both Groups E and F surpassed that from Group D, demonstrating the effectiveness of ryegrass in increasing volumetric water content of Chinese loess. This increase can probably be attributed to the following reasons: ryegrass leaves obstruct a portion of sunlight and diminish direct solar radiation reaching the soil surface, while plant transpiration forms a humid air layer that contributes to water retention on the soil surface (Grantz, 1990; Lambers et al., 2008).

The improvement in volumetric water content caused by ryegrass was closely related to planting density, where Group E (20 g/m^2 planting density) had higher volumetric water content than Group F (40 g/m^2 planting density). The reasons behind this phenomenon are as follows: at high planting density, competition between plants increases, requiring more water to meet growth demands (Zhang et al., 2019). This competition may accelerate soil moisture consumption and reduce water-holding capacity. However, at relatively lower density, competition for soil water is reduced, and each plant can more easily access required water, resulting in relatively stable changes in soil water content.

Group E, which used a combination of polymer SH and ryegrass at relatively lower planting density, had the highest water-holding capacity. This result reflects the synergistic effects of combining polymer SH and ryegrass. As previously mentioned, polymer SH can effectively enhance water-holding capacity through its intricate spatial network, while ryegrass mitigates the impact of direct solar radiation on the soil surface and its transpiration process contributes to establishing a humid air layer.

3.2 Variation in Water Potential Under Different Treatments

Figure 5 [Figure 5: see original paper] shows variations in water potential among samples with various curing durations. The trend over the first 22 days was largely consistent with changes observed in the first 10 days [Figure 5: see original paper]a and b). Loess treated with polymer SH (Groups D, E, and F) had higher water potentials than untreated loess (Groups A, B, and C). Additionally, ryegrass-treated loess (Groups B and C) had higher water potentials than untreated loess (Group A). This phenomenon was consistent with observed changes in volumetric water content [Figure 4: see original paper]. Specifically, polymer SH-treated groups presented higher water potentials than polymer SH-free groups, and ryegrass-treated groups presented greater water potential than untreated groups. Water potential, which indicates the energy state of water in soil, increases with increasing water content (Bryan, 2000; Or and Wraith, 2002). Consequently, under identical experimental conditions, soils with higher volumetric water contents tend to have higher water potentials.

Group E exhibited the highest water potential among all groups. Through physical-chemical interactions with loess, polymer SH can strengthen connections among loess grains (Wang et al., 2005). Consequently, the spatial structure of the loess-ryegrass system may be strengthened by polymer SH, enhancing water-holding capacity. In addition, Group E had higher volumetric water content and water potential than Group F [Figure 4: see original paper] and [Figure 5: see original paper], clearly indicating that the feasibility of the combined technique lies in combining polymer SH with lower ryegrass planting density.

3.3 Fractal Characteristics of Volumetric Water Content and Water Potential

The volumetric water content and water potential of loess samples under different treatments for curing durations of 8–21 days were taken separately and subjected to linear fitting using Equation 6. Fitting results are presented in Figure 6 [Figure 6: see original paper], and Table 3 lists the corresponding correlation coefficient, fractal dimension, and soil water potential for the maximum pore diameter.

Correlation coefficients for all six groups were remarkably high, effectively demonstrating the applicability of the fractal dimension calculation method in this study. Volumetric water content and water potential displayed notable fractal behaviors, intrinsically reflecting strong fractal properties of soil pore distribution. Table 3 shows the ranking of calculated fractal dimensions: Group E > Group D > Group F > Group B > Group C > Group A. Additionally, fractal dimension was directly proportional to both volumetric water content and water potential. For example, for curing durations of 8–21 days, Group E had the highest fractal dimension (2.978; Table 3), highest volumetric water content [Figure 4: see original paper], and highest water potential [Figure 5: see original paper] among all groups. This finding indicated that when exposed to certain relative humidity levels under different conditions, soil water potential increases and soil pore volume decreases, improving water-holding capacity and increasing fractal dimension. Similarly, as soil pore volume decreases, fractal dimension increases and volumetric water content decreases (Russell, 2014; Liao et al., 2022; Yang et al., 2023).

Discussion

Soils on the Chinese Loess Plateau are characterized by severe erosion and water scarcity, high evapotranspiration rates, and excessive leaching of scant rainfall, leading to poor plant water use (Fu et al., 2011; Gao et al., 2014). To address these issues, we proposed a new combined treatment involving polymer SH and ryegrass. Our findings revealed that this treatment substantially enhanced the water-holding capacity of Chinese loess, aligning with results reported by several scholars documenting the effectiveness of polymer SH in increasing soil water-holding capacity (Cao et al., 2017; Hou et al., 2021; Zhang et al., 2023). We collected experimental data after cultivating ryegrass for 28 days with a 22-day data collection period. Although a 50-day observation period cannot fully reflect the impact of ryegrass on physical and mechanical properties and water-holding characteristics, it can reveal the influence pattern of ryegrass growth duration on water-holding capacity. Nonetheless, long-term monitoring is necessary to accurately reflect vegetation impacts on soil properties.

In our experiments, with a combination of 3.00% polymer SH and 20 g/m^2 ryegrass, Group E exhibited the highest volumetric water content and water potential and a calculated fractal dimension of 2.978, reflecting fractal characteristics of soil structure with the lowest soil porosity. For deeper insight into the implications of these findings for soil structure, an analysis of soil structural stability offers a crucial perspective. The structural stability of loess can be assessed via wet disintegration tests, where the disintegration ratio highly depends on the degree of particle cementation, pore structure, and soil porosity (Xie et al., 2018; Li et al., 2019; Xu et al., 2022). Here, six groups of disintegration tests were conducted on untreated and treated loess samples to investigate structural stability.

Disintegration test results for various treated loess samples are presented in Figure 7 [Figure 7: see original paper]. Figure 7a depicts disintegration behavior over time from 0 to 1000 seconds, and Figure 7b focuses on the first 180 seconds. Over the extended observation period of 1000 seconds, all samples exhibited a notable increase in disintegration ratio from 0 to approximately 500 seconds and a slight increase from 500 to 1000 seconds [Figure 7: see original paper]a). Since disintegration resistance can be determined from the disintegration ratio, a ranking of anti-disintegration ability can be drawn: Group D > Group E > Group F > Group A > Group B > Group C. This result showed that single polymer SH treatment (Group D) was most effective at reducing loess disintegration, with significantly stronger anti-disintegration ability than single ryegrass treatment, combined polymer SH and ryegrass treatment, and the control. Additionally, the ranking of Group A above Group B showed that ryegrass roots can adversely affect soil aggregate stability, but this influence could be greatly eliminated by polymer SH treatment, since Group E ranked above Group A.

The improvement in anti-disintegration ability by polymer SH is related to physical and chemical interactions with loess (Wang et al., 2005; Hou et al., 2021). Physically, polymer SH can fill soil pores, creating a spatial network structure that envelopes soil particles and effectively hinders water infiltration (Hou et al., 2021; Ying et al., 2024). Chemically, ion exchange reactions between polymer SH and loess clay particles can change the electrochemical state of the double layer surrounding clay particles and enhance attraction among them (Wang, 2016). Additionally, hydrogen bonds may form between the carboxyl (-COOH) groups of polymer SH and hydroxyl (-OH) groups on silicate surfaces (Wang et al., 2005).

Figure 7b shows that initial disintegration ratios during the first 180 seconds of ryegrass-treated loess (Groups B, C, E, and F) were greater than those of ryegrass-free groups (Groups A and D). The detrimental effect of ryegrass on soil disintegration performance is intricately linked to modifications in soil pores caused by root growth (Angers and Caron, 1998). Water movement and gaseous diffusion are considerably promoted by soil macropores created by plant roots penetrating the soil, which improves pore system connectivity and infiltration capacity (Gyssels et al., 2005; Fischer et al., 2015). Thus, enhanced infiltration capacity can expedite aggregate breakdown and disintegration, resulting in higher disintegration ratios in ryegrass-treated loess.

The disintegration ratios [Figure 7: see original paper] and calculated fractal dimensions (Table 3) lacked significant relevance. For example, Group E presented the highest fractal dimension, but its anti-disintegration ability was not the highest and was inferior to Group D. This discrepancy is reasonable because ryegrass roots adversely impact soil aggregate stability and potentially mitigate the positive influence of polymer SH on disintegration resistance of the combined treatment (Ying et al., 2024). Notably, although Group E had lower structural stability than Group D, it was more stable than the other four groups, so its structural stability was relatively good.

Conclusions

This study evaluated an innovative approach using both polymer SH and ryegrass to enhance the water-holding capacity of Chinese loess. A comparative analysis of untreated and treated samples highlighted several key outcomes. First, the combined technique significantly improved volumetric water content and water potential compared to either treatment alone. This enhancement can be attributed to synergistic effects that effectively promote water-holding capacity. Notably, the optimal ryegrass planting density for maximal improvement was identified as 20 g/m^2. Second, fractal dimension analysis revealed a direct correlation between loess moisture conditions and pore distribution characteristics. When loess moisture increased, water potential and fractal dimension increased, indicating stronger water-holding capacity. This observation underscored the importance of fractal dimension as an indicator of soil water-holding capacity. Finally, the combined technique outperformed ryegrass alone in disintegration resistance but did not outperform polymer SH alone, likely due to increased infiltration capacity facilitated by ryegrass roots, which inadvertently reduced water stability.

In summary, our study demonstrated the potential of the combined polymer SH and ryegrass technique for enhancing water-holding capacity of Chinese loess. However, it is necessary to investigate changes in physical properties (such as structure, bulk density, and porosity) under different treatments to provide more direct and solid evidence. Future research should delve deeper into additional parameters such as residual water content and air entry value to characterize water-holding capacity of treated loess, providing a more comprehensive understanding of the technique’ s effectiveness and guiding future applications.

Conflict of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements: This study was supported by the Natural Science Foundation of Qinghai Province (2024-ZJ-987) and the Natural Science Foundation of Qinghai University (2023-QGY-9).

Author Contributions: Conceptualization: YING Chunye, LI Lanxing; Methodology: YING Chunye, LI Chenglong; Investigation: LI Chenglong, ZHOU Chang; Formal analysis: YING Chunye, LI Chenglong, LI Lanxing, ZHOU Chang; Writing -original draft preparation: YING Chunye; Writing - review and editing: LI Lanxing, ZHOU Chang; Funding acquisition: YING Chunye; Supervision: LI Lanxing, ZHOU Chang. All authors approved the manuscript.

References

ASTM (American Society for Testing and Materials). 2011. Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System) (ASTM D2487-98). [2024-05-10]. https://www.astm.org.

Angers D A, Caron J. 1998. Plant-induced changes in soil structure: processes and feedbacks. *Biogeochemistry*, 42(1): 55-72.

Bryan R B. 2000. Soil erodibility and processes of water erosion on hillslope. *Geomorphology*, 32(3-4): 385-415.

Cao Y B, Wang B T, Guo H Y, et al. 2017. The effect of super absorbent polymers on soil and water conservation on the terraces of the loess plateau. *Ecological Engineering*, 102: 270-279.

Chen J S, Chen Y P, Wang K B, et al. 2024. Impacts of land use, rainfall, and temperature on soil conservation in the Loess Plateau of China. *Catena*, 239: 107883, doi: 10.1016/j.catena.2024.107883.

Chen W W, Zhang Q Y, Liu H W, et al. 2017. Reinforcing effect of relic soil sites penetrated with high polymer material SH. *Journal of Engineering Geology*, 25(5): 1307-1313. (in Chinese)

Comegna V, Damiani P, Sommella A. 1998. Use of a fractal model for determining soil water retention curves. *Geoderma*, 85(4): 307-323.

Dong Y Q, Lei T W, Li S Q, et al. 2015. Effects of rye grass coverage on soil loss from loess slopes. *International Soil and Water Conservation Research*, 3(3): 170-182.

Fischer C, Tischer J, Roscher C, et al. 2015. Plant species diversity affects infiltration capacity in an experimental grassland through changes in soil properties. *Plant and Soil*, 397(1-2): 1-16.

Fredlund D G. 2006. Unsaturated soil mechanics in engineering practice. *Journal of Geotechnical and Geoenvironmental Engineering*, 132(3): 286-321.

Fu B J, Liu Y, Lü Y H, et al. 2011. Assessing the soil erosion control service of ecosystems change in the Loess Plateau of China. *Ecological Complexity*, 8(4): 284-293.

Gao X D, Wu P T, Zhao X N, et al. 2014. Effects of land use on soil moisture variations in a semi-arid catchment: implications for land and agricultural water management. *Land Degradation and Development*, 25(2): 163-172.

Ghanbarian-Alavijeh B, Liaghat A, Huang G H, et al. 2010. Estimation of the van Genuchten soil water retention properties from soil textural data. *Pedosphere*, 20(4): 456-465.

Gomiero T. 2016. Soil degradation, land scarcity and food security: Reviewing a complex challenge. *Sustainability*, 8(3): 281, doi: 10.3390/su8030281.

Grantz D A. 1990. Plant response to atmospheric humidity. *Plant, Cell & Environment*, 13(7): 667-679.

Gyssels G, Poesen J, Bochet E, et al. 2005. Impact of plant roots on the resistance of soils to erosion by water: A review. *Progress in Physical Geography: Earth and Environment*, 29(2): 189-217.

Haruna S I, Anderson S H, Udawatta R P, et al. 2020. Improving soil physical properties through the use of cover crops: A review. *Agrosystems, Geosciences & Environment*, 3(1): e20105, doi: 10.1002/agg2.20105.

Hou Y F, Li P, Wang J D. 2021. Review of chemical stabilizing agents for improving the physical and mechanical properties of loess. *Bulletin of Engineering Geology and the Environment*, 80: 9201-9215.

Huang G H, Zhang R D. 2005. Evaluation of soil water retention curve with the pore-solid fractal model. *Geoderma*, 127(1-2): 52-61.

Huang L M, Shao M A. 2019. Advances and perspectives on soil water research in China' s Loess Plateau. *Earth-Science Reviews*, 199(2): 102962, doi: 10.1016/j.earscirev.2019.102962.

Jabro J D, Evans R G, Kim Y, et al. 2009. Estimating in situ soil-water retention and field water capacity in two contrasting soil textures. *Irrigation Science*, 27(3): 223-229.

Koudahe K, Allen S C, Djaman K. 2022. Critical review of the impact of cover crops on soil properties. *International Soil and Water Conservation Research*, 10(3): 343-354.

Lal R. 2020. Soil organic matter and water retention. *Agronomy Journal*, 112(5): 3265-3277.

Leenaars J G B, Claessens L, Heuvelink G B M, et al. 2018. Mapping rootable depth and root zone plant-available water holding capacity of the soil of sub-Saharan Africa. *Geoderma*, 324: 18-36.

Li H K, Mei L X, Gao H. 2009. The effect of grass orchard on the microclimate of orchard in dryland of the Loess Plateau. *Acta Prataculturae Sinica*, 17(5): 615-620. (in Chinese)

Li M, Chai S X, Du H P, et al. 2016. Rain erosion resistance of type soils solidified by SH dust suppressant at construction site. *Chinese Journal of Environmental Engineering*, 10(6): 3105-3110. (in Chinese)

Li S Q, Zhao S F, Wang X Z. 2006. Matric suction of unsaturated soils in one-dimensional steady flow. *Rock and Soil Mechanics*, 27(S1): 90-94. (in Chinese)

Li X A, Wang L, Yan Y L, et al. 2019. Experimental study on the disintegration of loess in the Loess Plateau of China. *Bulletin of Engineering Geology and the Environment*, 78(2): 4907-4918.

Liao H J, Liu S H, He Y Q, et al. 2022. Study on fractal dimension of pore size and water retention characteristics of loess. *Journal of Northwest University (Natural Science Edition)*, 52(3): 416-422. (in Chinese)

Malik R K, Green T H, Brown G F, et al. 2000. Use of cover crops in short rotation hardwood plantations to control erosion. *Biomass and Bioenergy*, 18(6): 479-487.

Ministry of Housing and Urban-Rural Development of the People' s Republic of China. 2008. Standard for Geotechnical Testing Method (GB/T 50145-2008). [2024-05-15]. http://www.mohurd.gov.cn. (in Chinese)

Ministry of Housing and Urban-Rural Development of the People' s Republic of China. 2019. Standard for Geotechnical Testing Method (GB/T50123-2019). [2024-05-15]. http://www.mohurd.gov.cn. (in Chinese)

Or D, Wraith J M. 2002. *Handbook of Soil Sciences: Properties and Processes.* New York: CRC Press, 49-84.

Pittaki-Chrysodonta Z, Moldrup P, Knadel M, et al. 2018. Predicting the Campbell soil water retention function: Comparing visible-near-infrared spectroscopy with classical pedotransfer function. *Vadose Zone Journal*, 17(1): 1-12.

Qin M. 2016. Experimental study on the influence of root systems on soil anti-erosion durability during the growth of typical grass vegetation in loess regions Shaanxi. MSc Thesis. Xi' an: Shaanxi Normal University. (in Chinese)

Qin Y H, Liu F H, Zhou Q. 2008. Influencing factors of compressive strength of solidified inshore saline soil using SH lime-ash. *Journal of Central South University of Technology*, 15(S1): 386-390.

Qiu D X, Xu R R, Gao P, et al. 2024. Effect of vegetation restoration type and topography on soil water storage and infiltration capacity in the Loess Plateau, China. *Catena*, 241: 108079, doi: 10.1016/j.catena.2024.108079.

Ramos J C, Bertol I, Barbosa F T, et al. 2014. Influence of the surface conditions and soil cultivation on water erosion in an inceptisol. *Revista Brasileira de Ciência do Solo*, 38(5): 1587-1600.

Russell A R. 2014. How water retention in fractal soils depends on particle and pore sizes, shapes, volumes and surface areas. *Géotechnique*, 64(5): 379-390.

Shi H, Shao M A. 2000. Soil and water loss from the Loess Plateau in China. *Journal of Arid Environments*, 45(1): 9-20.

Suzuki S, Noble A D, Ruaysoongnern S, et al. 2007. Improvement in water-holding capacity and structural stability of a sandy soil in Northeast Thailand. *Arid Land Research and Management*, 21(1): 37-49.

Tao G L, Kong L W, Xiao H L, et al. 2014. Fractal characteristics and fitting analysis of soil-water characteristic curves. *Rock and Soil Mechanics*, 35(9): 2443-2447. (in Chinese)

Trindade H, Coutinho J, Jarvis S, et al. 2009. Effects of different rates and timing of application of nitrogen as slurry and mineral fertilizer on yield of herbage and nitrate-leaching potential of a maize/Italian ryegrass cropping system in north-west Portugal. *Grass and Forage Science*, 64(1): 2-11.

Tyler S W, Wheatcraft S W. 1990. Fractal processes in soil water retention. *Water Resources Research*, 26(5): 1047-1054.

Vanapalli S K, Fredlund D G, Pufahl D E, et al. 1996. Model for the prediction of shear strength with respect to soil suction. *Canadian Geotechnical Journal*, 33(3): 379-392.

Wang Y M, Yang Z C, Chen W W, et al. 2005. Strength characteristics and mechanism of loess solidified with new polymer material SH. *Chinese Journal of Rock Mechanics and Engineering*, 24(14): 2554-2559. (in Chinese)

Wang Y M. 2016. Shear strength characteristics of loess stabilized by new polymer materials. *Low Temperature Architecture Technology*, 38(2): 116-118. (in Chinese)

Wei Y, Wang Y Q, Han J C, et al. 2019. Analysis of water retention characteristics of oil-polluted earthy materials with different textures based on van Genuchten model. *Journal of Soils and Sediments*, 19(1): 373-380.

Williams K, Caldwell M M, Richards J H. 1993. The influence of shade and clouds on soil water potential: The buffered behavior of hydraulic lift. *Plant and Soil*, 157(1): 83-95.

Xie J J, Su D R. 2020. Water-holding characteristics of litter in meadow steppes with different years of fencing in Inner Mongolia, China. *Water*, 12(9): 2374, doi: 10.3390/w12092374.

Xie W L, Li P, Zhang M S, et al. 2018. Collapse behavior and microstructural evolution of loess soils from the Loess Plateau of China. *Journal of Mountain Science*, 15(8): 1642-1657.

Xu P, Lin Q W, Fang L Y. 2022. Study on the mechanical properties of loess improved by lignosulfonate and its mechanism analysis and prospects. *Applied Sciences*, 12(19): 9843, doi: 10.3390/app12199843.

Xue P, Fu Q, Li T X, et al. 2022. Effects of biochar and straw application on the soil structure and water-holding and gas transport capacities in seasonally frozen soil areas. *Journal of Environmental Management*, 301(4): 113943, doi: 10.1016/j.jenvman.2021.113943.

Yang C L, Wu J H, Li P Y, et al. 2023. Evaluation of soil-water characteristic curves for different textural soils using fractal analysis. *Water*, 15(4): 772, doi: 10.3390/w15040772.

Yang T, Xing X G, Gao Y, et al. 2022. An environmentally friendly soil amendment for enhancing soil water availability in drought-prone soils. *Agronomy*, 12(1): 133, doi: 10.3390/agronomy12010133.

Ying C Y, Li L X, Makeen G M H, et al. 2024. Erosion control of Chinese loess using polymer SH and ryegrass. *Journal of Mountain Science*, 21(6): 2043–2058.

Young J A, Evans R A, Kay B L. 1975. Germination of Italian ryegrass seeds. *Agronomy Journal*, 67(3): 386–389.

Yuan B X, Chen W J, Li Z H, et al. 2023. Sustainability of the polymer SH reinforced recycled granite residual soil: properties, physicochemical mechanism, and applications. *Journal of Soils and Sediments*, 23(1): 246–262.

Zeng L, Huang Y H. 2010. Study on the evolution of river valleys and geological disasters in the Loess Plateau—A case study of Zichang County, Shaanxi Province. *Chinese Journal of Geological Hazard and Control*, 21(3): 67–72. (in Chinese)

Zhang H L, Wang G H, Du J, et al. 2023. Effects of several polymeric materials on the improvement of the sandy soil under rainfall simulation. *Journal of Environmental Management*, 345: 118847, doi: 10.1016/j.jenvman.2023.118847.

Zhang Q Y, Chen W W, Yuan P B. 2020. Experimental study on impregnation and consolidation effects of modified polyvinyl alcohol solution for coarse-grained soils: a case study on the Subashi Buddhist Temple Ruins of China. *Bulletin of Engineering Geology and the Environment*, 79(3): 1487–1500.

Zhang Q Y, Chen W W, Zhang J K. 2021a. Wettability of earthen sites protected by PVA solution with a high degree of alcoholysis. *Catena*, 196: 104929, doi: 10.1016/j.catena.2020.104929.

Zhang X C, Zhong Y J, Pei X J, et al. 2021b. A cross-linked polymer soil stabilizer for hillslope conservation on the Loess Plateau. *Frontiers in Earth Science*, 9: 771316, doi: 10.3389/feart.2021.771316.

Zhang Y H, Wang R, Wang S L, et al. 2019. Effect of planting density on deep soil water and maize yield on the Loess Plateau of China. *Agricultural Water Management*, 223(2): 105655, doi: 10.1016/j.agwat.2019.05.039.

Zhang Y W, Wang K B, Wang J, et al. 2021c. Changes in soil water holding capacity and water availability following vegetation restoration on the Chinese Loess Plateau. *Scientific Reports*, 11(1): 9692, doi: 10.1038/s41598-021-88914-0.

Zheng W J, Zeng S Q, Bais H, et al. 2018. Plant growth-promoting rhizobacteria (PGPR) reduce evaporation and increase soil water retention. *Water Resources*

Research, 54(5): 3673-3687.

Zhou Z C, Shangguan Z P. 2007. The effects of ryegrass roots and shoots on loess erosion under simulated rainfall. *Catena*, 70(3): 350-355.

Zhou Z C, Shangguan Z P. 2008. Effect of ryegrasses on soil runoff and sediment control. *Pedosphere*, 18(1): 131-136.

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

Source: ChinaXiv —Machine translation. Verify with original.