Research Article

Effect of Dry-Wet Cycles and Freeze-Thaw Cycles on the Antierosion Ability of Fiber-Reinforced Loess

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Compared with plain soil, polypropylene (PP) fiber-reinforced soil has markedly improved mechanical properties and can be used in slope protection projects. To investigate the reduction law of the antierosion ability parameters of PP fiber-reinforced loess under dry-wet (D-W) cycles and freeze-thaw (F-T) cycles, we took loess from Yan'an, China, mixed them with PP fiber, and did shear strength tests, disintegration tests, and permeability tests under D-W cycles and F-T cycles. The experimental results show that D-W cycles or F-T cycles had a less deteriorating effect on the cohesion, disintegration rate, and permeability coefficient of the fiber-reinforced samples than on plain loess; however, the reduction in their internal friction angle was more obvious. Under D-W cycles or F-T cycles, the cohesion and internal friction angle of the reinforced soil decreased as the number of cycles increased, while the disintegration rate and permeability coefficient increased as the number of cycles increased. The relation between the reduction in the antierosion ability parameters of reinforced soil and the number of D-W cycles or F-T cycles accorded with the hyperbolic function fitting results. The most obvious reduction effect the D-W cycles had on the reinforced soil was on the disintegration rate, followed by cohesion, internal friction angle, and permeability coefficient. The most obvious effect of F-T cycles was also on the disintegration rate, followed by cohesion, permeability coefficient, and internal friction angle. Compared with D-W cycles, F-T cycles had a stronger effect on the reduction in the cohesion, disintegration rate, and permeability coefficient of reinforced soil, but the reduction in the friction angle was greater in D-W cycles.

1. Introduction

Loess is widely distributed in the middle and western regions of China [1, 2]. In recent years, an increasing number of engineering construction projects have been done in the Loess Plateau, such as road construction and urban expansion. Those projects inevitably produce many steep loess slopes [3, 4]. Under the influence of external factors such as rainfall erosion, shallow slope problems such as gullies and spalling are very common [5–7]. Therefore, protection for loess slopes is particularly important. Traditional slope protection methods such as mortar, flagstones, and mortar plastering often offered poor slope surface protection and poor ecological features. This was due to the aging of the materials, the differences in stiffness of the loess, and meteorological conditions such as

concentrated rainfall. However, one type of comprehensive slope protection—fiber reinforcement of the soil—has gradually attracted the attention of scholars [8, 9].

Fiber-reinforced soil is essentially a type of soil reinforced by evenly distributed fibers. Mixing fibers with the soil improves several of its mechanical properties [10]. The fibers used may be natural or synthetic [11–15]. Polypropylene (PP) fiber is highly elastic, resistant to extreme temperatures, acid and alkalis, and absorbs little water [16], so research on PP fiber-reinforced soil has attracted extensive attention from scholars and engineers. Studies have shown that the influence of rainfall splash erosion on slope soil is closely related to soil shear strength [17], so it is necessary to study the shear strength of reinforced soil. Jiang et al. [18] reported that PP fiber-reinforced clayey soil had a

greater unconfined compressive strength and greater cohesion and internal friction angles than those of the parent soil. They also found that the best fiber content was 0.3 wt% of the parent soil and the best fiber length was 15 mm. Lian et al. [19] did a series of triaxial compression tests and found that the addition of fibers to loess markedly improved the failure stress and shear strength of the loess compared with unreinforced loess specimens. Han et al. [20] found that PP fiber can effectively improve the shear strength of clay and that a fiber content of 0.3 wt% with a fiber length of 9 mm was the optimum mixing ratio for the polypropylene-reinforced clay system. Costas et al. [21] found that the shear strength of PP fiber-reinforced soil increased with the inclusion of fibers up to the optimum dose, beyond which it decreased or remained constant, and the impaction of soil particles on the fiber surface was the dominant factor controlling the interfacial strength. Soil permeability is a property that describes the flow of fluid through the soil and is an important factor affecting soil erosion. Saghari et al. [22] found that increasing the length and weight percentages of fibers initially increased the permeability coefficient of polymer fiber-reinforced soil and when it exceeded 0.6%, a decreasing trend began. Zhao et al. [23] reported that the permeability of fiber-reinforced soil was improved with an increase in fiber content. The water stability characteristics of soil indicate that the soil can resist the dispersion of soil particles in water and remain stable, which is the main feature of soil erosion resistance and reflects the difficulty of dispersing soil by rainfall or runoff. Wang et al. [24] did field and disintegration laboratory tests and found that the main factors influencing the disintegration of loess samples were shape, size, and clay mineral content. Qi et al. [25] did a series of tests on the disintegration of prisms and cylinders with the same volumes and different bottom side lengths (diameters) and reported that the disintegration rate of samples increased with the increase in specific surface area and water depth. An et al. [26] found that the disintegration rate of loess could be effectively reduced by adding polypropylene fiber.

Two typical weathering processes, dry-wet (D-W) cycles and freeze-thaw (F-T) cycles are common in China's Loess Plateau [27, 28], affecting the physical and mechanical properties of its loess [29–31], and causing shallow diseases of loess slopes to become more prominent [32–34]. Therefore, when PP fiber-reinforced loess is applied in loess areas, it is necessary to study the effects of D-W cycles and F-T cycles on that reinforced loess. Zaimoglu [35] did a series of tests to study the effect of F-T cycles on the strength characteristics and durability of PP fiber-reinforced fine-grained soil. They found that the fiber-reinforced specimens showed more ductile behavior than the unreinforced soil and the mass losses in the fiber-reinforced soils were almost 50% lower than those in the unreinforced soil. The research results of Ghazavi et al. [36] indicated that after F-T cycles, adding fibers increased the unconfined compressive strength of the soil and reduced its frost heaving. On the basis of a triaxial compression test and a dynamic triaxial test, Kravchenko et al. [37, 38] concluded that the shear strength, the resilient modulus, the dynamic axial stress, the dynamic

shear modulus, and the damping ratio of PP fiber-reinforced soil all decreased with an increase in the number of F-T cycles. Liu et al. [39] found that the unconfined compressive strength of fiber-reinforced soil decreased exponentially with the number of F-T cycles. Chaduvula et al. [14] found that the addition of fiber markedly inhibited the formation of cracks in clayey soil while it dried.

Existing research focuses on the observation and description of the deformation characteristics and strength characteristics of reinforced soil enduring D-W cycles and F-T cycles. However, if PP fiber-reinforced loess is to be applied to protect a loess slope, it is also important to study the antierosion ability of the reinforced soil in those conditions.

The purpose of this study was to investigate the effect of D-W cycles and F-T cycles on the antierosion ability of PP fiber-reinforced loess. We did a series of laboratory experiments including a direct shear test, a disintegration test, and a permeability test on PP fiber reinforced loess under D-W cycles or F-T cycles. On the basis of the test results, we formulated a reduction law of the antierosion ability parameters of PP fiber-reinforced loess in those conditions.

2. Materials and Methods

2.1. Materials and Preparation of Samples. The test materials included mainly loess and PP fiber.

The loess used in the test was taken from a loess slope in Yan'an, Shaanxi province; the loess was yellowish-brown with small pores. Geotechnical test results indicated that the basic physical and mechanical indicators were density 1.38 g/cm^3 , water content 12%, maximum dry density 1.6 g/cm^3 , and optimum moisture content 14%. The grain size distribution of the soil is shown in Figure 1. The physical and mechanical properties of PP fiber is shown in Table 1.

To prepare experimental samples, we added PP fiber 15 mm long with a content of 0.5% by weight (of the dry weight of the loess) into the loess [26]. We also prepared plain loess samples for controls. Samples were prepared by the compression method. The dry density of the samples was controlled to 1.6 g/cm^3 , and the moisture content was 14% (these were the maximum dry density and the optimal moisture content obtained from a compaction test). Cylindrical samples of $\Phi 61.8 \text{ mm} \times 20 \text{ mm}$ were made for a shear strength test, and cylindrical samples of $\Phi 61.8 \text{ mm} \times 40 \text{ mm}$ were made to determine the disintegration resistance and permeability coefficient of the sample. The prepared samples were sealed with plastic wrap and placed in a moisturizing tank, and after curing for 48 h, they were taken out for D-W cycles or F-T cycles and determination of their antierosion parameters.

2.2. Test Methods

2.2.1. Dry-Wet Cycle Test. Under natural conditions, the soil in the surface layer of a loess slope alternates between wet and dry for many cycles due to rainfall infiltration and evaporation. According to our field investigation of the loess cut slope in Yan'an, the moisture content of the surface soil in the natural state was basically between 9% and 22%.

FIGURE 1: Particles gradation curve of loess soil.

Therefore, to better simulate the actual environmental conditions in Yan'an, we controlled the D-W cycle amplitude to be 9% to 22%. The first D-W cycle path of the samples was 14% to 22% to 9% to 22%, and the subsequent D-W cycle paths were 22% to 9% to 22%. We humidified the samples using the water film transfer method [40] and dehumidified them by natural air drying. After the humidification or dehumidification process of the samples was completed, we sealed the samples with plastic wrap and put them in a moisturizing tank for 24 hours to ensure that the moisture content in the samples was evenly distributed. In the process of humidification and dehumidification, the moisture content of the samples was monitored by weighing, and the numbers of D-W cycles were set as 0, 2, 4, 6, 8, and 10 times.

2.2.2. Freeze-Thaw Cycle Test. According to the meteorological data of the Yan'an area in recent years, in late winter and early spring, the daily mean minimum temperature was -11°C , and the daily mean maximum temperature was 5°C . Therefore, we set the samples' frozen temperature to -11°C and the thawed temperature to 5°C . In this experiment, one F-T cycle comprised freezing for 12 h and thawing for 12 h. Samples were frozen in a DW-40 low-temperature test box, and samples were thawed in an HN-25 S constant temperature drying box. The numbers of F-T cycles were set at 0, 2, 4, 6, 8, and 10 times.

2.2.3. Shear Strength Test. The shear strength parameter of fiber-reinforced soil is an important index to evaluate the effect of fiber on the reinforcement. Direct shear tests were done on the reinforced and control loess samples after D-W cycles and F-T cycles. We used a ZJ strain-controlled direct shear apparatus to do the direct shear test on the cylindrical samples. The shear rate was 0.8 mm/min, and the vertical loads were 50 kPa, 100 kPa, 150 kPa, and 200 kPa.

2.2.4. Disintegration Test. The disintegration test was done on the cylindrical samples that had completed the D-W

cycles and F-T cycles using a clay soil disintegration tester developed by Li [41].

2.2.5. Permeability Test. The permeability coefficient of soil is an important index of its permeability. The cylindrical samples that had completed the D-W cycles and F-T cycles were placed in a TST-55 penetration tester, and their permeability coefficients were measured by the variable water head.

2.3. Evaluation Index. To quantitatively determine the reduction law of the antierosion ability of fiber-reinforced loess under D-W cycles and F-T cycles, we defined the following evaluation indices.

- (1) Disintegration coefficient and average disintegration rate:

$$B_i = \frac{\Delta V_i}{V}, \quad (1)$$

$$V_{Bi} = \frac{\Delta V_i}{t_i},$$

where B_i and V_{Bi} are the disintegration coefficient and average disintegration rate of a sample respectively, ΔV_i is the disintegration volume when the sample reaches a stable disintegration after i D-W cycles or F-T cycles, V is the volume of a sample without the disintegration test, and t_i is the duration required for a sample to reach disintegration stability after i D-W cycles or F-T cycles.

- (2) Cohesion reduction:

$$D_{ci} = \frac{(c_0 - c_i)}{c_0} \times 100\%, \quad (2)$$

where c_i is the cohesion of a sample after i D-W cycles or F-T cycles, and c_0 is the initial cohesion of a sample before the D-W cycles or F-T cycles.

- (3) Internal friction angle reduction:

$$D_{\varphi i} = \frac{(\varphi_0 - \varphi_i)}{\varphi_0} \times 100\%, \quad (3)$$

where φ_i is the internal friction angle of a sample after i D-W cycles or F-T cycles, and φ_0 is the initial internal friction angle.

- (4) Average disintegration rate reduction:

$$D_{V_{Bi}} = \frac{(V_{Bi} - V_{B0})}{V_{B0}} \times 100\%, \quad (4)$$

where V_{Bi} is the average disintegration rate of a sample after i D-W cycles or F-T cycles, and V_{B0} is the initial average disintegration rate.

- (5) Permeability coefficient reduction:

TABLE 1: Physical and mechanical properties of PP fiber.

Fiber type	Density (g/cm ³)	Diameter (μm)	Tensile limit (%)	Tensile strength (MPa)	Elastic modulus (MPa)
Single fiber	0.91	48	17	>358	>3500

$$D_{ki} = \frac{(k_i - k_0)}{k_0} \times 100\%, \quad (5)$$

where k_i is the permeability coefficient of a sample after i D-W cycles or F-T cycles, and k_0 is the initial permeability coefficient.

3. Results and Discussion

3.1. Antierosion Ability of Reinforced Loess Samples. Table 2 shows the antierosion ability parameters of the control and PP fiber-reinforced loess samples before D-W cycles or F-T cycles. Compared with the control samples, the cohesion of the reinforced loess increased by 135.3%, the internal friction angle increased by 8.7%, the disintegration coefficient decreased by 42%, and the permeability coefficient increased by 39.9%. We believe that the fiber contributed to the marked increase in the cohesion of the loess but had little influence on its internal friction angle. This was due mainly to the spatial restraining force between the fibers and soil particles through interleaving. The connections between soil particles improved, but the fiber had little influence on the roughness of the soil particles and their crisscross arrangement. Fibers in the soil interweaved with each other to form a 3D network structure, which delayed the disintegration and cracking of the soil in water. At the same time, the fibers created many seepage channels in the soil, which markedly improved the loess permeability.

3.2. Dry-Wet Cycle Characteristics of Reinforced Loess

3.2.1. Effect of Dry-Wet Cycles on Strength. As shown in Figure 2, after D-W cycles, the shear strength parameters c and φ of the control loess and the fiber-reinforced loess decreased. The cohesiveness of the control loess samples decreased first during cycles 0 to 6 and remained stable during cycles 6 to 10, while the internal friction angle remained unchanged during cycles 0 to 2 and gradually decreased during cycles 2 to 10. The cohesion and internal friction angle of the reinforced samples showed the same trend with the number of cycles; those parameters decreased rapidly during cycles 0 to 2, changed gradually during cycles 2 to 4, decreased again during cycles 4 to 6, and remained basically stable during cycles 6 to 10.

After 10 D-W cycles, the amount of reduction in cohesion and the internal friction angle of the control samples were 31.3% and 7.2%, respectively, and those of the reinforced samples were 17.3% and 9.1%, respectively. The reduction in the cohesion of the reinforced loess was markedly lower than that of the control loess, but the reduction in the internal friction angle of the reinforced loess was higher than that of the control loess, indicating that the durability of the cohesion of the reinforced loess was higher than that of the

control loess, while the durability of the internal friction angle of the reinforced loess was worse than that of the plain loess. After 10 D-W cycles, the cohesion and internal friction angle of the reinforced loess were 39.1 kPa and 26°, respectively, and compared with the control loess without D-W cycles, the cohesion of the reinforced loess was still improved to 94.5%, while the internal friction angle was only reduced by 1.1%, indicating that the strength characteristics of fiber-reinforced loess after D-W cycles were still better than those of the control loess.

3.2.2. Effect of Dry-Wet Cycles on Disintegration. After D-W cycles, the disintegration coefficient of control loess remained unchanged, the samples were completely disintegrated, and the disintegration coefficient always reached 100%. However, with an increase in the number of D-W cycles, the duration for the control loess to reach a stable disintegration was continually shortened, and the disintegration rate of the control loess gradually increased (Figure 3(a)). The disintegration rate of the control loess increased linearly with the number of cycles during cycles 0 to 4 and decreased gradually during cycles 4 to 10. The changes in the disintegration coefficient and average disintegration rate of the reinforced loess corresponded with the number of D-W cycles (Figure 3(b)). After two cycles, both rates increased noticeably, and the growth rate decreased slightly during cycles 2 to 6. The change was gradual during cycles 6 to 10.

After 10 cycles, the average disintegration rate of the control loess increased from 1.667 cm³/s to 2.222 cm³/s, with a rate of increase of 33.3%. The disintegration coefficient of the reinforced loess increased from 58% to 63.5%, and the average disintegration rate increased from 0.138 cm³/s to 0.175 cm³/s, with an increase rate of 9.5% and 26.8%, respectively. Compared with the control loess, the reduction rate of the reinforced loess was only 80.5% of the former, showing that D-W cycles had a more noticeable effect on the reduction in the disintegration resistance of the control loess. Also, after 10 cycles, the disintegration coefficient and average disintegration rate of the reinforced loess were far lower than those of the control loess without D-W cycles, indicating that the fiber could markedly improve the anti-disintegration property of the loess.

3.2.3. Effect of Dry-Wet Cycles on Permeability. Figure 4 shows the effects of D-W cycles on the permeability coefficients of the control loess and reinforced loess. The permeability coefficients of the two kinds of samples showed a gradually increasing trend with the number of cycles. After 8 cycles, the permeability coefficients of the samples reached their maximum value and remained stable during cycles 8 to 10. After 10 cycles, the permeability coefficient of the control

TABLE 2: Antierosion ability parameters of the control loess and the reinforced loess.

Type	Cohesion (kPa)	Internal friction angle (°)	Disintegration coefficient	Disintegration rate (cm ³ /s)	Permeability coefficient (cm·s ⁻¹)
Plain loess	20.1	26.3	1	1.667	4.46×10^{-6}
Reinforced loess	47.3	28.6	0.58	0.138	6.24×10^{-6}

FIGURE 2: The effects of D-W cycles on strength with the number of cycles: (a) control loess; (b) fiber-reinforced loess.

FIGURE 3: The effects of D-W cycles on disintegration with the number of cycles: (a) control loess; (b) fiber-reinforced loess.

loess was still lower than that of reinforced loess without D-W cycles. The permeability coefficient of the control loess increased from 4.46×10^{-6} cm/s to 5.44×10^{-6} cm/s, with a rate increase of 22%, and the permeability coefficient of

reinforced loess increased from 6.24×10^{-6} cm/s to 6.81×10^{-6} cm/s, with a rate increase of only 9.1%, indicating that the D-W cycles had a more obvious influence on the permeability of the control loess. This phenomenon

FIGURE 4: The effects of D-W cycles on permeability with the number of cycles.

occurred because the fibers effectively inhibited the soil from cracking [14, 42, 45], thus reducing the seepage channels in the soil.

3.2.4. Reduction in Antierosion Ability Parameters of Reinforced Loess. The reduction in fiber-reinforced loess cohesion, internal friction angle, disintegration rate, and permeability coefficient varied with the number of D-W cycles (Figure 5). It can be seen that the reduction in the four antierosion ability parameters increased first and then tended to be stable with the number of D-W cycles. To better describe the influence of D-W cycles on the reduction in the antierosion ability of reinforced loess, we used the hyperbolic equation (6) to fit the change of each antierosion ability parameter with the number of cycles. The R^2 of the fitted curves were all greater than 0.95; the specific fitting results are shown in Figure 5 and Table 3.

$$D = A - \frac{B}{(1 + (n/C))}, \quad (6)$$

where D is the reduction degree of each antierosion ability parameter, n is the number of D-W cycles, and A , B , and C are fitting parameters.

According to Figure 5, the reduction in each antierosion ability parameter showed the same change trend with the number of D-W cycles, which increased first during cycles 0 to 8 and remained stable at cycles 8 to 10. During the entire D-W cycle process, the reduction degrees all showed $D_{Vb} > D_c > D_\phi > D_k$, so we considered that a D-W cycle had the greatest effect on the antidisintegration of reinforced loess, followed by the cohesion, internal friction angle, and permeability coefficients. Also, Table 4 shows that fitting parameters A and B were basically equal, and Figure 5 shows that the reduction in the antierosion ability parameters eventually tended to be stable with the increase in the number of cycles. That indicated that the antierosion ability parameters of the reinforced loess had the maximum

amount of reduction. Combined with (6), it can be considered that this fitting function can predict the maximum reduction in the antierosion ability parameters of reinforced loess; that is, the maximum reduction $D = A$. However, the accuracy of the maximum degree of reduction predicted by the fitting function needed to be verified by doing a higher number of D-W cycle tests.

3.3. Freeze-Thaw Cycles Characteristics of Reinforced Loess Samples

3.3.1. Effect of Freeze-Thaw Cycles on Strength. Figure 6 shows the variation curves of the shear strengths of the control loess and reinforced loess with various numbers of F-T cycles. The cohesion of the control loess and reinforced loess generally decreased with the increase in the number of F-T cycles. The cohesion of the control loess decreased first during cycles 0 to 8 and remained stable during cycles 8 to 10. The cohesion of the reinforced loess decreased slightly during cycles 0 to 2, but decreased markedly during cycles 2 to 4, decreased slightly at cycles 4 to 8, and remained stable during cycles 8 to 10. The internal friction angle of the control loess showed a “wave-shaped” fluctuation trend with the number of F-T cycles, and the range of variation was within 0.4° . The internal friction angle of the reinforced loess decreased first during cycles 0 to 8, and increased slightly at cycles 8 to 10.

After 10 cycles, the cohesion reduction in the control loess was 21.4%, while that of the reinforced loess was 19.7%: slightly lower than that of the control loess, indicating that the cohesion durability of the reinforced loess was better than that of the control loess. Also, the cohesion of the reinforced loess was 38 kPa, which was still 89.1% higher than that of the control loess without F-T cycles. Under the effect of F-T cycles, the internal friction angle of the control loess did not show a marked downward trend but showed a fluctuating change process, and after 10 cycles the amount of reduction was only 0.4%, which indicates that the influence of F-T cycles on the internal friction angle of the control loess was not obvious. While under the influence of F-T cycles, the maximum amount of reduction in the internal friction angle of reinforced soil was 4.2%, which was obviously larger than that of the control loess, indicating that the durability of the internal friction angle of reinforced loess was inferior to that of unreinforced loess. However, under the effect of F-T cycles, the minimum internal friction angle of the reinforced loess was 27.4° , which was still 4.2% higher than that of the control loess without F-T cycles, which further indicates that fiber can obviously improve the shear strength of loess.

3.3.2. Effect of Freeze-Thaw Cycles on Disintegration. As shown in Figure 7(a), similar to D-W cycles, the disintegration coefficient of the control loess after F-T cycles was always 1, but the disintegration rate increased with the increase in F-T cycles, increased first during cycles 0 to 8 and remained stable during cycles 8 to 10. With the increase in F-T cycles, the disintegration coefficient and rate of the reinforced loess showed a gradually increasing trend; both of

FIGURE 5: The effects of D-W cycles on the reduction of the antierosion ability parameters with the number of cycles.

TABLE 3: Fitting parameters of antierosion ability parameter reduction of the reinforced loess during D-W cycles.

Parameter	D_c	D_ϕ	D_{Vb}	D_k
A	0.24984	0.11344	0.40622	0.14571
B	0.24875	0.11322	0.40622	0.14691
C	4.22599	2.29447	4.7287	5.34984
R^2	0.96767	0.95242	0.99722	0.98551

TABLE 4: Fitting parameters of antierosion ability parameter reduction of the reinforced loess during F-T cycles.

Parameter	D_c	D_ϕ	D_{Vb}	D_k
A	0.58078	0.05702	0.41682	0.16847
B	0.58095	0.05705	0.41682	0.16846
C	17.05626	5.93519	2.77541	4.74593
R^2	0.9587	0.84992	0.99882	0.99169

them increased at cycles 0 to 6 and kept stable during cycles 6 to 10 (Figure 7(b)). After 10 cycles, the reduction rate of the control loess reached 41.2%, and the reduction rate of the reinforced loess was 31.9%. The disintegration coefficient of the reinforced loess increased from 0.58 to 0.646, which was still 35.4% lower than that of the control loess. This indicates that the durability of fiber-reinforced loess under F-T cycles was better than that of unreinforced loess. It also shows that the fiber markedly improved resistance to loess disintegration.

3.3.3. Effect of Freeze-Thaw Cycles on Permeability. As shown in Figure 8, the permeability coefficients of the control loess and reinforced loess showed a gradually increasing trend with the number of F-T cycles. They increased first during cycles 0 to 6 and gradually changed during cycles 6 to 10. After 10 F-T cycles, the amount of reduction in the permeability coefficient of the control loess was 15.5%, and that of reinforced loess was 11.2%. However, after F-T cycles, the permeability coefficient of the control loess was

5.15×10^{-6} cm/s, which was still 17.5% lower than that of the reinforced loess without F-T cycles, which indicated that the influence of F-T cycles on the permeability of the control loess was more obvious, but the permeability coefficient of the reinforced loess was always higher than that of the control loess.

3.3.4. Amount of Reduction in Antierosion Ability of Reinforced Loess. Figure 9 shows the reduction in the antierosion ability of the fiber-reinforced loess and the number of F-T cycles. Similar to the variation trend of the antierosion ability parameters under D-W cycles, the amount of reduction in four antierosion ability parameters all showed a trend of first increasing and then becoming stable with the number of F-T cycles. We used equation (6) to fit the relation between the amount of reduction and the number of F-T cycles. Except for the R^2 of the fitting curve of the internal friction angle, which was 0.85, the R^2 of other anticorrosion ability parameter fitting curves was greater than 0.95. The specific fitting results are shown in Figure 9 and Table 4.

As shown in Figure 9, the reduction in the antierosion ability of the reinforced loess gradually increased with the number of F-T cycles, which increased first during cycles 0 to 8 and remained stable at cycles 8 to 10. During F-T cycles, the amount in reduction of each antierosion ability parameter showed $D_{Vb} > D_c > D_k > D_\phi$, which indicated that F-T cycles had the most obvious influence on the antierosion ability of the reinforced loess, followed by cohesion, the permeability coefficient, and the internal friction angle.

3.4. Comparison of Dry-Wet Properties and Freeze-Thaw Properties of Reinforced Loess. From the above experiments, we found that the effects of D-W cycles and F-T cycles on the antierosion ability parameters of the reinforced loess were different. To better analyze this difference, we plotted the amount of reduction in each antierosion ability parameter of the reinforced loess, as shown in Figure 10.

As shown in Figure 10(a), under the effect of F-T cycles, the cohesion reduction in the reinforced loess was not obvious after two cycles but increased sharply after four cycles and gradually increased with the number of cycles. Under the effect of D-W cycles, the cohesion reduction in the reinforced soil increased markedly after two cycles and showed a gradually increasing trend with the number of cycles. However, except for cycle two, the cohesion reduction in the reinforced loess under D-W cycles was clearly greater than that under F-T cycles, but the cohesion reduction under F-T cycles was greater than that under D-W cycles in the other cycles. After cycles 4, 6, 8, and 10, the cohesion reductions of the reinforced loess under F-T cycle were 19.8%, 7.1%, 18%, and 13.9%, respectively, higher than those of D-W cycles, which indicated that the cohesion reduction under F-T cycles was stronger than that of D-W cycles, but the reduction under D-W cycle was more advanced.

According to Figure 10(b), after cycles 2, 4, 6, 8, and 10, the reduction in the internal friction angle under D-W cycles was 8, 3, 2.4, 2.1, and 3.8 times that of F-T cycles, which indicated that the reduction under D-W cycles was stronger than that of F-T cycles, and the reduction was more advanced.

FIGURE 6: The effects of F-T cycles on strength with the number of cycles: (a) control loess; (b) fiber-reinforced loess.

FIGURE 7: The effects of F-T cycles on disintegration with the number of cycles: (a) control loess; (b) fiber-reinforced loess.

The amount of reduction in the disintegration rate and the permeability coefficient of the reinforced loess showed a gradually increasing trend with the number of cycles under the D-W cycles or F-T cycles (Figure 10(c) and 10(d)). Compared with D-W cycle effects, the degradation rates under F-T cycles increased by 41.5%, 37.4%, 24.3%, 19.5%, and 19%, and the reduction in the permeability coefficient increased by 64.7%, 3.1%, 23.8%, 23.9%, and 23.1%, which indicated that the effects of F-T cycles on the disintegration rate and permeability coefficient of the reinforced loess were stronger than the effects of D-W cycles.

As shown in Figure 11, under load, fibers and soil particles produce inconsistent deformations and relative displacements due to the differences in moduli, which

cause friction and interlocking actions at the contact positions of soil particles and fibers [43]. At the same time, the dislocation of soil particles and fibers makes the fiber tensile, and the soil bears part of the load borne by the fiber. The shear strength of the soil is improved because of the good tensile performance of the PP fiber. The PP fibers are randomly distributed in the soil, and the fibers are interwoven into a 3D network structure in the soil, thus playing an “interleaving” role [44]. When a fiber is subjected to tensile force, other fibers in the network structure are stressed at the same time so that the load is distributed over a wider area, and the soil force is more uniform. Also, to a certain extent, the PP fiber imposes a spatial constraint on the soil. After the D-W cycles or F-T cycles, the

FIGURE 8: The effects of F-T cycles on permeability with the number of cycles.

FIGURE 9: The effects of F-T cycles on reduction of the antierosion ability parameters with the number of cycles.

FIGURE 10: Continued.

FIGURE 10: The effects of D-W cycles and F-T cycles on the reduction of antierosion ability parameters: (a) cohesion; (b) internal friction angle; (c) average disintegration rate; (d) permeability coefficient.

FIGURE 11: Schematic diagram of fiber-reinforced loess.

migration and phase transformation of water damage the structure of the soil, the cracks in the soil gradually increase in size, and the soil is divided into independent blocks. Thereby, the shear strength of the sample decreases, and the disintegration rate and permeability coefficient increase. After adding PP fiber into the soil, the “interleaving” effect of the PP fiber strengthens the connection between soil particles, inhibits the generation of cracks in the soil [45, 46], and reduces the structural

damage caused by D-W or F-T cycles. Therefore, the reduction in shear strength, disintegration resistance, and permeability coefficient of PP fiber-reinforced loess is lower.

4. Conclusions

This study examined the effects of D-W cycles and F-T cycles on the antierosion ability of PP fiber-reinforced loess. A series

of laboratory experiments such as direct shear tests, disintegration tests, and permeability tests of PP fiber-reinforced loess samples were done after D-W cycles and F-T cycles. In accordance with the test results, we drew the following conclusions:

- (1) The D-W cycles and F-T cycles obviously degraded the antierosion abilities of the control loess and the reinforced loess. D-W cycles or F-T cycles had less degradation of the cohesion, the disintegration rate, and the permeability coefficient of the reinforced loess than that of the control loess, but the degradation of the internal friction angle of the reinforced loess was more obvious.
- (2) During the D-W cycles, as the number of cycles increased, the cohesion and the internal friction angle of the reinforced loess first decreased, then changed gradually, then decreased to stability. For the reinforced loess, the disintegration coefficient, average disintegration rate, and permeability coefficient increased at first and then stabilized with the increase in cycle times.
- (3) During the F-T cycles, as the number of cycles increased, the cohesion of the reinforced loess first decreased slightly, then decreased obviously, and finally tended to be stable. The internal friction angle decreased at first and then increased slightly. The disintegration coefficient, average disintegration rate, and permeability coefficient increased first and then remained stable with the increasing number of cycles.
- (4) Under D-W cycles or F-T cycles, the relation between the reduction in the antierosion ability and the number of cycles conformed to the hyperbolic function fitting results. The D-W cycles had the most obvious reduction in the average disintegration rate of the reinforced loess, followed by cohesion, internal friction angle, and the permeability coefficient. The F-T cycles had the greatest reduction in the average disintegration rate, followed by cohesion, the permeability coefficient, and the internal friction angle.
- (5) Compared with the D-W cycles, the F-T cycles more severely reduced cohesion, average disintegration rate, and the permeability coefficient of the reinforced loess, but the reduction of the internal friction angle was more obvious during the D-W cycles.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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References

- [1] H. Zheng, H. Lin, W. Zhou et al., "Revegetation has increased ecosystem water-use efficiency during 2000-2014 in the Chinese Loess Plateau: evidence from satellite data," *Ecological Indicators*, vol. 102, pp. 507-518, 2019.
- [2] H. Zheng, H. Lin, X. J. Zhu, Z. Jin, and H. Bao, "Divergent spatial responses of plant and ecosystem water-use efficiency to climate and vegetation gradients in the Chinese Loess Plateau," *Global and Planetary Change*, vol. 181, Article ID 102995, 2019.
- [3] C. H. Juang, T. Dijkstra, J. Wasowski, and X. Meng, "Loess geohazards research in China: advances and challenges for mega engineering projects," *Engineering Geology*, vol. 251, pp. 1-10, 2019.
- [4] T. A. Dijkstra, J. Wasowski, M. G. Winter, and X. M. Meng, "Introduction to geohazards of Central China," *Quarterly Journal of Engineering Geology and Hydrogeology*, vol. 47, no. 3, pp. 195-199, 2014.
- [5] L. P. Li, H. X. Lan, and J. B. Peng, "Loess erosion patterns on a cut-slope revealed by LiDAR scanning," *Engineering Geology*, vol. 268, Article ID 105516, 2020.
- [6] M. L. Li, X. C. Zhang, Z. J. Yang, T. Yang, and X. J. Pei, "The rainfall erosion mechanism of high and steep slopes in loess tablelands based on experimental methods and optimized control measures," *Bulletin of Engineering Geology and the Environment*, vol. 79, no. 9, pp. 4671-4681, 2020.
- [7] L. Wu, M. Peng, S. Qiao, and X.-Y. Ma, "Effects of rainfall intensity and slope gradient on runoff and sediment yield characteristics of bare loess soil," *Environmental Science and Pollution Research*, vol. 25, no. 4, pp. 3480-3487, 2018.
- [8] N. EsmailpourShirvani, A. TaghaviGhalesari, M. Khaleghnejad Tabari, and A. Janalizadeh Choobbasti, "Improvement of the engineering behavior of sand-clay mixtures using kenaf fiber reinforcement," *Transportation Geotechnics*, vol. 19, pp. 1-8, 2019.
- [9] Y. K. Wu, Y. B. Li, and B. Niu, "Investigation of mechanical properties of randomly distributed sisal fiber reinforced soil," *Materials Research Innovations*, vol. 18, pp. 953-959, 2014.
- [10] S. M. Hejazi, M. Sheikhzadeh, S. M. Abtahi, and A. Zadhoush, "A simple review of soil reinforcement by using natural and synthetic fibers," *Construction and Building Materials*, vol. 30, pp. 100-116, 2012.
- [11] S. Bordoloi, R. Hussain, A. Garg, S. Sreedeeep, and W.-H. Zhou, "Infiltration characteristics of natural fiber reinforced soil," *Transportation Geotechnics*, vol. 12, pp. 37-44, 2017.
- [12] Y. X. Wang, P. P. Guo, W. X. Ren et al., "Laboratory investigation on strength characteristics of expansive soil treated with jute fiber reinforcement," *International Journal of Geomechanics*, vol. 17, Article ID 04017101, 2017.
- [13] Y. X. Wang, P. P. Guo, X. Li, H. Lin, Y. Liu, and H. P. Yuan, "Behavior of fiber-reinforced and lime-stabilized clayey soil in triaxial tests," *Applied Sciences-Basel*, vol. 9, no. 5, Article ID 900, 2019.
- [14] U. Chaduvula, B. V. S. Viswanadham, and J. Kodikara, "A study on desiccation cracking behavior of polyester fiber-

- reinforced expansive clay," *Applied Clay Science*, vol. 142, pp. 163–172, 2017.
- [15] Y. X. Bai, J. Liu, Z. Z. Song, F. Bu, C. Q. Qi, and W. Qian, "Effects of polypropylene fiber on the liquefaction resistance of saturated sand in ring shear tests," *Applied Sciences-Basel*, vol. 9, no. 19, Article ID 4078, 2019.
 - [16] M. H. Maher and Y. C. Ho, "Mechanical properties of kaolinite/fiber soil composite," *Journal of Geotechnical Engineering*, vol. 120, no. 8, pp. 1381–1393, 1994.
 - [17] M. M. Al-Durrah and J. M. Bradford, "Parameters for describing soil detachment due to single waterdrop impact," *Soil Science Society of America Journal*, vol. 46, no. 4, pp. 836–840, 1982.
 - [18] H. Jiang, Y. Cai, and J. Liu, "Engineering properties of soils reinforced by short discrete polypropylene fiber," *Journal of Materials in Civil Engineering*, vol. 22, no. 12, pp. 1315–1322, 2010.
 - [19] B. Lian, J. Peng, H. Zhan, and X. Cui, "Effect of randomly distributed fibre on triaxial shear behavior of loess," *Bulletin of Engineering Geology and the Environment*, vol. 79, no. 3, pp. 1555–1563, 2020.
 - [20] C. P. Han, Y. L. He, J. Y. Tian et al., "Shear strength of polypropylene fibre reinforced clay," *Road Materials and Pavement Design*, pp. 1–18, 2020.
 - [21] C. A. Anagnostopoulos, D. Tzetzis, and K. Berketis, "Shear strength behaviour of polypropylene fibre reinforced cohesive soils," *Geomechanics and Geoengineering*, vol. 9, no. 3, pp. 241–251, 2014.
 - [22] S. Saghari, G. Bagheri, and H. Shabanzadeh, "Evaluation of permeability characteristics of a polymer fibers-reinforced soil through laboratory tests," *Journal of the Geological Society of India*, vol. 85, no. 2, pp. 243–246, 2015.
 - [23] Y. Zhao, Z. Xiao, C. Fan, W. Shen, Q. Wang, and P. Liu, "Comparative mechanical behaviors of four fiber-reinforced sand cemented by microbially induced carbonate precipitation," *Bulletin of Engineering Geology and the Environment*, vol. 79, no. 6, pp. 3075–3086, 2020.
 - [24] J. D. Wang, T. F. Gu, M. S. Zhang et al., "Experimental study of loess disintegration characteristics," *Earth Surface Processes and Landforms*, vol. 44, pp. 1314–1329, 2019.
 - [25] Y. Z. Qi, Y. F. Guan, L. Y. Wang et al., "The influence of soil disintegration in water on SlopeInstability and failure," *Advances in Civil Engineering*, vol. 2020, Article ID 8898240, 9 pages, 2020.
 - [26] N. An, C. G. Yan, Y. C. Wang et al., "Experimental study on antierosion ability of polypropylene fiber-reinforced loess," *Rock and Soil Mechanics*, vol. 42, 2021.
 - [27] J. Xu, Y. Li, S. Wang, Q. Wang, and J. Ding, "Shear strength and mesoscopic character of undisturbed loess with sodium sulfate after dry-wet cycling," *Bulletin of Engineering Geology and the Environment*, vol. 79, no. 3, pp. 1523–1541, 2020.
 - [28] Y. L. Guo, W. Ma, Y. H. Mu, F. Wang, S. Z. Fan, and Y. H. Wu, "Effects of freeze-thaw cycle on engineering properties of loess used as road fills in seasonally frozen ground regions North China," *Journal of Mountain Science*, vol. 14, pp. 356–368, 2017.
 - [29] C. G. Yan, Z. Q. Zhang, and Y. L. Jing, "Characteristics of strength and pore distribution of lime-flyash loess under freeze-thaw cycles and dry-wet cycles," *Arabian Journal of Geosciences*, vol. 10, pp. 1–10, 2017.
 - [30] Z. Zhou, W. Ma, S. Zhang, Y. Mu, and G. Li, "Effect of freeze-thaw cycles in mechanical behaviors of frozen loess," *Cold Regions Science and Technology*, vol. 146, pp. 9–18, 2018.
 - [31] H. Lu, J. Li, W. Wang, and C. Wang, "Cracking and water seepage of Xiashu loess used as landfill cover under wetting-drying cycles," *Environmental Earth Sciences*, vol. 74, no. 11, pp. 7441–7450, 2015.
 - [32] J. Xu, Z.-Q. Wang, J.-W. Ren, S.-H. Wang, and L. Jin, "Mechanism of slope failure in loess terrains during spring thawing," *Journal of Mountain Science*, vol. 15, no. 4, pp. 845–858, 2018.
 - [33] W. J. Ye, Z. P. Zhao, G. S. Yang, J. M. Xi, and Y. Y. Zhang, "Influence of soil moisture state on loess slope spalling hazards," *China Journal of Highway and Transport*, vol. 28, pp. 18–24, 2015.
 - [34] W. J. Ye, G. S. Yang, J. B. Peng, Q. B. Huang, and Y. F. Xu, "Test research on mechanism of freezing and thawing cycle resulting in loess slope spalling hazards in luochuan," *Chinese Journal of Rock Mechanics and Engineering*, vol. 31, pp. 199–205, 2012.
 - [35] A. S. Zaimoglu, "Freezing-thawing behavior of fine-grained soils reinforced with polypropylene fibers," *Cold Regions Science and Technology*, vol. 60, no. 1, pp. 63–65, 2010.
 - [36] M. Ghazavi and M. Roustaie, "The influence of freeze-thaw cycles on the unconfined compressive strength of fiber-reinforced clay," *Cold Regions Science and Technology*, vol. 61, no. 2-3, pp. 125–131, 2010.
 - [37] E. Kravchenko, J. Liu, W. Niu, and S. Zhang, "Performance of clay soil reinforced with fibers subjected to freeze-thaw cycles," *Cold Regions Science and Technology*, vol. 153, pp. 18–24, 2018.
 - [38] E. Kravchenko, J. K. Liu, A. Krainiukov, and D. Chang, "Dynamic behavior of clay modified with polypropylene fiber under freeze-thaw cycles," *Transportation Geotechnics*, vol. 21, Article ID 100282, 2019.
 - [39] C. Liu, Y. Lv, X. Yu, and X. Wu, "Effects of freeze-thaw cycles on the unconfined compressive strength of straw fiber-reinforced soil," *Geotextiles and Geomembranes*, vol. 48, no. 4, pp. 581–590, 2020.
 - [40] C. M. Hu, Y. L. Yuan, X. Y. Wang, Y. Mei, and Z. Liu, "Experimental study on strength deterioration model of compacted loess under wetting-drying cycles," *Chinese Journal of Rock Mechanics and Engineering*, vol. 37, pp. 2804–2818, 2018.
 - [41] J. C. Li, S. F. Cui, and W. P. Tian, "Erosion characteristic of road and test of soil disintegration," *Journal of Chang'an University (Natural Science Edition)*, vol. 27, pp. 23–26, 2007.
 - [42] T. Harianto, S. Hayashi, Y.-J. Du, and D. Suetsugu, "Effects of fiber additives on the desiccation crack behavior of the compacted Akaboku soil as a material for landfill cover barrier," *Water, Air, and Soil Pollution*, vol. 194, no. 1-4, pp. 141–149, 2008.
 - [43] C.-S. Tang, B. Shi, and L.-Z. Zhao, "Interfacial shear strength of fiber reinforced soil," *Geotextiles and Geomembranes*, vol. 28, no. 1, pp. 54–62, 2010.
 - [44] L. Gao, G. H. Hu, N. Xu et al., "Experimental study on unconfined compressive strength of basalt fiber reinforced clay soil," *Advances in Materials Science and Engineering*, vol. 2015, Article ID 561293, 8 pages, 2015.
 - [45] C.-S. Tang, B. Shi, Y.-J. Cui, C. Liu, and K. Gu, "Desiccation cracking behavior of polypropylene fiber-reinforced clayey soil," *Canadian Geotechnical Journal*, vol. 49, no. 9, pp. 1088–1101, 2012.
 - [46] Y. Li, X. Ling, L. Su, L. An, P. Li, and Y. Zhao, "Tensile strength of fiber reinforced soil under freeze-thaw condition," *Cold Regions Science and Technology*, vol. 146, pp. 53–59, 2018.