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Erosion Control and Growth Promotion of W-OH Material on Red Clay Highway Slopes: A Case Study in South China

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Abstract: Ecological restoration is difficult on the red clay highway slopes in the rainy areas in South China that experience severe soil erosion. By using the hydrophilic polyurethane material W-OH to solidify and protect red clay slopes, the erosion control will be substantially improved. We employed simulated rainfall erosion experiments and pot experiments to evaluate the anti-corrosion and growth promotion performances. We found that, (1) in the initial stage of protection, W-OH had the effect of accelerating slope drainage, solidifying the soil structure, and reducing soil loss, with the sediment reduction benefit reaching 37.4–65.3%. (2) The anti-erosion effect was mainly based on soil solidification. (3) The W-OH was affected by rainfall intensity and the W-OH concentration, and the soil erosion prediction equation was constructed according to the observation. (4) W-OH had a promising water retention performance and can promote the germination and late growth of slope plants to reduce the influence of eluviation. (5) The suitable W-OH solution concentration was 3–5% for slope protection herbs and shrubs, which were commonly used in South China. (6) The reduction in porosity was the fundamental cause of water retention improvement. The ecological restoration of slopes is a comprehensive process. Therefore, both anti-erosion performance and later plant growth are necessary. Our research provides a theoretical and experimental basis for applying the W-OH in the ecological restoration of the red clay slopes in subtropical areas and expanding the scope of the W-OH.

Keywords: W-OH; red clay; slope restoration; soil erosion; growth promotion performance

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Citation: Qin, X.-c.; Ni, A.-c.; Zhang, N.; Chen, Z.-h. Erosion Control and Growth Promotion of W-OH Material on Red Clay Highway Slopes: A Case Study in South China. *Sustainability* **2021**, *13*, 1144. https://doi.org/10.3390/su13031144

Academic Editor: Teodor Rusu
Received: 8 December 2020
Accepted: 18 January 2021
Published: 22 January 2021

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1. Introduction

The red clay hilly area of South China is located in the subtropical monsoon climate zone. The area is crisscrossed with low mountains and hills. The red clay is highly erodible. Soil erosion in this area is very extensive and severe and is second only to that in the Loess Plateau [1] due to frequent human activities. In recent years, bare red clay slopes have formed from the large-scale construction of highway traffic networks in the region. Red clay has a high porosity, high compressibility, low compaction, and decreased strength under moist conditions [2]. Therefore, soil erosion will be more severe in the rainy areas. At the same time, low erosion resistance and insufficient nutrient supplementation also hinder the ecological restoration of the red clay slopes [3].

Traditional ecological restoration methods are both engineering and ecological measures. The former mainly includes slope engineering, ditch protection engineering, and trench engineering. It focuses mainly on the water interception and drainage to reduce the runoff erosion. It utilizes "gray" materials such as concrete to reinforce the surface soil of slopes. The major disadvantages are the small protective effect, heavy environmental pollution, and the high cost of investment [4]. With the gradual improvement of ecological protection, seeking alternative ecological protection measures has slowly become the first choice. Common ecological measures mainly include slope grass planting, coconut fibre networks, three-dimensional net seeding, ecological bags, and so on. Plant roots have

an effect on the interception and soil reinforcement. Although ecological measures have achieved specific results, there are still weak surface structures, low durability, high rework rates, easily washed seeds, and low effects on planting back to green cover [5–8].

Combining the chemical and ecological measures provides new ideas for soil erosion control, especially for rainy areas in southern China. With adequate reinforcement and water retention effects, polymer water-absorbing resin cementing materials are important in the research concerning chemical reinforcement materials [9,10]. At present, polymer water-absorbent resin materials have been successfully applied to the reinforcement of loess and pisha sandstone [11–13]. However, the application and study of red clay urgently need to be carried out. Moreover, the results of previous research have mostly focused on soil erosion characteristics or the effects of improvement and growth promotion. However, as the ecological repair is a comprehensive process, it is necessary to consider both at the same time.

This paper is based on the W-OH for the gel-solidified ecological restoration of red clay slopes. To investigate the effects of erosion resistance and the promotion of plant growth, simulated rainfall erosion experiments and pot experiments were carried out. The characteristics of runoff generation and sediment production, effects of growth promotion, and W-OH water retention performance on red clay slopes under diverse concentrations were comprehensively explored. The conclusions provide a theoretical and experimental basis for applying W-OH materials in the ecological restoration of red clay road slopes in rainy areas.

2. Material and Methods

2.1. Experimental Materials

2.1.1. Soil Samples

The red clay used in the experiment was collected from the Huiqing Highway road slopes in Conghua District, Guangzhou, Guangdong Province (Figure 1). The sampling area was an exposed slope that was newly formed during construction. After cleaning the surface of gravel and weeds, the soil (Figure 2a) was collected from 0–30 cm on the slope's surface with a shovel using a multipoint sampling method. The soil was mixed and sealed in bags for storage. Basic soil property parameters were measured. Dry density was 1.54–1.68 g/cm^3. Moisture content was 21.8–25.9%. The specific gravity of the soil was 2.73. The Porosity ratio was 1.232. The saturation was 57.4%. The soil particle gradation was <0.002 mm, 0.002–0.02 mm, and >0.02 mm, measured as 15.1%, 17.4%, and 67.5%, respectively.

2.1.2. W-OH Material

The main component is the modified hydrophilic polyurethane resin (Figure 2b). The resin's appearance is a light yellow or brown oily body. Furthermore, after mixing with water as a curing agent, carbon dioxide gas is generated (Equation (1)). The resin produces an environmentally friendly, porous elastic gel with both anti-seepage and anti-flush properties and does not react with water. Moreover, the gel is insoluble in water. Basic material parameters include the following values. The density was 1.1 g/cm^3. The reliable content was 60%. The viscosity was 200–800 cps. The hardening time was 4–7 min. The pH value was 6.7–7. This material is environmentally friendly, as it will not cause harm to animals or plants, and has a high degree of safety [9].

$$2R - NCO + H_2O \rightarrow NHCONH + CO_2 \quad (1)$$

2.1.3. Other Materials

The water-retaining agent (polyacrylamide) (Figure 2c) has the effect of improving soil, regulating soil moisture, and enhancing soil nutrients. Human-made fibers (Figure 2d) are spun from natural raw materials such as straw, coconut shell, bamboo, and wood, after being dissolved. It can form a self-locking structure. After use, it can quickly heal and

cover the slope surface. Moreover, the cover layer is porous with good moisture absorption performance. Peat is used as a fertilizer, which contains rich nutrients and improves the planting layer.

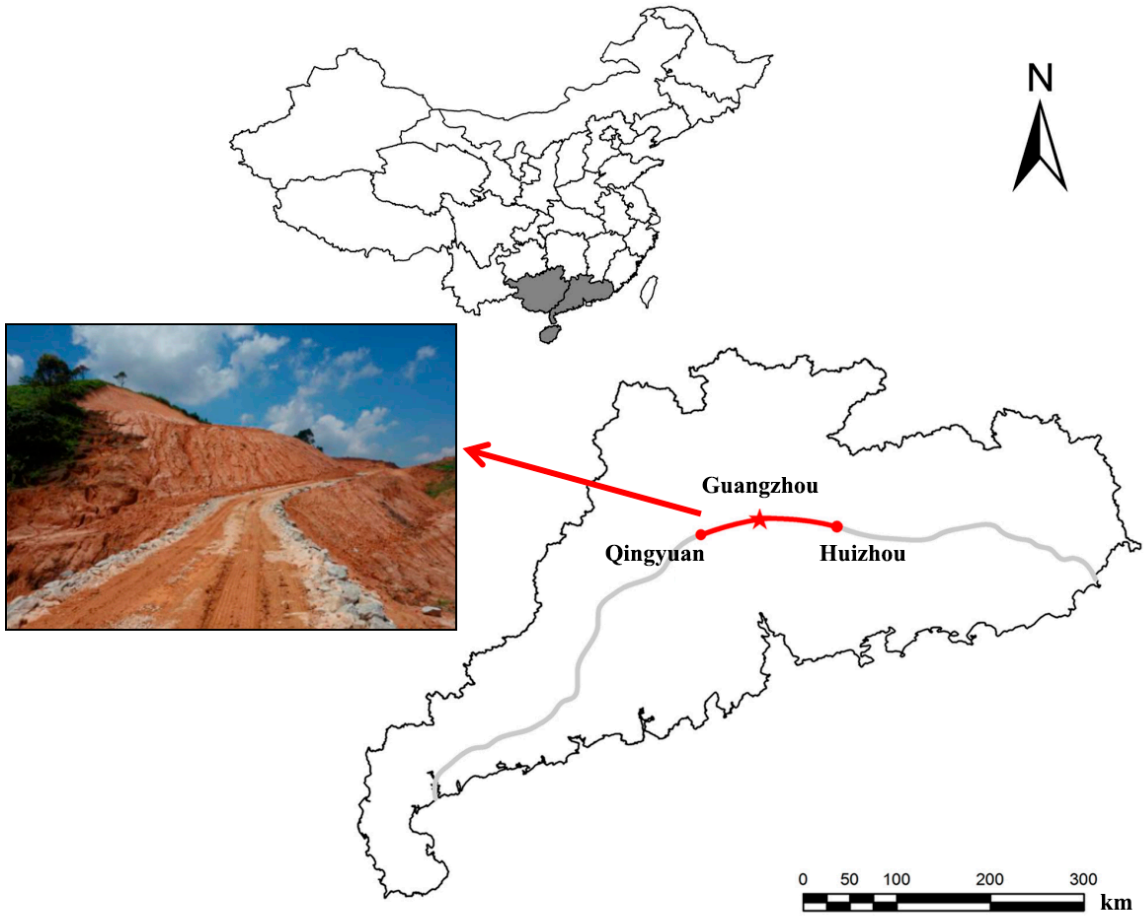


Figure 1. The location of southern China and the sampling area.

2.2. Technical Process

The operation of ecological restoration for slopes based on W-OH required hydroseeder, dual-tube sprayers, and sprinklers. First, the hydroseeder was used to mix the substrate material (including water-retaining agent, human-made fibers, peat, clear water, and seeds) evenly and to spray it to the slope surface to form a uniform covering layer for improving the soil and nutrients. Then, a dual-tube sprayer (Figure 3) was used to spray the W-OH solution. The two tubes of the sprayer supplied water and W-OH material respectively, and then mixed them evenly at the mixer tube. The tubes sprayed the mixture to the slope surface. The W-OH material condensed and solidified in about 5 min when it met with water, forming an elastic gel that was anti-seepage and anti-erosion to reduce slope soil erosion. Finally, the nonwoven fabric was laid for maintenance. Sprinklers were mainly used for water supply during construction and future maintenance operations.

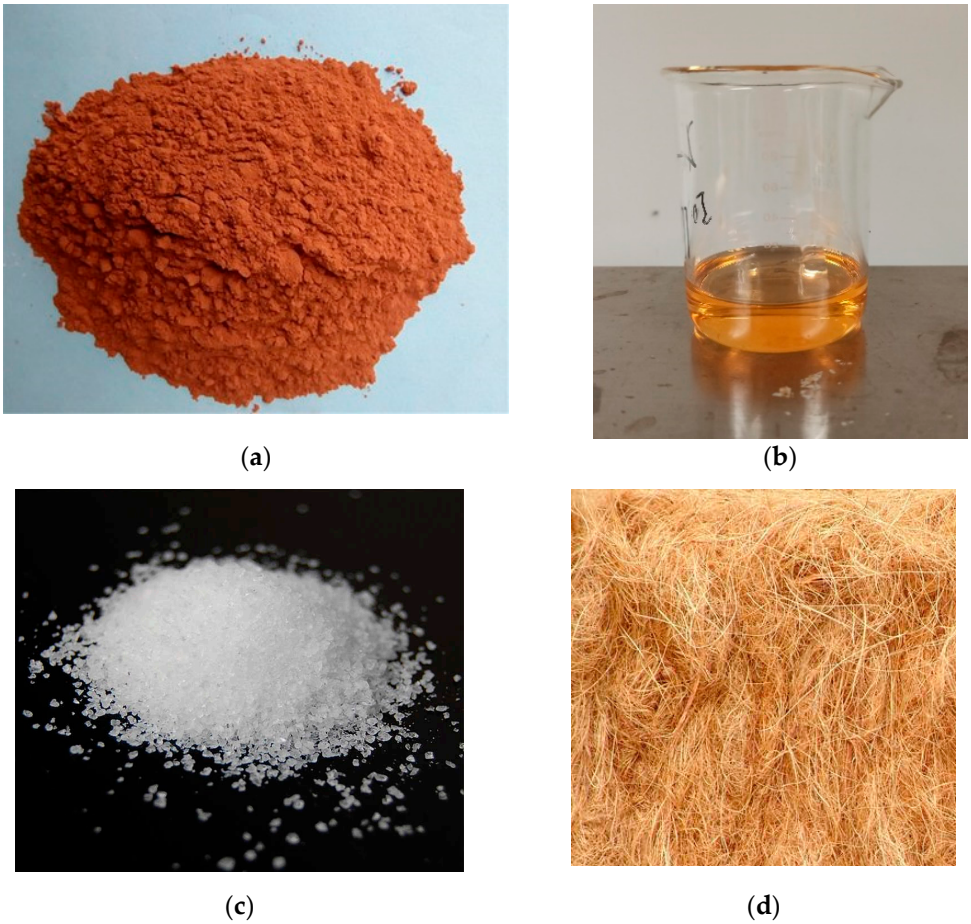


Figure 2. (**a**) Red clay; (**b**) W-OH material; (**c**) Water-retaining agent; (**d**) Human-made fibers.

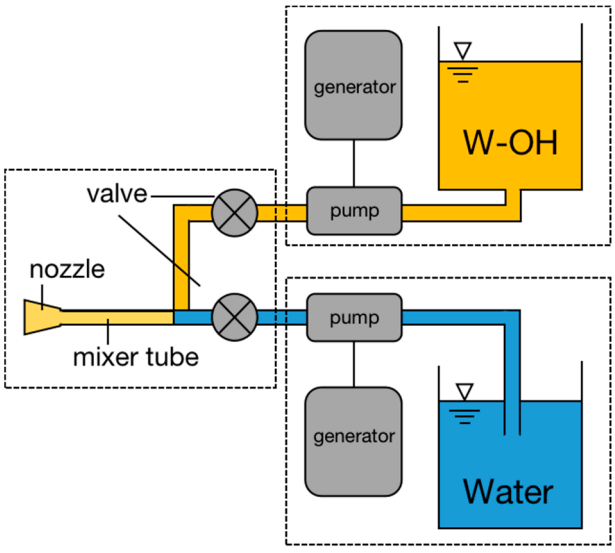


Figure 3. Schematic diagram of experimental set-up.

2.3. Simulated Rainfall Erosion Test

2.3.1. Rainfall Devices

The experiment was completed by relying on the "Rainfall intelligent simulation hall" (Figure 4a) of the highway traffic experiment site at the Ministry of Transport. The rainfall hall uses a combination of a downspray rainfall system and a rainfall wastewater treatment

system. The effective rainfall height in the downspray rainfall area is 8 m. It can achieve a continuous change in rainfall intensity from 0.2 mm/min to 3.0 mm/min. The rainfall simulation experiment system adopts integrated operation management software. The experiment can realize automatic control and data recording of all operational processes.

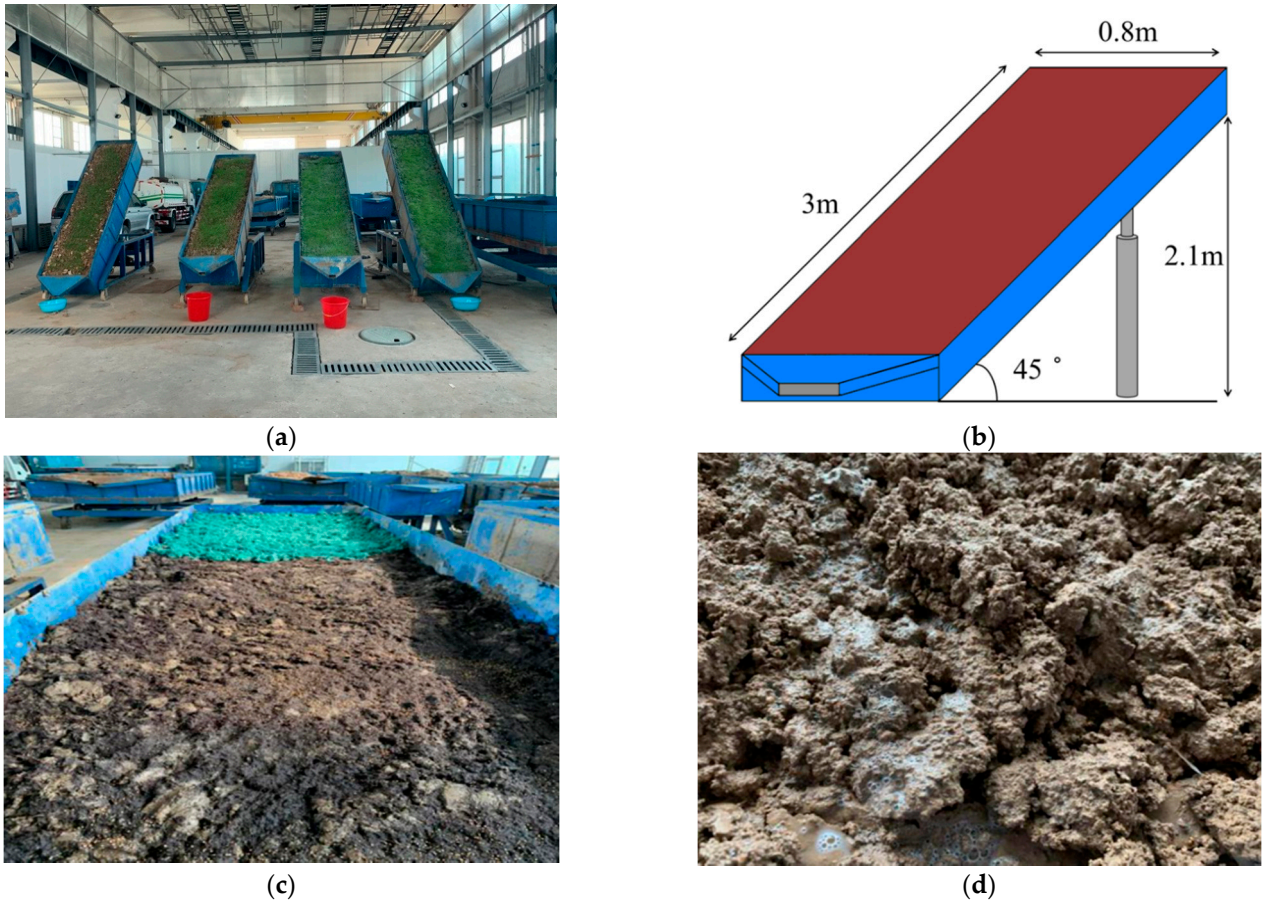


Figure 4. (**a**) Rainfall intelligent simulation hall, (**b**) Simulated slope; (**c**) Runoff plot; (**d**) After spraying W-OH solution.

2.3.2. Simulated Slope

The simulated slope and related parameters are shown in Figure 4b,c. Before the experiment, 5 cm of fine sand was filled at the bottom of the steel trough to guarantee drainage conditions. The red clay sample was mixed and evenly spread in a layer of 5 cm thick in order to ensure even layering and compaction. The slope was then smoothed with wooden boards to avoid slippage between the layers and to ensure that the slope approximated its natural state. The incline of the simulated slope was set to 45°. Moreover, the precipitation and sediment collection device was placed at the runoff collection port of the biological soil cultivation bed.

2.3.3. Experimental Design

The experiment was designed in four groups. W-OH solutions with mass concentrations of 3%, 5%, and 7% were sprayed on the surface of each simulated slope at 3 L/m^2 (Figure 4d). The other group was used as a control without treatment. The solution condensed and solidified in approximately 5 min, which was followed by the placement of nonwoven fabrics for 3–5 h after the completion of solidification. Prerainfall was carried out with a rainfall intensity of 0.5 mm/min the day before the experiment. Furthermore, it terminated after the start of runoff generation and was left for 24 h to ensure that the soil water content was consistent.

The simulated rainfall experiment was carried out with rainfall intensities of 1.0 mm/min (light to moderate rain) and 3.0 mm/min (heavy rain). Moreover, each group was repeated twice. The time of the start of runoff generation on each slope was recorded from the beginning of the time of rainfall. After runoff generation on the slope, runoff sediment was collected at the collection tank outlet with a numbered, standard runoff bucket. A sample was taken every 1 min during the first 3 min. After 3 min, a sample was taken every 3 min. The design runoff generation time was 20 min after initial runoff generation for each rainfall intensity until the end of the experiment. After the experiment, sediment in the runoff bucket was thoroughly stirred according to the order. Therefore, the particles were evenly dispersed and sampled quickly in the runoff bucket with a numbered sample bottle of known quality after stirring. Moreover, the sampling was repeated three times in each runoff bucket to ensure that the sediment had been stirred well. After sampling, the volume of runoff sediment was determined in the sample bottle. Furthermore, an electronic scale was used to measure the mass of the sediment samples. The sediment samples taken from the runoff were dried at 105°C. They were weighed with a precision of 0.01 g on the electronic scale. The sediment yield of runoff was calculated. Moreover, the sediment yield per unit area was obtained through unit conversion. The sediment reduction benefits of different measures on the plot's slope were calculated using the sediment yield of the bare slope as a control. Moreover, the equation was as follows.

$$EI = \frac{Y_b - Y_m}{Y_b} \times 100\% \quad (2)$$

where EI is the sediment reduction efficiency index, Y_b is the sediment yield of the bare slope, and Y_m is the sediment yield of the runoff plot.

2.4. Planting and Water Retention Experiment

A planting experiment was carried out at the environmental engineering laboratory of the Ministry of Transport using potted plants with diameters of 20 cm and a depth of 15 cm (Figure 5a). Furthermore, there were eight groups, with three replicates in each group. *Paspalum natrum* (herb) and *Tephrosia* were grown separately (shrub). The seeds were purchased in Guangzhou, Guangdong Province. The collected red clay was evenly mixed with a water-retaining agent of 5 g/m^2, plant fiber of 100 g/m^2, and peat of 4 L/m^2 and used as a soil matrix in the pot. The seeds were disinfected with 5% sodium hypochlorite solution for 10 min. Afterward, these seeds were rinsed with clean water and evenly spread on the soil surface. The seeds were then covered with thin soil and sprayed with 3%, 5%, and 7% W-OH solutions. Moreover, these plants were cultured at room temperature. After germination, the number of buds was calculated. After 28 days of plant germination and growth, fresh plant stems and leaves were cut along the soil surface to collect each sample. Furthermore, withered stems and leaves were collected at the same time. After drying, the aboveground biomass under the action of different concentrations of W-OH solution was calculated. Then, the whole remaining pot of the root system was removed, rinsed, and dried. Moreover, underground biomass was measured (Figure 5b).

In the water retention experiment, the red clay was evenly paved with a water content of 25.9% in a flowerpot. Then, 3%, 5%, and 7% W-OH solutions were sprayed onto the soil surface. The experiment contained a total of four groups, including control groups. Moreover, each group had three replicates. After the curing layer formed, the 10–15 cm layer under the soil surface was heated and dried to analyze the moisture content on the 7th, 14th, 21st, and 28th days.



(**a**) (**b**)

Figure 5. (**a**) Spray W-OH solution and (**b**) Underground biomass.

2.5. Data Analysis

The date of runoff generation and sediment yield characteristics, and soil improvement were statistically processed by SPSS software (version 19.0, SPSS Inc., Chicago, IL, USA). Analysis of variance (ANOVA) was conducted to examine significant differences between runoff and sediment concentration among the treatments of the three W-OH solution concentration. The values presented in the article are the average of two repeated treatments. The least significant difference (LSD) method was used at the 95% confidence level. The soil erosion equation was processed by MATLAB 2019 software (MathWorks Inc., Natick, MA, USA) for nonlinear fitting. The processing flow and the actual meaning of each equation are referenced in the literature [14]. The conversion between rainfall intensity and inflow rate is shown in Equation (3). The soil erosion equation is meaningful for evaluating soil loss when the determination coefficient (R_2) is >0.5 and the Nash coefficient (E_{NS}) is >0.5. Half of the stabilization period data were randomly chosen to fit the equation. The remaining data were used to experiment with the equation. The simulated slope illustrations were created according to AutoCAD 2014 software (Autodesk Inc., San Rafael, CA, USA). The geographic location illustrations were created using ArcGIS (version 10.2, ESRI Inc., Redlands, CA, USA).

$$I = RS \tag{3}$$

where I is the inflow rate ($L \cdot min^{-1}$), R is the rainfall intensity ($mm \cdot min^{-1}$), and S is the simulated slope surface area (m^2).

3. Anti-Erosion Performance

3.1. Initial Runoff Generation Time

The initial runoff generation time reflects the slope soil's response to the scouring flow under different W-OH concentrations. The characteristics of the initial runoff generation time change of each measured area are shown in Table 1. The initial runoff generation time tended to decrease in all experimental plots with increased rainfall intensity. In light and medium rainfall, the initial runoff generation time was prolonged by 17.3% in the W3 group compared to the B group. Moreover, the W5 group and W7 group were shortened by 4.3% and 13.9%, respectively. In heavy rainfall, the initial runoff generation time was shortened by 8.3%, 19.4%, and 36.1% in the three groups. The protective effect of the initial W-OH material depended on the concentration of the material and the intensity of rainfall. The low-concentration W-OH solution had a delayed effect during small and medium rain. However, the initial runoff generation time during heavy rain was shortened. The longer the initial runoff generation time was, the stronger the soil infiltration effect at the beginning of rainfall. Furthermore, the runoff reduction effect was better. This result indicates that the presence of W-OH material affected the hydrodynamic characteristics of the slope.

Table 1. Initial runoff time (s).

Number	Experimental Group	1.0 mm/min	3.0 mm/min
B	Bare Slope	115	36
W3	3% W-OH	135	33
W5	5% W-OH	110	29
W7	7% W-OH	99	23

3.2. Runoff Processes

The runoff processes under different rainfall intensities are shown in Figure 6. When the rainfall was small or medium, the B group's runoff increased gradually with time and then fluctuated steadily. The stabilization time of group B was 9–12 min, and the stabilization runoff was 210.2 mL/min. After treatment with the W-OH solution, the changing trend of the plot runoff also increased first and then stabilized. Nevertheless, the stabilization time and stabilization runoff were different according to different concentrations. The stabilization time of the W3 group was after 12 min. However, the stabilization time of the W5 group and W7 group was earlier. The stabilization runoff was 201.1 mL/min, 216.3 mL/min, and 237.4 mL/min, respectively. The ranking of the runoff was W7 > W5 > B > W3. During the rainstorm, the B group's runoff rapidly entered the stable fluctuating state after a short rise. Furthermore, the steady runoff was 528.4 mL/min after 2 min. The changing trend of the W3 group was similar to that of the B group. Moreover, the final stable runoff was 541.5 mL/min. However, no distinct growth stage was observed in the W5 group and W7 group. These directly entered the steady fluctuating state. The final stable runoff was 619 mL/min and 687.1 mL/min, respectively. The ranking of runoff during heavy rainfall was W7 > W5 > W3 > B. This finding further shows that the 3% concentration of W-OH solution can reduce the red clay slope runoff in small and medium rainfall. Moreover, the 5–7% concentration of W-OH solution can increase the runoff of the slope regardless of the rainfall intensity. This concentration can reduce the length of stay of water on the slope and accelerate the drainage of the slope. Our statistical analysis results also supported the above conclusions (Table 2). The acceleration effect of 5–7% W-OH solution on red clay slope drainage was significantly different from that of the control group regardless of the rainfall intensity. However, there were no significant differences between the 3% W-OH solution and the control group. The effect of enhancing drainage was negligible. Combining the observation results with the statistical analysis provided a reference for applying W-OH solution on the red clay slopes in South China.

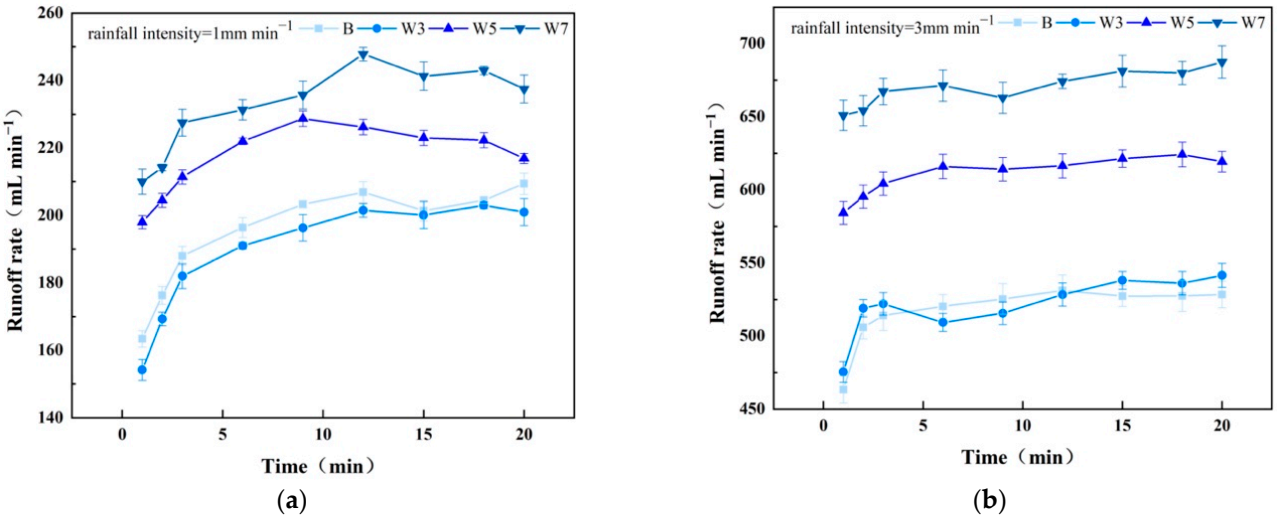


Figure 6. (**a**) The runoff generation process under 1 mm min^{-1}; (**b**) The runoff generation process under 3 mm min^{-1}.

Table 2. Total runoff for treatments with four at 1.0 mm/min and 3.0 mm/min rainfall intensities.

Rainfall Intenstiy (mm/min)	Total Runoff (mL min^{-1})			
	B	**W3**	**W5**	**W7**
1.0	194.4 c	188.7 c	217.1 b	232.1 a
3.0	515.9 c	520.6 c	610.6 b	669.9 a

Values for different W-OH solution concentration with the same rainfall intensity followed by different letters (a, b and c) are significantly different at $p < 0.05$ according to LSD test.

As a hydrophilic material, the W-OH material will form an elastic network on the soil surface when it encounters water (Figure 7). Furthermore, it will wrap the soil surface. The mesh structure can absorb and release water that is similar to a "water reservoir" [15]. The structure reduces evaporation and retains moisture. After W-OH contacted with the agglomerate, the curing agent's polymer chain contained a large number of active groups, which was capable to be wrapped on the surface of the agglomerate through hydrogen bonding or ion exchange effects. Additionally, the hydrophobic long carbon chain was capable to penetrate, diffuse, and entangle on the surface of soil particles with the aid of the early fluidity of the curing agent, which improved the stability of the particles and kept them from being corroded by water or wind.

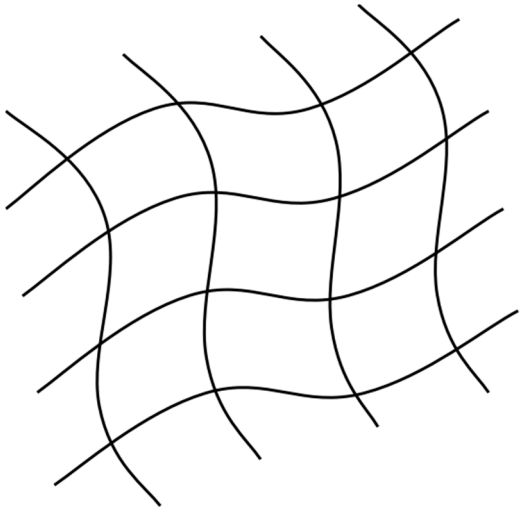


Figure 7. Gel network structure.

However, the porosity of the surface solid layer is influenced as the concentration of W-OH increases. After rainwater reaches the slope, it first infiltrates and then runs off when the soil layer is wet. The drastic decrease in soil porosity at high concentrations may be the main reason for the reduction in the infiltration rate and the steady runoff forming directly on the slope. This result explains the differences between the effects of different concentrations of W-OH solution. In general, the W-OH solution is mainly used to accelerate the drainage of the slope, so drainage measures should be taken at the foot of the slope in the initial application.

3.3. Soil Loss Processes

The soil loss processes of each group under different rainfall intensities are shown in Figure 8. The sediment yield of group B increased and then decreased with time during small and medium rainfall. The sediment yield fluctuated between 24.6 g/L and 31.2 g/L. The sediment yields of the W3 group, W5 group, and W7 group gradually decreased with time, fluctuating between 11.8 g/L and 17.1 g/L. The final sediment yield ranking was B > W3 ≈ W5 ≈ W7. After treatment with W-OH solution, the slope sediment yield was approximately equal in small and medium rainfall. Moreover, it was substantially smaller

than that of the bare slope. The sediment reduction efficiency ranged from 40.2 to 53.8%. During heavy rain, the B group sediment yield decreased and then fluctuated steadily with time. Furthermore, the steady time was 9 min. The sediment yield fluctuated between 39.9 g/L and 52.4 g/L. The W3 group, W5 group, and W7 group all had a small increase in sediment yield with time and then a gradual decrease. The W5 group and W7 group had relatively delayed turning times. The W3 group sediment yield fluctuated between 21.8 g/L and 29.1 g/L. Moreover, the W5 group and W7 group fluctuated between 14.3 g/L and 19.6 g/L. The sediment yield was ranked in the following order: B > W3 > W5 ≈ W7. The W5 group and W7 group had the best sediment reduction effect. The sediment reduction efficiency ranged from 55.7% to 65.3%. The sediment reduction efficiency of the W3 group was as follows. The sediment reduction efficiency ranged from 37.4 to 48.5%. The results show that the 3–7% W-OH solution had good soil reinforcement in both small and medium rainfall. However, the 5–7% W-OH solution had a better effect in heavy rain. The statistical analysis results also support the above conclusions (Table 3). Regardless of rainfall intensity, there were significant differences in soil consolidation effect between the use of W-OH solution and the control group. Moreover, there were significant differences in the soil consolidation effect of 3% W-OH solution and 5–7% W-OH solution. In summary, the South China red clay slope should be treated with 5–7% W-OH solution for slope protection.

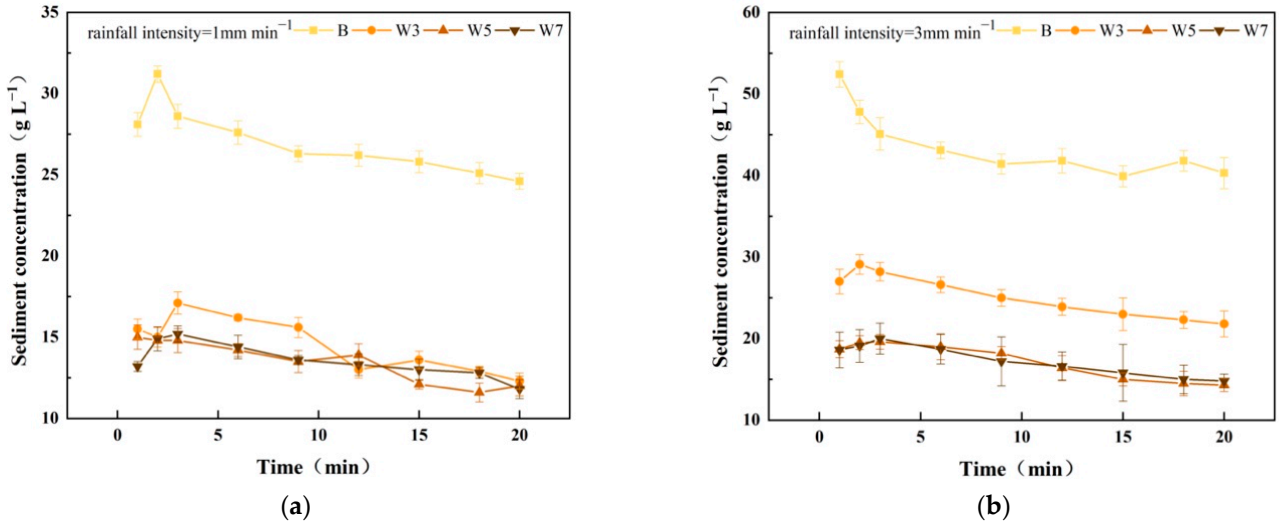


Figure 8. (**a**) Sand production characteristics under 1 mm min^{-1}; (**b**) Sand production characteristics under 3 mm min^{-1}.

Table 3. Sediment concentration for treatments with four at 1.0 mm/min and 3.0 mm/min rainfall intensities.

Rainfall Intenstiy (mm/min)	Sediment Concentration (g L^{-1})			
	B	**W3**	**W5**	**W7**
1.0	27.1 a	14.6 b	13.5 c	13.6 c
3.0	43.7 a	25.2 b	17.2 c	17.3 c

Values for different W-OH solution concentration with the same rainfall intensity followed by different letters (a, b and c) are significantly different at $p < 0.05$ according to LSD test.

After runoff formed on the slope surface, the surface's fine soil particles were first transported. This transport is why each group increased in terms of sediment production in the early stages of protection in small and medium rainfall. During heavy rain, the slope surface directly formed massive runoff. The fine particles and large aggregates were transported and stripped away from the soil. The sediment yield could fluctuate during the latter part of the rainstorm. The -NCO groups on W-OH polymer chain were capable to react quickly with the -OH of water and form a high-strength elastic gel in a short time. The

gel was inert when exposing to water again, which was equivalent to putting a "raincoat" above the slope surface [16].

To reduce slope erosion and sediment production, there are generally two ways to begin. The first way is to reduce the runoff generation of the slope to minimize the runoff's erosive force. The second way is to increase the soil's reinforcement capacity on the slope and to reduce the supply of materials to the slope [17–20]. Combined with the runoff characteristics above, we can see that the W-OH solution is mainly used to improve the slope's soil reinforcement capacity. The good affinity and permeability between the W-OH solution and the soil particles can encapsulate the soil particles in a net-like gel, while improving the surface roughness. The solution tightly bonds the particles to each other and effectively prevents the scouring effect of water. Previous studies on W-OH solution soil reinforcement have mainly been conducted on sand and Pisha sandstone. This paper demonstrates that it is also suitable for red clay slope protection.

3.4. Soil Loss Equation

According to Section 2.5, the soil erosion equation that considers the effects of inflow rate and W-OH concentration is shown in Equation (4) after a nonlinear fit.

$$S = 1.799C^{0.22}I^{1.174} \quad \left(R^2 = 0.98,\ n = 6\right) \tag{4}$$

where S is the soil erosion rate (g/min), C is the concentration of W-OH solution (%), and I is the inflow rate (L/min).

The soil erosion rate is a power function of the W-OH solution concentration and inflow rate. Moreover, the indices are 0.22 and 1.174, respectively. The impact of water erosion on the initial W-OH solution slope protection is more substantial. It also shows that the W-OH solution on slope protection is characterized by low runoff reduction and mainly a soil reinforcement effect. The predicted effect of Equation (4) is verified using the remaining data. Furthermore, the results are shown in Figure 9. The R_2 and E_{NS} are 0.96 and 0.95, respectively. The prediction results are in good agreement with the experimental results. This finding indicates that the soil erosion equation can effectively predict soil erosion at the initial stage of the W-OH solution on slope protection.

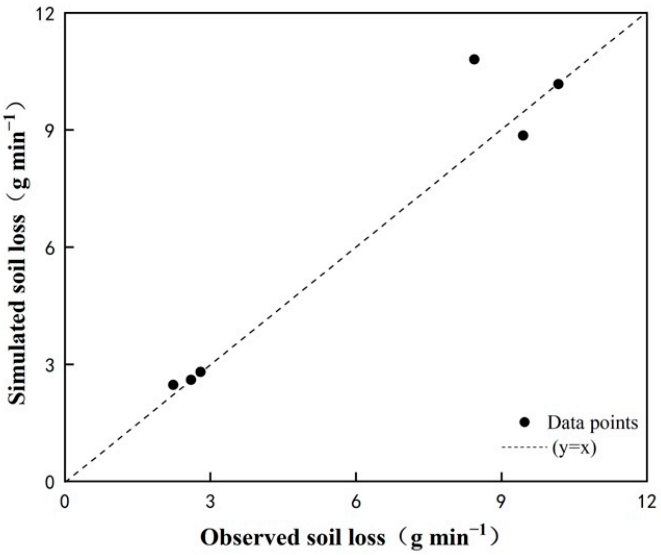


Figure 9. Comparison of predicted and observed soil loss (g min^{-1}).

Notably, the simulated rainfall erosion experiment mainly focused on the initial effect of the W-OH solution on slope protection. The experiment does not consider the interception and drainage of plants on the slope. The good soil reinforcement effect of the W-OH solution can prevent the loss of seeds by erosion and ensure plant coverage and

uniformity on the slope. In Section 4, we will discuss the effect of the W-OH solution on growth promotion.

4. Soil Improvement

4.1. The Budding Amount of Plant

The plants were treated with different concentrations of W-OH solution. The budding amount of plant is shown in Figure 10. For *P. natrum*, the budding amount of the W3 group, W5 group, and W7 group increased by 30.9%, 23%, and 4.6%, respectively, after applying the W-OH solution. For *Tephrosia*, the budding amount of the W3 group and W5 group increased by 93.3% and 120%, respectively, after using the W-OH solution. However, the budding amount of the W7 group decreased by 13.3%. This finding shows that the W-OH solution had an effect on promoting growth. Moreover, as the concentration increased, the effect of promoting growth gradually presented a downward trend. The W-OH solution restrained sprouting when the W-OH solution was used too much. When the W-OH solution concentration was too high, the gel layer was too tight and thick. Furthermore, the budding of plants cannot pass through the gel layer, which restrains the budding of plants. Therefore, the solution concentration should not be too large at the beginning of application of the W-OH solution to the slope. Moreover, it also depends on the type of plants. There is research about promoting the growth of corn in the literature [17]. In this paper, a concentration of 5% restrained budding. Therefore, this concept needs to be examined on a case-by-case basis.

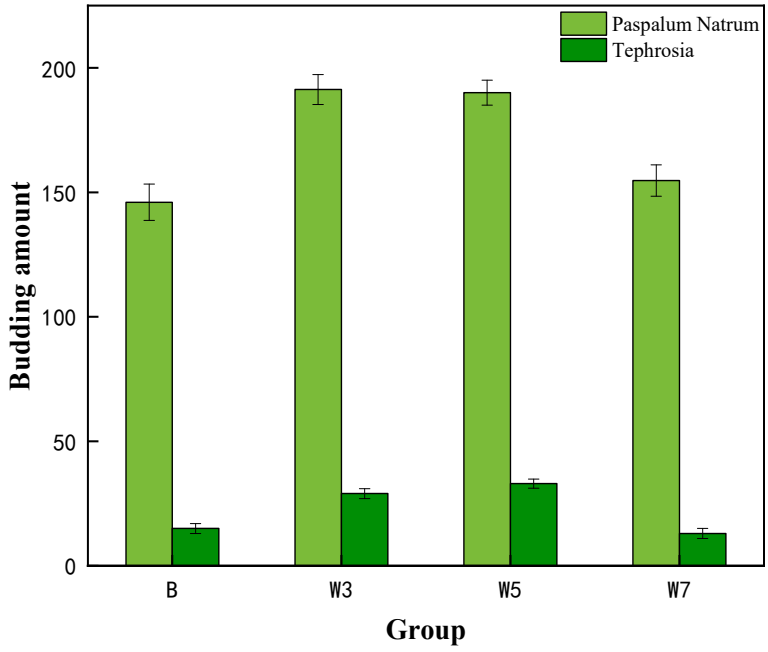


Figure 10. Budding effect comparison.

4.2. Biomass

The comparison of the aboveground biomass on the 28th day after treatment with the different concentrations of W-OH solution is shown in Figure 11a. For *P. natrum*, the budding amount of the W3 group, W5 group, and W7 group increased by 30.5%, 33%, and 11.6%, respectively, compared with that of group B. With increasing concentration, the promoting growth effect of the W-OH solution presented a trend of first increasing and then decreasing during the growing period. For *Tephrosia*, the budding amount of the W3 group, W5 group, and W7 group increased by 58.2%, 74.7%, and 7.6%, respectively, compared with that of group B. The variation in the trend of promoting the growth effect was the same as that of *P. natrum*. *Paspalum Natrum* sprouted quickly and grew well. The plant heights of the W3 group, W5 group, and W7 group was between 4.5 cm and 7 cm on

the 28th day. The growth trend was better than that of group B. Although the amount of budding of *Tephrosia* was small, the plants grew quickly. The plant heights of the W3 group, W5 group, and W7 group were between 13.2 cm and 22.8 cm on the 28th day. The growth of the W3 group and W5 group was better than that of the W7 group in group B. The root system of the plant reinforced the surface soil of the slope. Therefore, the larger the root system, the greater the underground biomass. Furthermore, it was beneficial to the steady slope soil. As shown in Figure 11b, the underground biomass of the W3 group, W5 group, and W7 group increased by 22.3%, 59.6%, and 64%, respectively, compared with that of *P. natrum* in group B. The underground biomass of the W3 group, W5 group, and W7 group increased by 18.7%, 67.9%, and 72%, respectively, compared with that of *Tephrosia* in group B. As the concentration of W-OH solution increased, the underground biomass of plants increased gradually.

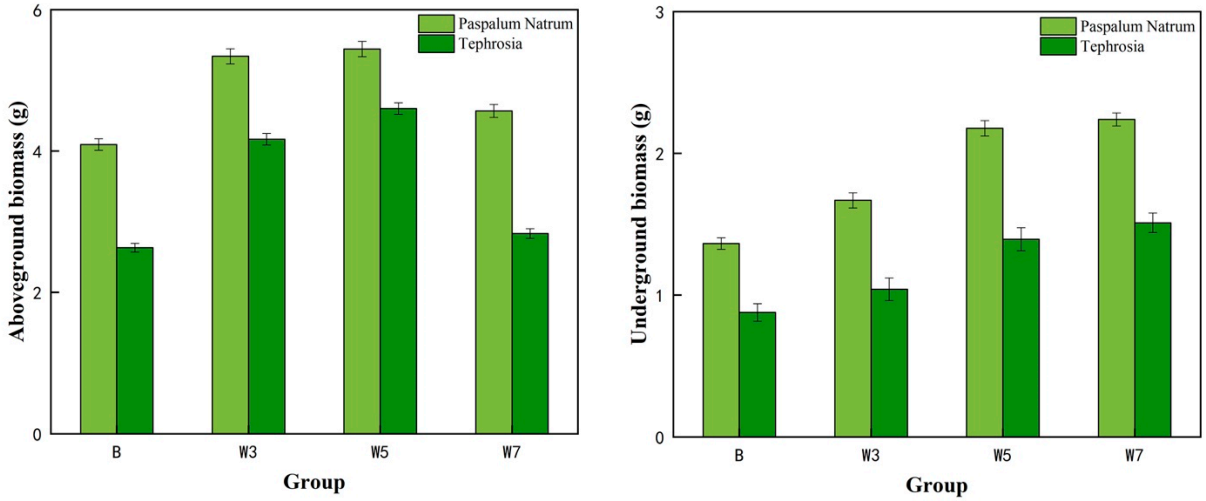


Figure 11. (**a**) Aboveground biomass; and (**b**) Underground biomass.

The W-OH solution improved the structure of the surface soil of the slope. Moreover, the loose clay particles tightly combined. It played a role in retaining water and preventing soil nutrient loss. These are all beneficial to the absorption and utilization of water and nutrients by the plant. Therefore, it makes the slope surface soil more suitable for plant growth. However, the soil-reinforcement effect of different concentrations of W-OH solutions was different. There were differences in the promotion effect of initial germination and later plant growth. For slope protection plants, *P. natrum* (herb) and *Tephrosia* (shrub) in subtropical regions in southern China, using 3–5% W-OH solution can have a beneficial effect in promoting growth.

4.3. Water Retention Effect

The change in soil moisture content with time is shown in Figure 12a. The moisture content of each group of soils gradually decreased with increasing time. Moreover, the speed gradually decreased with time. It was mainly related to the strength of evaporation on the soil surface. In the entire experimental process, the water content had a fast experimental decline rate in group B on the 7th day. Furthermore, the water content was reduced the most. The water content of the W3 group, W5 group, and W7 group treated with W-OH solution substantially slowed, especially the W5 group and W7 group. Compared with the untreated group B, the water content of the W3 group, W5 group, and W7 group increased by 56.4%, 94.1%, and 115.8%, respectively, on the 28th day. Meanwhile, the water retention effect was substantially improved.

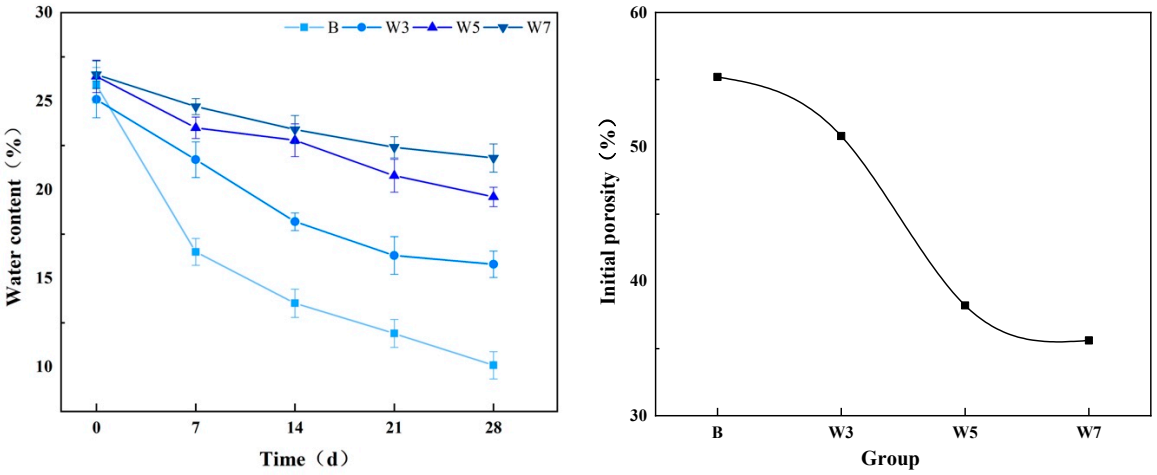


Figure 12. (**a**) Change in moisture content; and (**b**) Change in initial porosity (%).

The improvement in the water retention effect is one of the main reasons why the W-OH solution promoted growth. W-OH reacts with water to form an elastic network structure. The structure can absorb and store a certain amount of water and release it to plants when needed. Therefore, it can connect loose particles in the soil through an elastic net. It improves the soil structure, reduces the porosity, and reduces the rate of water evaporation in the soil. The microenvironment of plant growth reduces heat exchange and reduces the temperature difference between day and night. As the W-OH solution concentration increased, the initial porosity gradually decreased, as shown in Figure 12b. The decrease was most substantial when it rose from 3% to 5%. It also explains the increase in slope runoff in Section 2.2. This is the most fundamental reason for the difference in the water retention effect. At present, the W-OH solution has been successfully applied in arid and sandy soil areas. The substantial improvement in water retention performance prolongs the survival time of plants and improves their rate of survival. As rainfall is abundant in South China, it easily causes soil looseness to form interflow. It is easy to leach the nutrients in the soil to cause the nutrients to migrate vertically. Moreover, improving the water retention effect will reduce the loss due to leaching to ensure plant nutrient supply. Therefore, the W-OH material can also play a useful role in promoting plant growth on red clay slopes in South China, even in subtropical regions.

5. Conclusions

This paper is based on the anti-erosion and plant growth-promoting performance of W-OH materials on South China's red clay slopes. It used simulated rainfall erosion experiments and pot-planting experiments to carry out corresponding studies. The conclusions are as follows:

(a) The application of the W-OH solution will affect the hydrodynamic characteristics of the red clay slopes. Its effect is related to the concentration and rainfall intensity. The W-OH solution mainly increased the slope runoff and accelerated the drainage effect. The soil reinforcement effect of the W-OH solution was also affected by the concentration and rainfall intensity. Under small and medium rainfall, the effect of sand reduction was less affected by the concentration, and the difference was not significant. Under heavy rain, the effect of sediment reduction increased substantially with increasing concentration. After applying the W-OH solution to solidify the slope, a soil erosion equation was established, regardless of the initial stage of slope vegetation interception and drainage. The relationship between erosion rate (S), flow rate (I), and solution concentration (C) is $S = 1.799C^{0.22}I^{1.174}$. Moreover, the coefficient of determination is 0.98.

(b) W-OH solution has a certain growth-promoting effect on red clay slope plants. Furthermore, its growth-promoting effect is closely related to its concentration. If the concentration is too high, it will hinder the germination of plants. For the commonly used slope protection herbs and shrubs in South China, the recommended W-OH solution concentration is 3–5%. After solidification with the W-OH solution, the water retention performance of red clay slopes was improved, and the influence of leaching was weakened. This is mainly related to the reduction in soil porosity.

In summary, the W-OH solution can be extended to the protection of red clay slopes in rainy areas in South China. It has a good anti-erosion and growth promotion effect. However, the influence of slope angle and vegetation growth on the effect of interception and sediment reduction needs further study.

Author Contributions: Conceptualization, X.-c.Q.; data curation, N.Z.; formal analysis, A.-c.N.; funding acquisition, X.-c.Q.; investigation, Z.-h.C.; methodology, X.-c.Q.; visualization, A.-c.N.; writing—original draft, N.Z. All authors have read and agreed to the published version of the manuscript.

Funding: The research work was supported by the National Natural Science Foundation of China (grants no. 51878039, no. 52078034).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to the project privacy.

Acknowledgments: We both thank AJE (https://www.aje.cn) and Chen Ding (Texas AM Forest Service TAMU) for linguistic assistance during the revision of this manuscript. And we were very grateful for the helpful comments of the anonymous reviewers.

Conflicts of Interest: The authors declare no conflict of interest.

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