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Disintegration Resistance of Steep-Rocky-Slope Wall-Hanging Soil Based on High-Performance Ester Materials

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Abstract: Ecological restoration is difficult on the steep rocky slopes (SRS) in rainy areas in South China that experience severe soil erosion. The disintegration resistance of steep-rocky-slope wall-hanging soil (SRSWS) is a crucial topic in the field of new ecological restoration. The formation of a transient saturated zone of wall-hanging soil (WS) under high-intensity rainfall can easily lead to soil disintegration. The subsequent rain erosion can cause the loss of growth substrate required for early plants, resulting in a poor greening effect or even landslides. Therefore, improving the disintegration resistance of WS and ensuring the stability of the early-plant-growth environment are at the core of SRS protection. In this paper, structural and static underwater disintegration tests of red soil modified by high-performance ester materials (HEMs) were carried out. According to the damage ratio of the soil structure and the disintegration rate and disintegration amount of red soil, the structural properties and disintegration resistance of improved red soil were quantitatively measured. The results show that absorbent HEMs generally increased the content of water-stable aggregates (WAs) in red soil. However, when the content was excessively large, it destroyed the WAs and accelerated the overall disintegration rate and amount. Based on the structure and disintegration resistance test of red soil, optimal proportions of adhesive HEMs of 10 g \( \cdot \) m\(^{-3} \) and absorbent HEMs of 80 g \( \cdot \) m\(^{-3} \) were obtained. The optimal proportions obtained from the above experiments showed good adaptability and an improvement effect on the structural properties and disintegration resistance of red soil. This solves the problem of the growth substrate required for early plant disintegration and loss in water. This paper provides a theoretical and experimental basis for the ecological restoration of SRSWS with disintegration resistance. It has guiding significance for the steady progress of greening construction on SRS sites.

Keywords: high-performance ester materials; steep rocky slope; wall-hanging soil; disintegration resistance

1. Introduction

Steep rocky slopes (SRS) lack the necessary soil layers for plants, and the soil is traditionally hung by using platform technology [1–3]. Wall-hanging soil (WS) on SRS is one of the necessary conditions for greening work. Therefore, it is essential to ensure the stability of WS on SRS. In the early stage of construction, traditional protection engineering technology enhances the stability and anti-erosion ability of slopes, but the protective effect is not ideal [4]. One reason is the lack of attention to the stability of the WS on the slope. The collapse of soil is related to saturation. Generally speaking, unsaturated WS may collapse under the condition of long-term weathering [5]. Under rainfall conditions, the rainfall intensity is significantly greater than the infiltration capacity of the soil. The water content of WS on SRS will increase rapidly in a short time. A transient saturated zone is formed, and the accumulation of water on the slope surface is aggravated (Figure 1). WS is prone to
collapse under saturated conditions. As a result, the loss of growth substrate required for early plants causes a poor landscape planting effect and can even lead to landslides. To solve this problem caused by rainfall, it is important to study the prevention and control of WS disintegration. At the core of preventing and controlling the disintegration of WS is improving the structural properties and disintegration resistance of the soil. Therefore, studying and evaluating the soil’s structural properties and disintegration resistance can provide a theoretical basis for the design of greening projects on SRS walls. This has guiding significance for the steady progress of site greening construction.

At present, the traditional technology to protect SRSWS mainly adopts geotechnical patterning, catchwater drains, slope weep holes, and planting bags. These are employed to assist with greening protection of SRS soil reinforcement or slope drainage. Greening protection uses plant roots to fix soil to improve its structural properties and disintegration resistance, so as to prevent erosion. However, when the rainwater in WS is ignored, this results in the formation of aquiclude, leading to soil disintegration. The final plant survival rate is low, and the protection effect is not good, resulting in high maintenance management costs [6]. In recent years, soil solidification technology has been used to improve WS. The techniques improve the waterproofing properties and water retention in soil by forming solidified surface layers. The technology of soil solidification is to enhance the connection between soil particles and reduce the porosity of soil. The integrity of soil is improved, and the connection between soil particles is more stable, so that the soil surface has the ability to resist the erosion of large water flow. Simultaneously, the permeability of the surface soil layer is reduced, so as to increase the strength of the soil surface. After a certain thickness of the solidified layer is formed, the evaporation of water in the soil is reduced. It achieves the function of waterproofing and water retention [7–10]. In this way, plants can grow normally on steep slopes for a long time, and the dual effects of slope protection and ecological environmental protection are achieved. Various types of soil stabilizers provide different mechanisms for soil interaction. They essentially enhance the interaction of soil particles by changing the soil structure, thereby enhancing the strength of soil. Commonly used soil improvement materials can be divided into three categories: inorganic, biological, and organic.

The main inorganic soil improvement materials are cement, gypsum, and fly ash. Although they can effectively improve the mechanical strength of soil, the improved
soil has many problems, such as too high strength, too high stiffness, poor permeability, and many residual inorganic materials, which is not conducive to plant growth and soil ecological restoration [11–16].

Microbial-induced calcium carbonate precipitation (MICP) reinforcement is mainly used for sandy soil. With MICP, bacterial solutions and nutrients, such as urea and calcium, are injected into the sand. The engineering properties of the soil are improved through biological cementation and anti-seepage. Due to its long curing process and complex operation, it is not suitable for use in wall-hanging green planting [17–20].

Organic soil improvement materials, such as straw polysaccharides, cellulose, and high-performance ester materials (HEMs), do not pollute and damage the environment because of their degradability. They maintain an exceptional growth-promoting effect on early wall-hanging green plants [21–26].

In summary, the traditional protection technology has the problem of soil disintegration caused by accumulated water and perched groundwater. This leads to the loss of growth substrates required for early plants. In addition, inorganic and biological enzyme soil stabilizers are unsuitable for solidifying wall-hanging soil due to their limited environmental protection, strong selectivity, and long solidification time [27–29]. Therefore, it is crucially important to explore the improvement effect of organic soil stabilizers on underwater disintegration resistance for the stability of SRSWS.

In view of the aforementioned problems, in this paper, we selected typical SRS wall-hanging red soil in South China as the research object. Structural and static underwater disintegration tests were conducted on the red soil with HEMs. In the experiments, different proportions of HEMs were used to improve the red soil. The composition of water-stable aggregates (WAs) in the red soil and the overall disintegration rate and total disintegration amount after soaking were quantitatively studied. The addition of HEMs improved the structural properties and disintegration resistance of red soil. From the perspective of soil modification, this provides a reference for the protection of SRSWS.

2. Test and Method

To measure the soil loss characteristics of WS disintegration after saturation, in this paper, we designed structural and static underwater disintegration tests of red soil. In the experiments, different proportions of HEMs were used to improve the red soil. The composition of WAs in the red soil and the overall disintegration rate and total disintegration amount after soaking were quantitatively studied. The test scheme is shown in Figure 2. Firstly, the red soil used in the experiment was sampled from typical SRSWS in South China. Then, through the structural test, the optimal proportion of HEMs to improve the particle size distribution of WAs in red soil was obtained. Through the static underwater disintegration test, the optimal proportion of improved disintegration resistance to control the overall disintegration rate and percentage of red soil was obtained. Finally, the optimal proportion of HEMs to improve the disintegration resistance of red soil was obtained.

2.1. Test Purpose

The research group designed structural and static underwater disintegration tests of red soil. Through the structural test, the optimal proportion of HEMs to improve the particle size distribution of WAs in red soil was obtained. Through the static underwater disintegration test, the optimal proportion of improved disintegration resistance to control the overall disintegration rate and percentage of red soil was obtained. Ultimately, the final ratio was obtained by combining the results of the two tests.

2.2. Test Material

2.2.1. Soil Sample

The red soil used in the experiment was sampled from typical SRSWS in South China (Figure 3). We selected typical SRS wall-hanging red soil in South China as the research object for three reasons. Firstly, the object of our experiment is red soil, so we chose red soil
in South China. Second, red soil is widely distributed in South China, and the problem of slope erosion is particularly serious. Finally, because red soil is widely distributed in South China and has the characteristics of viscosity and fertility, it is widely used in guest soil. The sampling area was a newly formed exposed slope during construction. Initially, gravel and weeds on the slope were removed. Subsequently, utilizing the multipoint sampling method, we collected soil from the slope surface at a depth of 0–30 cm with a shovel. We mixed the soil and stored it in sealed bags. Before the test, the soil samples were mixed and dried and passed through a 2 mm sieve. We used a high-speed mixer to mix it well. Finally, the volumetric weight, water content, and particle size composition of the soil were analyzed (Table 1).

![Figure 2](image2.png)

**Figure 2.** Schematic diagram of disintegration resistance test of WS.

| Sample collection and location of research area. |

![Figure 3](image3.png)

**Figure 3.** Sample collection and location of research area.
Table 1. Basic properties of test soil.

| Soil          | Volumetric Weight (g·cm⁻³) | Water Content (%) | Grain Size Distribution |
|---------------|----------------------------|-------------------|-------------------------|
|               |                            |                   | ≥2 mm | 2–1 mm | 1–0.5 mm | 0.5–0.25 mm | ≥0.25 mm |
| Red soil      | 1.42                       | 9.32              | 40.16 | 3.86   | 5.75      | 8.98        | 58.75    |

2.2.2. Introduction to High-Performance Ester Materials (HEMs)

The ecological technology of high-performance ester materials (HEMs) is typically employed to effectively improve soil disintegration resistance in experiments. This technology was used in the red bed soil as an ecological material. The HEMs we used consisted of nano dispersed materials. The materials used in tests are primarily divided into two types, absorbent and adhesive. By mixing absorbent HEMs and adhesive HEMs into the red bed soil, the properties of soil water retention, bacteriostasis, and disease removal were improved. Soil consolidation and erosion resistance were enhanced, in addition.

The absorbent HEMs used in the field test were chiefly composed of polyacrylate sodium salt, a white particle with a size of less than 0.02 mm at ordinary temperatures. It is transparent and gelatinous when saturated with water. Its water absorption can typically reach 250%. The material expands when it absorbs liquid and shrinks when it loses liquid. In soil, absorbent HEMs can effectively conserve soil water for the growth of plant roots. In the process of water absorption and release, the volume expansion and contraction of high-strength synthetic water-absorption resin loosens the soil. The infinite addition of absorbent HEMs will inevitably lead to the overexpansion of soil particles and the accelerated collapse and destruction of soil. However, an appropriate concentration of absorbent HEMs can improve the soil structure and form an aggregate structure. Soil particles are wrapped by HEMs, which makes the soil particle size increase, so that more water can be stored. At the same time, the soil permeability is significantly increased, thus reducing the runoff under rainfall and controlling soil loss [30]. Thus, there should be a threshold concentration. Therefore, many research teams [31–33], including our team (Figure 4) [34,35], have carried out a lot of experimental research and field practice. These attempts were to find a suitable ratio to achieve the best soil disintegration resistance and plant growth. We find that this threshold is related to factors such as slope gradient and soil quality. According to previous research results and the practical engineering experience of our team [34,35], we determined the most suitable concentrations. The concentration of adhesive HEMs was 10 g·m⁻³. At this concentration of adhesive HEMs, the soil will not be too strong and hardened, affecting the germination and normal growth of plants. In addition, under general conditions, we obtain the concentration threshold of absorbent HEMs as 30–110 g·m⁻³. Under this concentration threshold, the soil will be improved poorly because the material concentration is too low. In addition, the soil will not be damaged due to excessive expansion due to high concentration [4,21–27,34–36]. This can effectively improve the soil structure and promote plant root growth [36].

The core component of adhesive HEMs is modified polyvinyl acetate, which is a white emulsion at ordinary temperatures. It has good dispersibility in water and can be prepared as an aqueous solution. This adhesive material can degrade by itself under natural environmental conditions, and the final degradation products are CO₂ and H₂O. When soil ester binder is prepared as an aqueous solution and applied to soil, it can effectively adsorb and agglomerate soil particles and form a soil aggregate structure. Improving the soil structure improves the anti-erosion ability of soil. Improving the soil properties can promote the rapid growth of vegetation.

2.3. Test Proportions

Applying an excessively high or low concentration of absorbent or adhesive HEMs has a terrible impact on soil. With concentrations that are too low, the absorbent material has no effect on the water-holding capacity of the soil. With concentrations that are too high, the absorbent material will cause soil looseness and too much soil moisture, resulting
in poor gas-exchange capacity of plants. With concentrations that are too low, adhesive material cannot guarantee erosion resistance of the soil. With concentrations that are too high, adhesive material will cause soil consolidation and affect the normal growth of plants. We followed the example of some researchers by varying the concentration of new functional materials to achieve an optimal ratio for improving soil properties [37–39]. Thus, according to previous research results and the practical engineering experience of our team [34,35], we determined the most suitable concentrations. The concentration of adhesive HEMs was 10 g·m$^{-3}$. This can achieve the most effective adsorption and soil particle agglomeration, improving the soil structure and erosion resistance. Therefore, the content of adhesive HEMs was kept unchanged in this experiment. The content of absorbent material was changed to adjust to the proportion of adhesive materials indirectly. Experimental groups were designed for structural and static underwater disintegration of red soil, as shown in Figure 5 and Table 2.

Figure 4. Some engineering examples of our team. (a) A slope project in South China; (b) Slope engineering of a reservoir bank in South China.
2.4. Test Method

2.4.1. Soil Structural Test

Water-stable aggregates (WAs), the key component of soil, are the basic unit of soil structure. They have a significant influence on the structural properties of soil [40]. The study on the stability mechanism of red soil aggregates shows that the formation of micro-aggregates (<0.25 mm) mainly depends on the adhesion between clay particles and trioxide. The formation of macro-aggregates (≥0.25 mm) typically depends on the interaction between organic cementitious materials and clay particles [41,42]. A large number of micro-aggregates with strong water stability in red soil mean it has a series of unique physical properties completely different from temperate soil, which dominate a series of motion characteristics of precipitation on the soil surface and in the soil [43]. It will affect the

Figure 5. Production and maintenance of red soil samples.

| Group Number | Adhesive High-Performance Ester Materials (hems) (g·m⁻³) | Absorbent High-Performance Ester Materials (hems) (g·m⁻³) |
|--------------|--------------------------------------------------------|--------------------------------------------------------|
| I            | 10                                                     | 0                                                      |
| II           | 10                                                     | 40                                                     |
| III          | 10                                                     | 60                                                     |
| IV           | 10                                                     | 80                                                     |
| V            | 10                                                     | 100                                                    |
| VI           | 10                                                     | 120                                                    |

Note: Test group VI sample was immersed in water, and disintegration rate was extremely fast. Balance reading of disintegration process could not be accurately recorded. Therefore, soil aggregate loss, overall disintegration rate, and total disintegration amount of sample VI were not recorded.
mean mass soil surface area, fractal dimension, dispersion coefficient and other structural characteristics of soil [44]. In addition, these indicators can also be used as one of the basis for the evaluation of soil erosion resistance [45].

The purpose of the structural test was to explore the effect of HEMs on the structural properties of red soil. In the course of the test, soil samples with different proportions of HEMs were mixed uniformly. Subsequently, they were put into aluminum boxes 20 cm in diameter and 5 cm in height and dried for 10 days. The particle analysis test was carried out according to the geotechnical test regulation (SL237–1999) of the Ministry of Water Resources. The soil samples were passed through 5, 2, 1, 0.5, and 0.25 mm sieves. The particle size distribution and loss of soil aggregates were determined by the dry–wet sieving method. Each group was repeated 3 times, and the average value was taken as the sieve test result [46].

With the different proportions of HEMs, the aggregate failure rate (FR) was used to evaluate the soil aggregate loss characteristics of the wet sieve compared with the dry sieve. The calculation formula of FR is as follows:

\[
FR = \frac{w_{d,i}(\geq 0.25 \text{mm}) - w_{w,i}(\geq 0.25 \text{mm})}{w_{d,i}(\geq 0.25 \text{mm})} \times 100\%
\] (1)

In the formula, \(i\) is the group tested, \(w_{d,i}(\geq 0.25 \text{mm})\) is the proportion of \(\geq 0.25 \text{mm}\) aggregates (dry sieve), and \(w_{w,i}(\geq 0.25 \text{mm})\) is the proportion of \(\geq 0.25 \text{mm}\) aggregates (wet sieve).

2.4.2. Static Underwater Disintegration Test

The purpose of the static underwater disintegration test was to quantitatively measure the disintegration rate of soil under saturated conditions and the loss of soil after disintegration. Combined with the actual situation of wall-hanging red soil under water (Figure 1), we developed a simple instrument for measuring soil immersion disintegration. The device is composed of a transparent glass cylinder (30 cm diameter, 40 cm height), an electronic balance, and a wire mesh frame (10 mm aperture) (Figure 6). The disintegration resistance of red soil was tested by the hydrostatic disintegration method. During the test, the loss process, disintegration rate, and total disintegration amount of agglomerates in red soil samples were observed and measured. The static underwater disintegration test was divided into the following steps:

![Figure 6. Schematic diagram of disintegration test instrument.](image)

1. The mixed soil samples were uniformly filled into aluminum boxes 20 cm in diameter and 5 cm in height. Subsequently, 6 groups of red soil samples were cured. After
10 days of curing, soil samples were collected with a cutting ring to make disintegration test samples.

During the disintegration test, the glass cylinder was first filled with water, and the sample was carefully placed on the wire mesh frame. Then, the wire mesh frame was hung on the electronic balance, and the sample was quickly immersed in the glass cylinder. It was necessary that the depth of water be about 1 cm higher than the surface of the soil sample [47,48]. We set the immersion depth to 1 cm for the following reasons. First, it refers to the geotechnical test standard (SL237-1999). Second, the natural soil contains a large number of bubbles, and the cohesive soil contains clay minerals, which have a certain expansibility. The deeper the depth is, the more bubbles will inevitably overflow and affect the test results [49]. Finally, some researchers have taken some measures to prevent bubble overflow, such as wrapping a layer of filter paper around the soil sample [50]. However, this is bound to affect the results of the disintegration test. Therefore, we set the immersion depth to 1 cm to carry out the underwater disintegration test.

Based on relevant studies showing that slope-red-soil erosion is mainly affected by rainfall intensity and rainfall, and maximum rainfall intensity of 30 min is closely related to soil erosion [51], the maximum immersion time of red soil was set as 30 min in the experiment. During the experiment, the readings of the balance were recorded every 30 s to observe the process of soil disintegration. If the soil samples completely disintegrated within 30 s, the balance reading and the corresponding time when they disintegrated were recorded. Each test group was tested twice and the average value was taken as the experiment result.

The amount of disintegration represents the total weight of soil particles that fall apart in each time period, expressed as m. To eliminate the influence of the dimension, a unified comparative analysis was conducted. In the experiment, the cumulative percentage of disintegration mass (A) was used to represent the degree of soil disintegration. Ultimately, we drew a disintegration curve. The calculation formula is as follows:

\[ m'_i = \frac{m_i - m_{i-1}}{m} = \frac{\Delta m_i}{m} \times 100\% \]  

\[ A = \sum_{i=1}^{60} \frac{\Delta m_i}{m} \times 100\% \]  

In the formula, \( m_i \) refers to the electronic balance reading of the soil at moment \( i \), \( m_{i-1} \) refers to the reading at moment \( i-1 \), and \( m'_i \) is the amount of disintegration of soil samples during periods \( i-1 \) and \( i \).

3. Test Results and Discussion

To study the structural properties and disintegration resistance of improved red soil, the aggregate content, disintegration amount, and disintegration time of red soil samples were analyzed. The soil aggregate composition was determined by the dry–wet sieving method. A digital camera was used for the real-time observation capture of the soil disintegration process. The quality change in soil samples was collected in real time by an electronic balance. Finally, soil aggregate grain size distribution, disintegration rate time, and cumulative disintegration percentage–time curves were obtained.

3.1. Effects of High-Performance Ester Materials (HEMs) on Water-Stable Aggregates (WAs) Content in Red Soil

The number and composition of soil WAs are significant in the stability of soil structure and affect soil disintegration resistance. Soil aggregates can be divided into macro-aggregates (\( \geq 0.25 \text{ mm} \)) and micro-aggregates (\(<0.25 \text{ mm} \)). Figures 7 and 8 show the particle size distribution of red-soil aggregates under different proportions of high-performance esters. Based on the dry and wet sieve test results of soil aggregates, the improvement effect of HEMs on WAs was studied.
Figure 7. Soil aggregate grain-size distribution curve of each group with (a) dry sieving and (b) wet sieving.
Figure 8. Particle size distribution of red soil aggregates of each group with (a) dry sieving and (b) wet sieving.
Using the dry sieving method, the content of soil aggregates with particle size $\geq 2$ mm under different proportions of HEMs differed. This was reflected in a trend of first increasing, then decreasing, and then increasing with higher content of absorbent HEMs. The content of soil aggregates with particle size $\geq 2$ mm in groups III and V (51.57 and 57.43%) was higher than in other treatments. This indicates that the appropriate addition of absorbent materials was conducive to the formation of hydrogel to absorb small soil particles. The content of soil aggregates with particle size 1–2 mm was greater in the four groups than in the control group, with a range of 8.3–11.04%. The content of group V was the highest. Accordingly, the aggregate content in the 0.25–1 mm size range was less in the four groups of red soil than in the control group. Comparing the content of soil aggregates $\geq 0.25$ mm in each test group, higher contents were found in the experimental groups than in the control group. Specifically, the content of aggregates with particle size $\geq 0.25$ mm increased with the increased content of absorbent HEMs. That is, the addition of this material can improve the structural properties of soil.

The test results and curve trend for the wet-sieving method are basically consistent with the dry-sieving method. The unique difference is that the content of soil aggregates with particle size $\leq 0.25$ mm increased by 21.16–28.19%; accordingly, the content of soil aggregates $\geq 2$ mm decreased by 12.18–22.71%. This may be because oversaturation of the soil damages the hydrogel; then, smaller soil particles disintegrate from hydrogel adsorption. Ultimately, the content of soil aggregates with particle size $\leq 0.25$ mm increased. Therefore, compared with the dry screening test, the average content of aggregates by wet screening increased as a whole. This is because soil aggregates with particle size $\geq 2$ mm disintegrate in water, resulting in more aggregates $\leq 2$ mm.

In summary, with increased content of absorbent HEMs, soil aggregates were mostly larger than 1 mm. These macro-aggregates have a beneficial effect on stabilizing soil structure, improving soil erosion resistance, preventing surface crust, and inhibiting soil evaporation.

### 3.2. Characterization of Red-Soil Aggregate Water Stability

The soil-aggregate failure rate (FR) can reflect the stability of soil structure. The smaller the value, the better the water stability of the aggregates, and vice versa. In this paper, FR was selected as a quantitative index. The aggregate loss characteristics of different proportions of HEMs in red soil were further analyzed.

There were differences in the failure rate of soil structure with different proportions of HEMs. As seen in Table 3 and Figure 9, the FR of groups III and V was smaller than the control group, while the FR of other groups was basically greater than the control group. As group V had the maximum content of absorbent HEMs, the FR was the highest.

### Table 3. Characterization of red-soil-aggregate water stability.

| Group Number | $wd(i \geq 0.25$ mm) | $ww(i \geq 0.25$ mm) | FR (%) | Amplitude of Variation (%) |
|--------------|-----------------------|-----------------------|--------|---------------------------|
| I            | 61.1                  | 74.03                 | 21.16  | /                         |
| II           | 67.55                 | 80.42                 | 19.05  | −9.97%                    |
| III          | 69.76                 | 84.94                 | 21.76  | 2.84%                     |
| IV           | 69.21                 | 81.62                 | 17.93  | −15.26%                   |
| V            | 70.63                 | 90.54                 | 28.19  | 33.22%                    |

In summary, absorbent HEMs generally increase the content of WAs in red soil. An appropriate amount of WAs can reduce FR, that is, improve the water stability of red-soil particles. However, its effect does not increase indefinitely with the increase in dosage, and even a reaction may occur. At a large dosage (100 g m$^{-3}$), it may destroy WAs. Therefore, based on the green area and purple area in Figure 8, combined with the interpolation method, the appropriate dosage of absorbent HEMs may be about 40 or 80 g m$^{-3}$.
In summary, absorbent HEMs generally increase the content of WAs in red soil. An appropriate amount of WAs can reduce FR, that is, improve the water stability of red-soil particles. However, its effect does not increase indefinitely with the increase in dosage, and even a reaction may occur. At a large dosage (100 g·m\(^{-3}\)), it may destroy WAs. Therefore, based on the green area and purple area in Figure 8, combined with the interpolation method, the appropriate dosage of absorbent HEMs may be about 40 or 80 g·m\(^{-3}\).

3.3. Effects of High-Performance Ester Materials (HEMs) on Overall Disintegration of Red Soil

The underwater disintegration test was carried out on groups I–VI, and one soil sample in group III was selected as a representative. Figure 10 shows the state of soil samples at different times, which intuitively reflects the disintegration process of red soil.

The process of red-soil sample disintegration proceeds from outside to inside in layers of flakes. First, the whole block collapses, and then it disintegrates into smaller blocks. At the beginning of the experiment, particles dispersed on the surface rapidly dissolved into the water, and the water immediately became turbid. Later, bubbles began escaping to the surface of the sample, and a slight uplift occurred at the center due to water absorption and expansion. Subsequently, the disintegration gradually proceeded from the sample edge to the inside. At the beginning of the test, a massive number of loose particles were exfoliated and the disintegration rate was fast, then it gradually slowed down to a constant. At a certain point (24 min), which can be seen in Figure 10g,h, the soil disintegration rate suddenly increased a little, but soon slowed down again. The reason may be that the soil sample blocks in water decompose into more small blocks under continuous disintegration, resulting in the increase in the specific surface area and the acceleration of the disintegration rate. However, the disintegration of small blocks was completed soon. At this time, these small blocks were difficult to disintegrate, and the collapse rate decreased until the disintegration stopped. In the whole process of disintegration, bubbles constantly escaped from the surface of the soil sample.

The disintegration rate of the group-VI sample immersed in water was extremely fast, and the balance reading of the disintegration process could not be accurately recorded. During the disintegration of group V, it was found that a cluster structure consisting of soil particles and absorbent high-performance ester materials appeared 13 min after disintegration, as shown in the red circle on Figure 11. This phenomenon lasted for 5 min. It may be because the carboxyl group (-COO-) on the surface of the absorbent material directly interacts with positively charged soil particles. Another possibility is that negatively charged soil particles bridge with cations in the soil. Finally, the soil particles around the absorbent material particles cemented together to form large aggregates, thus lowering the disintegration rate.
In summary, absorbent HEMs generally increase the content of WAs in red soil. An appropriate amount of WAs can reduce FR, that is, improve the water stability of red-soil particles. However, its effect does not increase indefinitely with the increase in dosage, and even a reaction may occur. At a large dosage (100 g·m$^{-3}$), it may destroy WAs. Therefore, based on the green area and purple area in Figure 8, combined with the interpolation method, the appropriate dosage of absorbent HEMs may be about 40 or 80 g·m$^{-3}$.

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The underwater disintegration test was carried out on groups I–VI, and one soil sample in group III was selected as a representative. Figure 10 shows the state of soil samples at different times, which intuitively reflects the disintegration process of red soil.

Figure 10. Underwater disintegration process of red soil: group III samples soaked for (a) 1 min, (b) 3 min, (c) 5 min, (d) 7 min, (e) 10 min, (f) 15 min, (g) 20 min, and (h) 30 min.
3.4. Effect of High-Performance Ester Materials (HEMs) on Red-Soil Disintegration Rate

According to the data fitting of multiple sets of disintegration test results, the fitted curves of disintegration rate (g·min$^{-1}$)—disintegration time (min) of soil samples in each dosage ratio test group were obtained (Figure 12).

We take the disintegration rate curve of group I as an example. The soil disintegration process can be divided into three stages—the initial, development, and stability stages—according to the disintegration rate. Figure 11 shows that the initial stage is 0–5 min. The disintegration of soil in water is faster, within 2–5 min. At the beginning of disintegration, the surface particles first dispersed into the water, and then expanded due to soil water absorption. Different expansion pressures and gas-escape pressures in pores result in uneven stress distribution in the soil. Finally, the soil was destroyed at the fragile structure first. In the 2–5 min period, because the soil bulk dispersed into many small pieces, the specific surface area increased, resulting in the rapid increase in the disintegration rate. The second development stage is 5–20 min. The disintegration of soil continued, and some internal pores connected to cause structural damage. Blocks fell off from the soil sample. The third stable stage is 20–30 min. The disintegration rate gradually decreased to a constant value, showing a slower disintegration process. The overall trend of the disintegration rate of soil samples in groups III was relatively gentle. In addition, the disintegration rate of group III was the lowest compared with other groups. There was no significant mutation in the development stage. This indicates that there was no large block disintegration and spalling during the disintegration of groups III. It shows that, when the concentration of absorbent HEMs is 80 g m$^{-3}$, absorbent HEMs can form a reliable bond between particles. Thus, there is no large soil-sample block falling and the disintegration rate is stable. In the stability stage, the disintegration rate of the other groups also reflected a general trend of gradual decreasing.

The disintegration quality of each group was statistically analyzed, and the change rule of disintegration quality percentage accumulation number (A) and time (t) was constructed (Figure 13).

It can be identified that the percentage of total disintegration mass was proportional to the amount of absorbent HEMs incorporated. This is because incorporating this absorbent material will increase the spacing between soil particles after swelling. The cement between soil particles is destroyed, and permeable pores are increased. Eventually, more water enters the pores, weakening soil cohesion and accelerating disintegration. Therefore, group I showed the lowest disintegration quality percentage. However, since absorbent HEMs were not added to group I, it has the phenomenon of the falling off of large blocks of soil samples. The cumulative number curve of disintegration mass percentage in groups II and III was approximately a straight line. There is almost no mutation, indicating that the disintegration rate was relatively constant in development stage. In group V, there

Figure 11. Group-V sample immersed in water and disintegrated for 13 min.
was a part of soil spalling in the first 3 min, and then the disintegration rate gradually slowed down.

![Image](image_url)

**Figure 12.** Relationship between disintegration rate and time in (a) group I, (b) group II, (c) group III, (d) group IV, and (e) group V.
rate is stable. In the stability stage, the disintegration rate of the other groups also reflected a general trend of gradual decreasing.

The disintegration quality of each group was statistically analyzed, and the change rule of disintegration quality percentage accumulation number ($A$) and time ($t$) was constructed (Figure 13).

![Figure 13. Cumulative chart of disintegration quality percentage of red soil samples.](image)

It can be identified that the percentage of total disintegration mass was proportional to the amount of absorbent HEMs incorporated. This is because incorporating this absorbent material will increase the spacing between soil particles after swelling. The cement between soil particles is destroyed, and permeable pores are increased. Eventually, more water enters the pores, weakening soil cohesion and accelerating disintegration. Therefore, group I showed the lowest disintegration quality percentage. However, since absorbent HEMs were not added to group I, it has the phenomenon of the falling off of large blocks of soil samples. The cumulative number curve of disintegration mass percentage in groups II and III was approximately a straight line. There is almost no mutation, indicating that the disintegration rate was relatively constant in development stage. In group V, there was a part of soil spalling in the first 3 min, and then the disintegration rate gradually slowed down.

In summary, unlimited increase in the content of absorbent HEMs will accelerate the disintegration rate and increase the total disintegration. The soil disintegration rate of group II and group III was constant and gentle, and there was no sudden spalling of bulk during the disintegration process. The overall disintegration rate of group III was the smallest of all groups. When preparing HEMs, the disintegration rate and disintegration percentage of red soil should be carefully considered and controlled. Considering the best disintegration resistance and the structural properties (water stability) of red-soil samples, a suitable content of absorbent HEMs should be about $80 \, \text{g} \cdot \text{m}^{-3}$.

Based on the structure and disintegration resistance test of red soil, optimal proportions of adhesive HEMs of $10 \, \text{g} \cdot \text{m}^{-3}$ and absorbent HEMs of $80 \, \text{g} \cdot \text{m}^{-3}$ were obtained.

4. Conclusions

(1) Based on structural and static underwater disintegration tests of red soil, we studied the improvement effect of high-performance ester materials (HEMs) on the structure and disintegration resistance of red soil. This solves the problem of soil disintegration caused by water retention in traditional protection technology that causes the loss of growth substrate required for early plants.

(2) High-performance ester materials (HEMs) have good adaptability and an improvement effect on the structure and disintegration resistance of red soil. Based on the structure and disintegration resistance test, optimal proportions of adhesive high-performance ester materials (HEMs) of $10 \, \text{g} \cdot \text{m}^{-3}$ and absorbent high-performance ester materials (HEMs) of $80 \, \text{g} \cdot \text{m}^{-3}$ were obtained. Using the optimal proportions, the content of water-stable aggregates (WAs) was increased. Moreover, the overall and total disintegration rates of red soil were controlled.
(3) This paper provides a theoretical basis for the ecological restoration of steep-rocky-slope wall-hanging soil (SRSWS) with disintegration resistance. It has guiding significance for the smooth process of greening construction on steep rocky slope (SRS) sites.

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