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Study on Ecological Mini-Aggregations Based on Polymer Composite Materials

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Abstract: In order to explore an efficient slope soil ecological restoration method that is environmentally friendly and conducive to plant growth, this paper conducted a study on ecological aggregations based on polymer composite materials. This paper developed ecological mini-aggregations, including ecological mini-clusters and ecological mini-bags, which can be used for the restoration of slopes with different steepnesses and surfaces. The developed materials are environmentally friendly and have good ecological performance. To study the mechanical stability, erosion resistance, and ecological performance of the ecological mini-aggregations, we conducted laboratory erosion resistance stability tests, shear strength tests, and plant growth tests, and variance analysis of the test result data was conducted to reveal the effects and laws of the aggregation materials. The results show that the mechanical stability of ecological mini-aggregations is strong, the erosion resistance is high, and the ecological performance is favorable. The performance is sufficient for slope soil ecological restoration, and there is an optimal material ratio for the addition of materials to ecological mini-aggregations. The above research revealed the mechanism controlling polymer composite materials in the development of ecological mini-aggregations; these materials can be included to create ecological mini-aggregations that exhibit strong erosion resistance stability and ecological performance. These research results can provide new technical means for the efficient ecological restoration of slopes.

Keywords: polymer adhesive material; ecological mini-aggregation; ecological restoration; ecological mini-bag; ecological mini-cluster

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1. Introduction

The ecological restoration of slopes is of great significance for engineering safety, ecological safety, and natural disaster prevention. Using ecological aggregations is an efficient technology in ecological slope protection; commonly used ecological aggregations include ecological bags and planting blankets. Ecological bags, also known as planting bags or grass belts, are made of nonwoven fabrics, shading nets, polypropylene, or polyester fibers as raw materials and filled with planting substrates and seeds [1–3]. Planting blankets are usually a three-dimensional composite grass blanket structure composed of plant fiber layers, plant seeds, and planting substrates. Research on ecological slope protection with these conventional ecological aggregations mainly focuses on improving the stability of the ecological aggregations, improving the materials adopted, optimizing the planting substrate, and improving ecological performance. Using ecological aggregations for slope protection has been proven to be an effective ecological restoration method [4–7].

Ecological aggregations can be used to protect highway slopes, riverbank slopes, etc. While ecological aggregation can be used for slope protection work, it can also restore the vegetation of the slope, promoting the restoration of the slope's ecological environment. This is a prominent advantage that distinguishes the technology from traditional geotechnical slope protection, but it also has the disadvantage of being suitable for only gentle slopes. Scholars have been trying to improve the materials used for ecological aggregation, seeking materials that can provide sufficient erosion resistance and stability to the planting substrate while also being environmentally friendly [1,8,9]. For example, Lutfi [10] studied using coir and water hyacinth to develop ecological bags to replace plastic bags and reduce environmental pollution. Shaari [2] utilized waste cotton nonwoven fabric and starch as material for ecological aggregation, resulting in ecological aggregations with sufficient strength and stability. Bhattarai [11] developed three different types of biodegradable erosion control blankets, all of which can reduce soil erosion to varying degrees. The optimization of planting substrates also plays a crucial role in the slope protection performance of ecological aggregation, where the ratio of planting substrate materials can affect the ecological performance of the ecological aggregation [12–14]. Faucette [15] added various fertilizers to planting blankets to enhance the plant growth rate of the blankets and found that using compost and a planting blanket can effectively reduce the soil erosion of the slope and enhance its erosion resistance [16]. Research on planting substrates still needs to be improved in terms of water retention, ecological performance, and erosion resistance. In response to the current problems in ecological aggregation research, it is necessary to seek new feasible materials for the development of ecological mini-aggregations.

This paper takes the ecological restoration of slope soil as an example and uses polymer composite materials to develop ecological mini-aggregations, including ecological mini-bags and ecological mini-clusters, and with polymer composite materials including red-bed soil, polymer adhesive material, and polymer water-retaining material. We conducted erosion resistance stability tests, shear strength tests, and planting tests on the ecological mini-aggregation materials, studied the effect and controlling mechanism of the ecological mini-aggregation materials, and found the optimal ratio of the materials. This study can provide new means for the efficient ecological restoration of slopes.

2. Materials and Methods

This study used polymer composite materials to develop an ecological mini-aggregation that can be applied to ecological restoration of slope soil. In order to study the mechanical stability, erosion resistance, and ecological performance of the ecological mini-aggregation, erosion resistance stability tests, shear strength tests, and plant growth tests were conducted. Analysis of variance on the test results was conducted to reveal the effectiveness of the polymer composite materials.

2.1. Development Process of Ecological Mini-Aggregation

2.1.1. Materials

Polymer composite materials include polymer adhesive material, polymer water-retaining material, and red-bed soil. The development of planting substrates for ecological mini-aggregations uses polymer adhesive material and polymer water-retaining material, and the development of red-bed ecological membranes uses weathered red-bed soil and polymer adhesive material. A description of the development of the utilized red-bed ecological membrane can be found in another paper by our team. The polymer adhesive used was a type of strong water-based nano-adhesive, and the polymer water-retaining material used was a type of water-retaining material with good water absorption and retention performance; both materials will eventually degrade into CO_2 and H_2O [14,17].

The planting soil used for the development of the ecological mini-aggregation was prepared from sandy loam widely distributed in mountainous areas. There are many steep rocky slopes to be ecologically repaired due to mountain excavation, and the need for ecological restoration of slopes is urgent. The particle grading curve of the test soil sample is shown in Figure 1, and its physical properties are shown in Table 1.

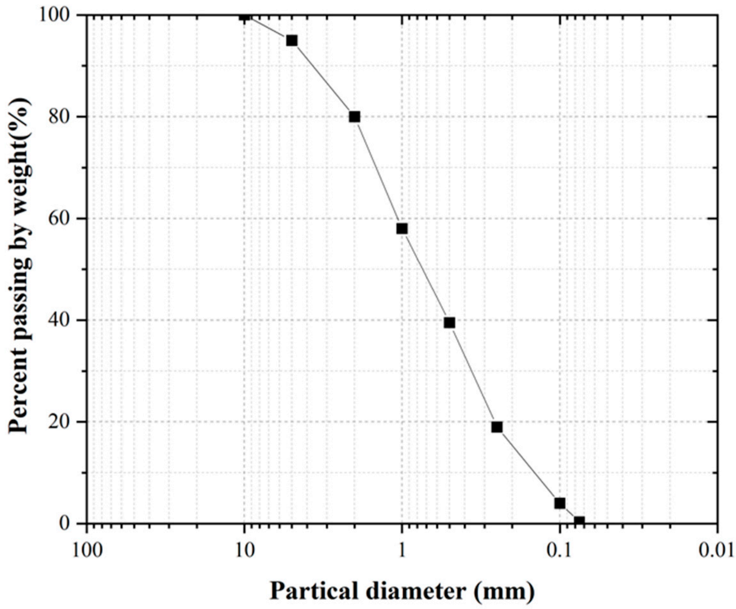


Figure 1. Grading curve of test soil samples.

Table 1. Properties of planting soil.

Saturated Moisture Content (%)	Dry Density (g/cm^3)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index
41.3	1.94	23.5	16.2	15

2.1.2. Basic Principles

Ecological mini-aggregations based on polymer composite materials aim to enhance the ecological self-healing ability of soil to achieve slope ecological restoration. The soil fixation and ecological effects of ecological mini-aggregations are mainly influenced by factors such as the physical properties of the red-bed ecological membrane and the material ratio of the materials. Ecological mini-aggregations can be applied in the ecological restoration of different slopes (especially steep slopes) and different slope conditions. By controlling factors such as the ratio of ecological mini-aggregation materials, the ecological slope protection effect of ecological mini-aggregations based on polymer composite materials can be controlled.

The development of ecological mini-aggregations involves the use of a red-bed ecological membrane. A red-bed ecological membrane is obtained by uniformly mixing red-bed soil and polymer adhesive material in a certain ratio and then using the film-casting method [17]. The ecological membrane has good slope protection performance, effectively improving the erosion resistance of the slope by relying on its material strength and viscosity. It can protect slopes from being directly washed by rainwater (as shown in Figure 2), and at the same time, it forms a stable and integral erosion-resisting slope surface layer by bonding with surface soil particles via its viscosity. It can also be used to develop ecological mini-bags.

The implementation of slope ecological restoration technology for ecological mini-clusters includes laying an ecological membrane on the slope surface and then placing ecological mini-clusters. Ecological membranes are materials with high strength, and covering the slope surface can greatly reduce the erosion of the slope by rainfall. The red-bed ecological membrane is viscous and can adhere to soil particles on the surface of the slope, enhancing the stability and integrity of the shallow soil. An ecological mini-cluster contains polymer adhesive material, and the surface is also viscous and can bond with the red-bed ecological membrane to fix it on the slope (as shown in Figure 2). Therefore, it can be fixed on steep slopes for ecological restoration. With polymer adhesive material, an ecological mini-aggregation forms a stable internal structure, which endows it with the ability to resist erosion and disturbances. After the plant seeds inside the ecological mini-aggregation germinate, they can penetrate the ecological mini-aggregation and grow. The root will eventually penetrate the red-bed ecological membrane and grow into the slope soil, achieving a soil fixation effect through the plant root system and, thus, ecological slope protection.

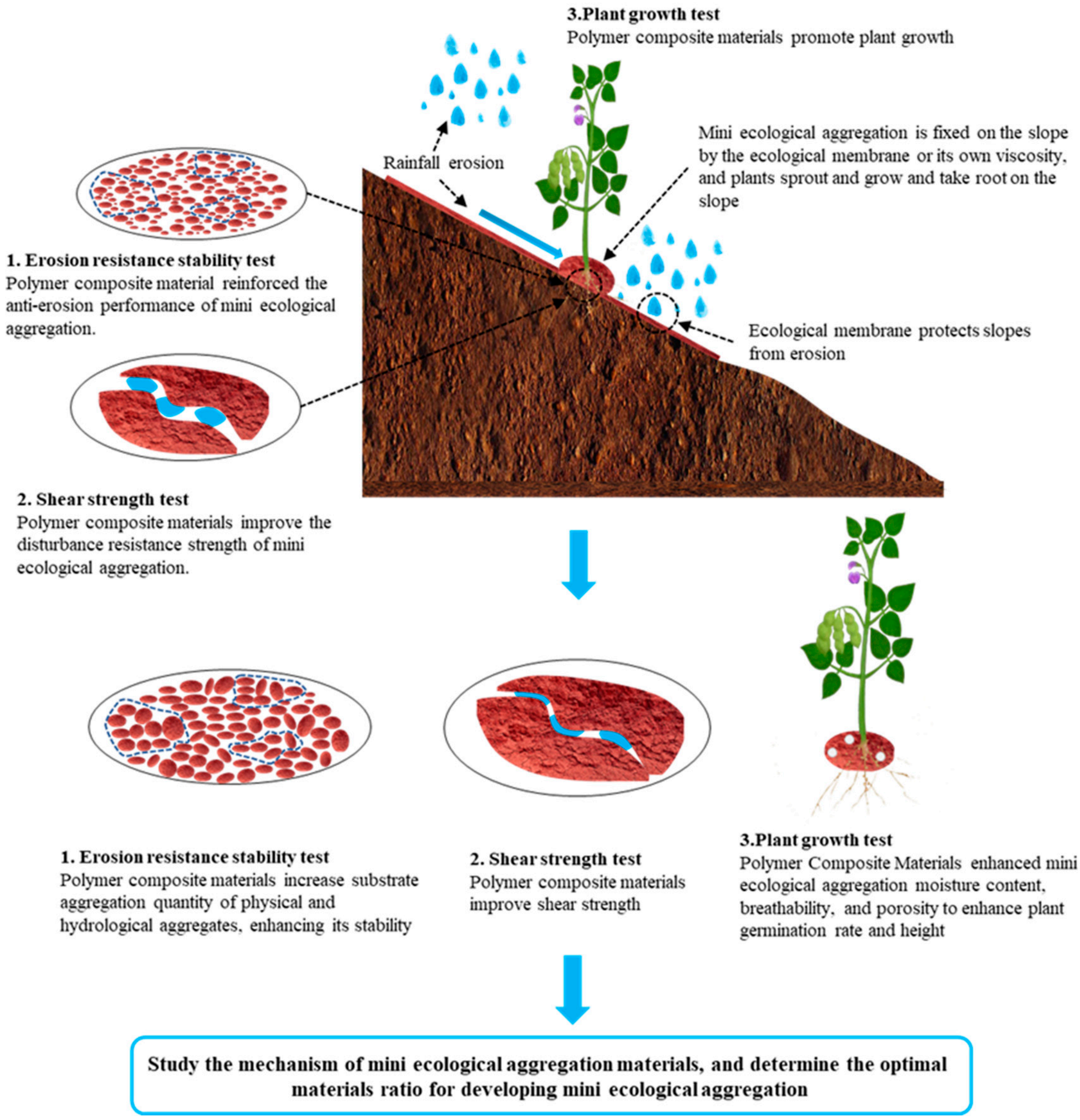


Figure 2. Content and principles of ecological mini-aggregation development based on polymer composite materials.

An ecological mini-bag is fixed on the slope by the adhesive force of the bag itself. Such a bag is made of red-bed ecological membranes with certain strength and viscosity, so it can be fixed on steep slopes for ecological restoration purposes. The planting substrate inside the bag includes planting soil, polymer adhesive material, and polymer water-retaining material. The planting substrate protected by the bag creates a good environment for plant growth. After the plant fully grows and develops, the reinforcement effect of shallow roots, the anchoring effect of deep roots, and the hydrological effect of plant stems and leaves are the core components of slope ecological protection. Compared to an ecological mini-cluster substrate, an ecological mini-bag substrate is protected by the bag, the bag is of strong stickiness and strength, and it is suitable for the ecological restoration of slopes with stronger erosion conditions and higher steepness.

2.1.3. Development Process

(1) Development of an ecological mini-cluster

An ecological mini-cluster is made from planting soil, plant seeds, polymer water-retaining material, and polymer adhesive material. A certain ratio of planting soil, polymer water-retaining material, and polymer adhesive material is evenly mixed with water. After adding plant seeds, the mix is kneaded into clusters to obtain an ecological mini-cluster. To ensure that plant seeds are included in the ecological cluster, as shown in Figure 3, ecological mini-clusters have a diameter of 4–6 cm.

Figure 3. Ecological mini-clusters based on polymer composite materials.

(2) Development of an ecological mini-bag

The development of an ecological mini-bag utilizes the tensile strength and viscosity of an ecological membrane. The high strength of the ecological membrane allows it to be made into a structurally stable bag, while its viscosity eliminates the need for additional adhesive material. By using an ecological membrane, an ecological mini-bag with erosion resistance can be developed. The specific development process of an ecological mini-bag is as follows. Cut the ecological membrane into a portion of approximately 10 cm × 11 cm using scissors or sharp tools, as shown in Figure 4. Fold it in half. Use a pointed cone to pierce and punch the folded red-bed ecological membrane. Wet the edge of the ecological membrane with water, and use the viscosity of the ecological membrane itself to press together the folded edges of the red-bed ecological membrane so that it forms a bag. Once the bag has been made, prepare the plantlet substrate. Mix the planting soil and polymer composite materials evenly in a certain ratio for later use. Fill the ecological mini-bag with prepared plant substrate and 3–5 plant seeds to ensure uniform distribution of plant seeds within the bag.

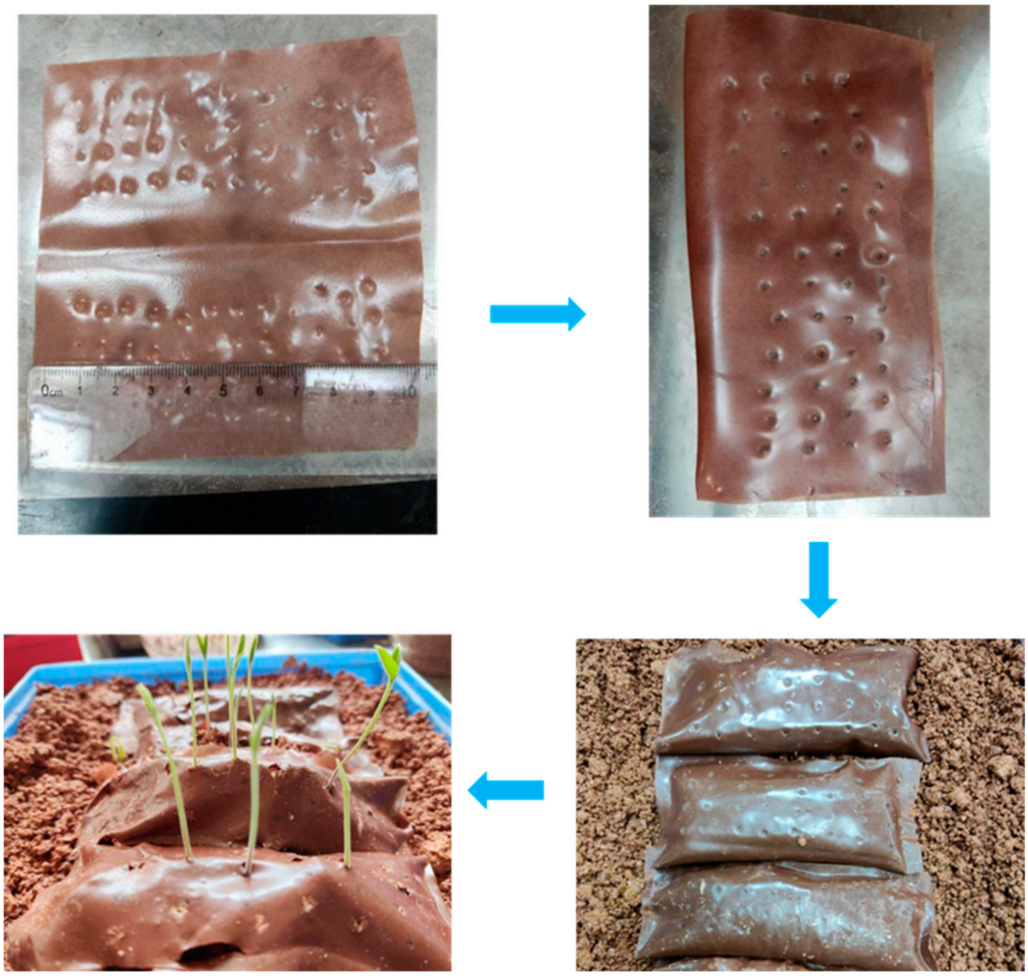


Figure 4. Development of an ecological mini-bag.

To study the stability and ecological performance of the ecological mini-aggregations, erosion resistance stability tests, shear strength tests, and planting tests were conducted on ecological mini-aggregation substrates made with nine different material ratios, as shown in Table 2, and a control group substrate without polymer composite materials. The mechanical stability and ecological performance of the ecological mini-aggregation substrates under different polymer composite material ratios were studied. We conducted variance analysis of the test results, to study the effectiveness and mechanism of developing an ecological mini-aggregation based on polymer composite materials.

Table 2. Substrate ratios of the ecological mini-aggregations.

Test Group	Polymer Water-Retaining Material (%)	Polymer Adhesive Material (%)
CK (0)	0	0
1	0.06	0.03
2	0.12	0.03
3	0.18	0.03
4	0.06	0.06
5	0.12	0.06
6	0.18	0.06
7	0.06	0.09
8	0.12	0.09
9	0.18	0.09

Note: The dosages in Table 2 are expressed as mass ratios.

2.2. Ecological Mini-Aggregation Stability Test

2.2.1. Erosion Resistance Stability Test of Ecological Mini-Aggregation Substrate

A soil aggregate is the size of the basic component unit of soil structure, which has an important impact on the formation and maintenance of the soil structure and can reflect soil fertility, water retention, and porosity to a certain extent. The characteristics of water-stable aggregates are closely related to the structural stability of the soil. The average weight diameter (MWD) and geometric average diameter (GMD) of soil aggregates are the most commonly used indicators to evaluate the resulting stability. The larger the MWD and GMD values, the higher the degree of aggregation, the better the structure, and the stronger the stability of the ecological mini-aggregation substrate [18].

Dry sieving and wet sieving methods were used to determine the structural stability and water stability of the ecological mini-aggregation substrates. The dry sieving method can effectively analyze the mechanical stability of ecological mini-aggregation substrates and serve as an important indicator for evaluating their sensitivity to disturbance. This study focused on ecological aggregation substrates made with 10 different material ratios, as shown in Table 2. After the substrates were cured under outdoor natural conditions for 48 h, dry and wet sieving methods were used to study the erosion resistance stability of the ecological mini-aggregation substrates [19]. The standard sieve groups used in the test had pore sizes of 5 mm, 2 mm, 0.5 mm, 0.25 mm, and >0.25 mm. During the wet sieving test, the aggregates were completely submerged in 3–4 cm of water and sieved for 30 min at a frequency of 20 times/min. Dry sieving was performed for 10 min on a sieve shaker.

The formula for calculating the M_1 content of non-water-stable aggregates within a certain particle size range is:

$$M_1 = \frac{m_1'}{m_1} \times 1000 \quad (1)$$

In the formula, m_1' is the mass of non-water-stable aggregates within a certain particle size range, g; m_1 is the mass of the dried test soil sample, g.

The formula for the M_2 content of water-stable aggregates within a certain particle size range is:

$$M_2 = \frac{m_2'}{m_2} \times 1000 \quad (2)$$

In the formula, m_2' is the mass of water-stable aggregates within a certain particle size range, g; m_2 is the mass of the dried test soil sample, g.

The water stability of aggregates in an ecological mini-aggregation substrate is an important indicator of erosion resistance, especially the number of water-stable aggregates with particle sizes greater than 0.25 mm. When the proportion of water-stable aggregates with particle sizes greater than 0.25 mm exceeds 70%, the ecological mini-aggregation substrate has good water stability and strong erosion resistance.

The calculation formulas for the average weight diameter MWD (mm) and GMD (mm) of soil aggregates are:

$$MWD = \sum_{i=1}^{n} x_i m_i \quad (3)$$

$$GMD = \exp\left(\frac{\sum_{i=1}^{n} m_i \ln x_i}{\sum_{i=1}^{n} m_i}\right) \quad (4)$$

Above, x_i is the average particle size of aggregates within a specific particle size range, mm, and m_i is the percentage of the mass of aggregates within a specific particle size range relevant to the dry weight of the tested soil sample, %.

2.2.2. Ecological Mini-Aggregation Substrate Shear Strength Test

The test subjects were ecological mini-aggregation substrates made with 10 different material ratios, as shown in Table 2, which were cured under outdoor natural conditions for 48 h. According to *Geotechnical Engineering Test Method and Criterion* (GB/T50123-1999) [20] and referring to actual engineering conditions, unconsolidated undrained shear testing was conducted. The ZJ quadruple strain-controlled direct shear apparatus was used, with vertical loads of 50 kPa, 100 kPa, 200 kPa, and 400 kPa and a strain rate of 0.8 mm/min. Three tests were conducted per group, and the average result was taken as the test result. The shear strengths of specimens under different vertical pressures were determined. Afterward, the shear strength–vertical pressure curve of each group of samples was drawn, and the cohesion and internal friction angle properties of the samples were obtained based on the curve intercepts and slopes. The substrate shear strength test is shown in Figure 5.

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

Figure 5. Substrate shear strength test: (**a**) Preparation of soil samples; (**b**) samples damaged from the shear tests.

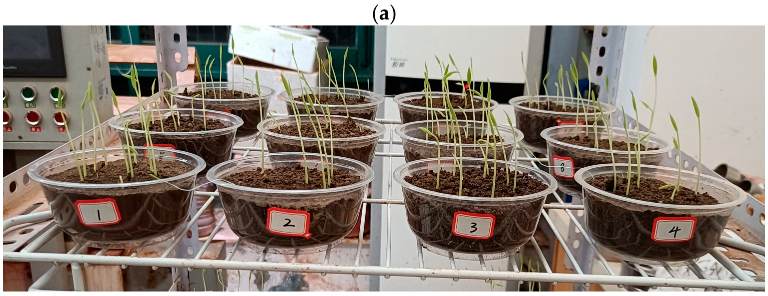
2.3. Ecological Mini-Aggregation Substrate Planting Test

To study the ecological performance of the ecological mini-aggregations and determine the optimal material ratio for the substrate, a substrate planting test of ecological mini-aggregation substrate was conducted. The substrate ratio for the test is shown in Table 2. The test was divided into a control group and nine test groups, totaling ten groups. The plant used in this testing was pigeonpea, which is a commonly used plant in ecological slope protection. Each test group included 400 g of planting soil, which was placed in a planting vessel. Materials were added to each group of soil samples in their designed material ratios. After uniform mixing, 10 pigeon pea seeds were sown in each group. Each sample was supplied with 50 mL of water during each watering time. Water was applied every other day for the first three days and then every three days. A dry situation was simulated, and the number of plant germinations was recorded. The height of plant growth was recorded every two days, and the test time was 20 days. Three parallel tests were performed for each group of samples, and the average of the results was taken. The calculation formula for the plant germination rate is as follows.

$$\chi = \frac{a}{a_0} \times 100\% \quad (5)$$

In the equation, χ is the plant germination rate of this group, %; a is the number of sprouted plants; and a_0 is the number of seeds sown in this group. The substrate planting test is shown in Figure 6.

(**a**)



(**b**)

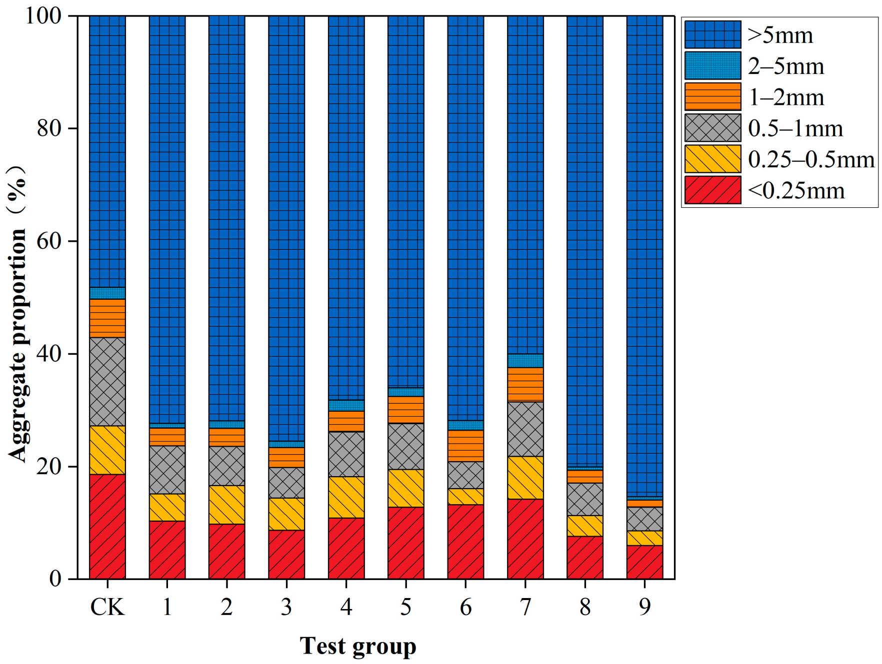
Figure 6. Substrate planting test: (**a**) on the 7th day; (**b**) on the 15th day.

3. Results

3.1. Stability of Ecological Mini-Aggregation

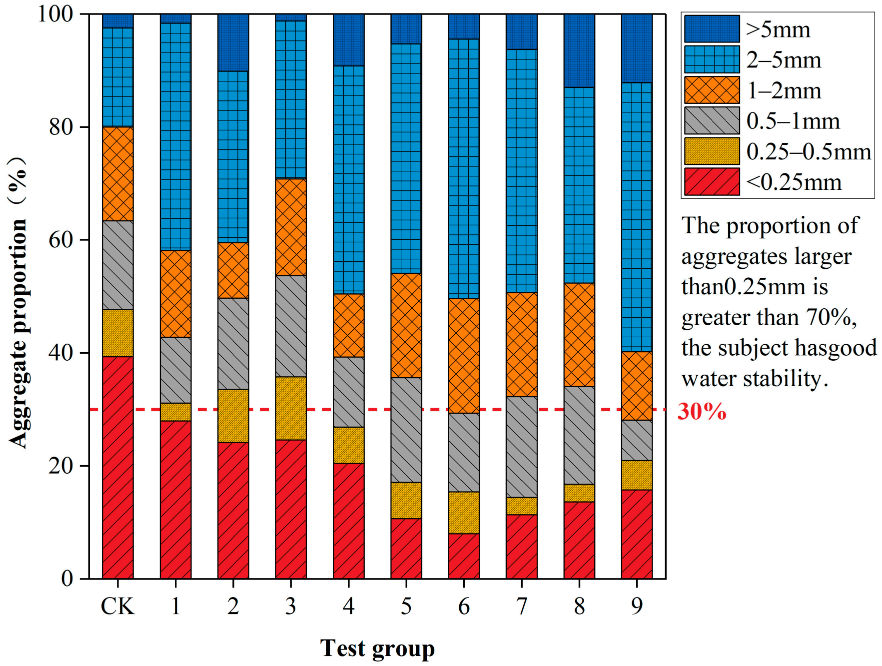
3.1.1. Erosion Resistance Stability of the Ecological Mini-Aggregations

Test results from the dry sieving method can reflect the mechanical stability of an ecological mini-aggregation substrate, while wet sieving method test results can reflect the water stability of an ecological mini-aggregation substrate; the better the water stability, the stronger the resistance to rainwater erosion. When the proportion of water-stable aggregates with a particle size greater than 0.25 mm is greater than 70%, the ecological mini-aggregation substrate has good water stability and strong erosion resistance. In Table 3 and Figure 7, the stability test results of the ecological mini-aggregation substrates are presented.



(**a**)

Figure 7. *Cont.*



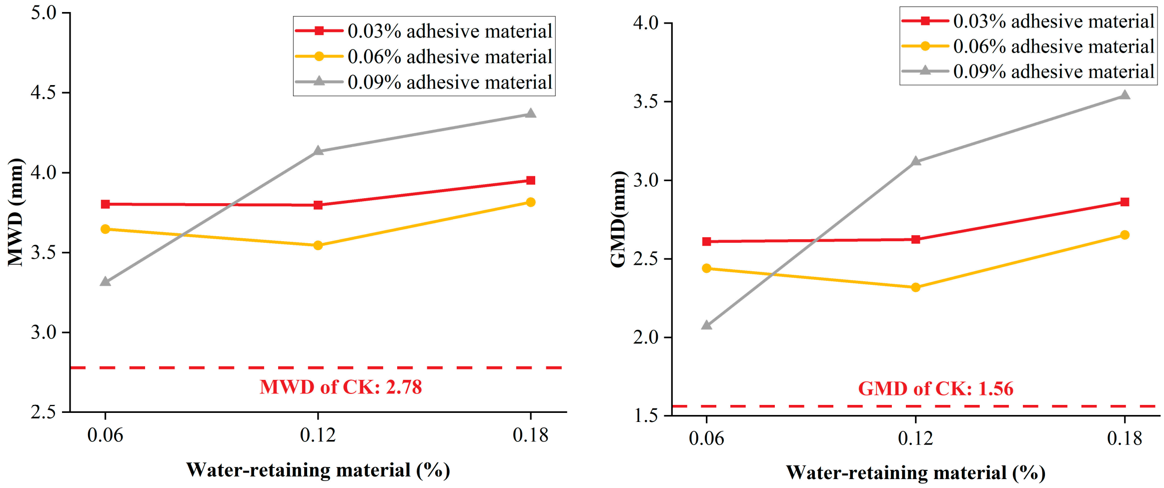
(**b**)

Figure 7. Results of aggregate stability tests of ecological mini-aggregation substrates: (**a**) Dry sieving test results; (**b**) Wet sieving test results.

Table 3. Stability test results of ecological mini-aggregation substrate.

Test Group	Method	<0.25 mm (%)	0.25–0.5 mm (%)	0.5–1 mm (%)	1–2 mm (%)	2–5 mm (%)	>5 mm (%)	MWD (mm)	GMD (mm)
CK	Dry sieving	18.6	8.7	15.7	6.8	2.1	48.2	2.78	1.56
	Wet sieving	39.3	8.3	15.7	16.6	17.5	2.5	1.23	0.71
1	Dry sieving	10.3	4.9	8.5	3.2	0.8	72.4	3.80	2.61
	Wet sieving	27.9	3.2	11.6	15.4	40.3	1.6	1.89	1.15
2	Dry sieving	9.8	6.9	6.9	3.2	1.3	72.0	3.80	2.62
	Wet sieving	24.1	9.4	16.2	9.9	30.3	10.2	1.93	1.12
3	Dry sieving	8.7	5.8	5.4	3.5	1.1	75.5	3.95	2.86
	Wet sieving	24.6	11.1	17.9	17.1	28.0	1.2	1.54	0.94
4	Dry sieving	10.8	7.3	7.9	3.7	2.0	68.1	3.65	2.44
	Wet sieving	20.4	6.5	12.4	11.1	40.4	9.2	2.21	1.37
5	Dry sieving	12.8	6.7	8.1	4.8	1.6	66.0	3.54	2.32
	Wet sieving	10.6	6.4	18.5	18.5	40.6	5.3	2.15	1.50
6	Dry sieving	13.2	2.9	4.8	5.6	1.7	71.8	3.82	2.65
	Wet sieving	8.0	7.4	14.0	20.3	45.9	4.5	2.29	1.66
7	Dry sieving	14.2	7.6	9.6	6.1	2.4	60.0	3.31	2.07
	Wet sieving	11.3	3.1	17.8	18.4	43.1	6.3	2.27	1.61
8	Dry sieving	7.6	3.7	5.8	2.3	0.6	80.0	4.13	3.12
	Wet sieving	13.6	3.1	17.3	18.4	34.6	13.0	2.31	1.57
9	Dry sieving	6.0	2.6	4.2	1.3	0.6	85.4	4.37	3.54
	Wet sieving	15.7	5.2	7.2	12.1	47.7	12.2	2.57	1.74

The MWD and GMD of the aggregates in an ecological mini-aggregation substrate can reflect the quality of the ecological mini-aggregation structure. The larger the value, the stronger the stability of the ecological mini-aggregation structure. The MWD and GMD of each test group for the aggregate stability tests of the ecological mini-aggregation substrates are shown in Figure 8. It can be seen that in both types of tests, the MWD and GMD results of the designed ecological mini-aggregation substrates are significantly improved over those of the control group. After adding certain amounts of material, the structure of the ecological mini-aggregation substrate is clearly more stable, and its resistance to disturbance is also stronger.



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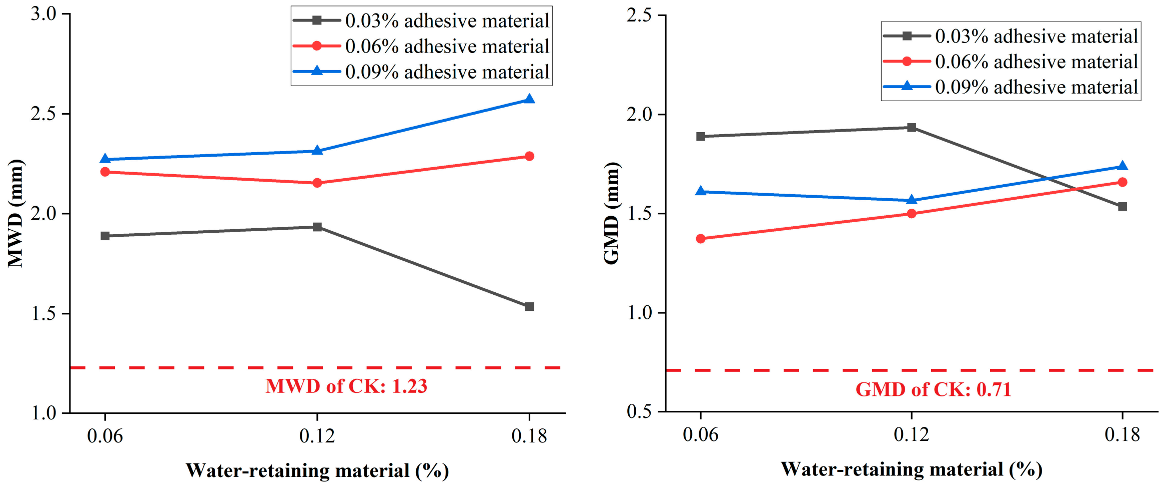
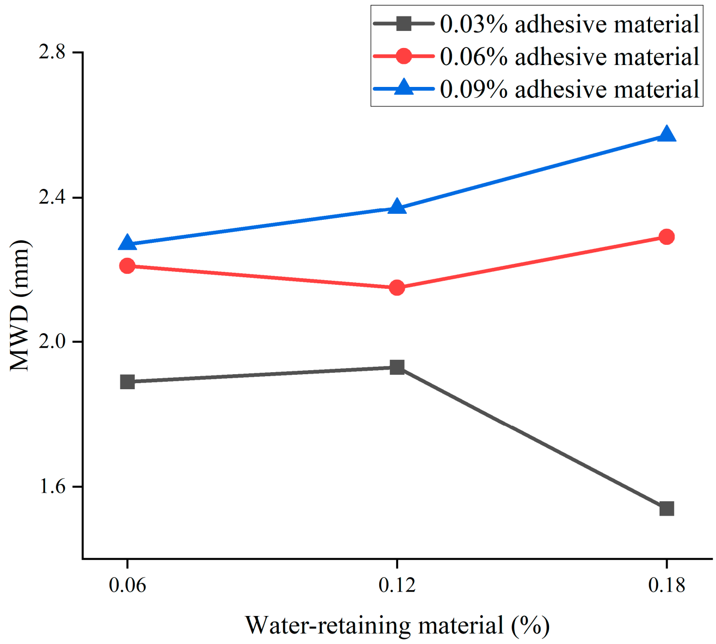


(**b**)

Figure 8. MWD and GMD of ecological mini-aggregation substrate: (**a**) Dry sieving test results; (**b**) Wet sieving test results.

The wet sieving test can reflect the aggregate structure and distribution of a mini-aggregation substrate, and the stability of the aggregates is the ability of the soil aggregates to maintain structural stability. A two-way analysis of variance on the MWD and GMD of aggregates in the wet sieving test results was conducted, with the addition of adhesive and water-retaining material as independent variables and the MWD and GMD of the aggregates as dependent variables. In the analysis of aggregate MWD, for variable adhesive material, F-test results showed that the significance p-value was $0.046 < 0.05$, showing that adhesive material has a significant impact and the main effect on MWD. For variable water-retaining material, F-test results showed that the significance p-value was $0.998 > 0.05$, showing that water-retaining material has no significant impact on MWD. In Figure 9, the mean values comparison of the variance analysis for the results of the wet sieving test is presented; combining with Figure 8b and observing the results of experimental groups 1–9, it can be seen that overall, when the amount of polymer water-retaining material is fixed, the more adhesive material added, the larger the MWD and GMD of the mini-aggregation substrate, and vice versa. When the amount of polymer adhesive material is fixed, the more water-retaining material added, the smaller the MWD and GMD of the mini-aggregation substrate. This indicates that adhesive material plays a main role in enhancing the stability and erosion resistance of the ecological mini-aggregation, while water-retaining material has a certain counterproductive effect.



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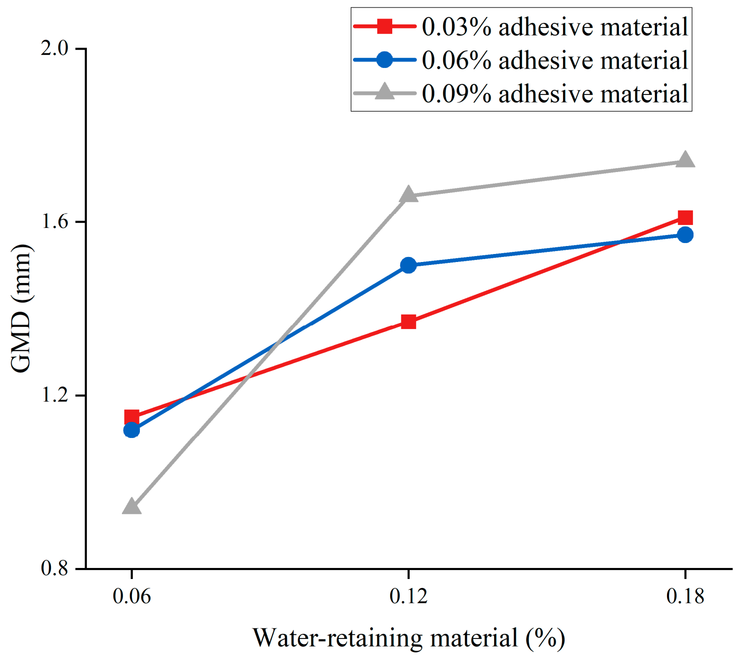


(**b**)

Figure 9. MWD and GMD of ecological mini-aggregation substrate: (**a**) Mean value of MWD; (**b**) Mean value of GMD.

Soil aggregate stability is the ability of aggregates to resist external disturbance and maintain structural stability and is the key factor in determining the quality of the aggregate structure. Soil aggregates are considered the "storage reservoir" of soil nutrients, and an increase in their quantity indicates enhancement of soil's ability to store nutrients, retain water, and enhance permeability. Therefore, aggregates are often one of the indicators of good soil ecological performance. Through the above analysis, it can be seen that compared to the control group CK without added material, the number of large aggregates and water-stable aggregates in ecological mini-aggregation substrates with the addition of polymer composite materials significantly increased. It can be inferred that the addition of polymer composite materials not only enhances the structural stability and erosion resistance of ecological mini-aggregations but also enhances their soil fertility and ecological performance.

3.1.2. Shear Strength of Ecological Mini-Aggregations

The shear strength parameter of an ecological mini-aggregation substrate also reflects its structural stability. The larger the shear strength parameters are, the more stable its structure. As shown in Figure 10, the shear strength test results of the ecological mini-aggregation substrates show that the cohesion and internal friction angle of the tested groups with added polymer composite materials are greater than those of the control group CK without material, indicating that the addition of polymer composite materials effectively enhances the mechanical stability of the ecological mini-aggregation. Observing test Groups 1–9, overall, when the amount of polymer water-retaining material is fixed, the more adhesive material added, the greater the cohesion and internal friction angle area, and vice versa; when the amount of polymer adhesive material is fixed, the more water-retaining material added, the smaller the cohesion and internal friction angle of the ecological mini-aggregation substrate, and vice versa. This indicates that the adhesive material plays the main role in enhancing the mechanical stability of ecological mini-aggregations, while the water-retaining material has a certain counterproductive effect. This is very similar to the conclusions of the aggregate stability test for the ecological mini-aggregation substrates.

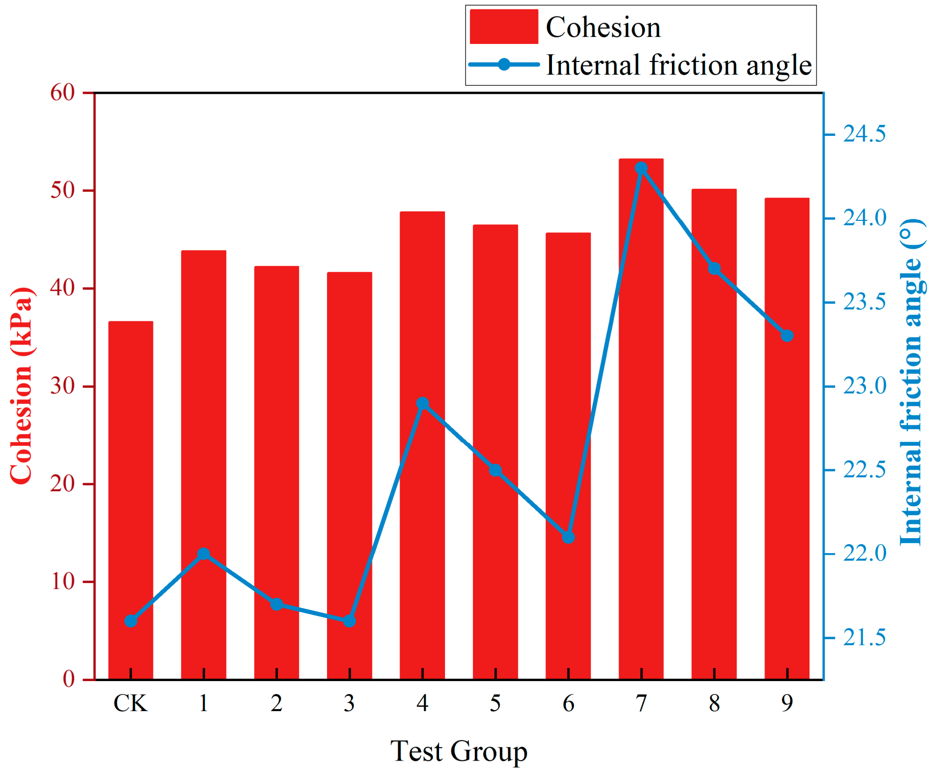


Figure 10. Shear strength test results of ecological mini-aggregation substrates.

3.2. Ecological Performance of Ecological Mini-Aggregations

The ecological performance of ecological mini-aggregations is crucial for slope ecological restoration. The plant germination rate and plant height in plant growth tests can reflect the ecological performance of ecological mini-aggregation substrates made of different material ratios. In Figure 11, the planting test results of the ecological mini-aggregation substrates are shown. From the figure, it can clearly be seen that the germination rate and plant height of the test groups with the addition of polymer water-retaining material and polymer adhesive material are higher than those of the control group CK, which indicates that the added materials effectively promote plant growth and development and that these substrates create a good growth environment for plant growth and development. By comparing and analyzing plant growth, it can be seen from the graph that Group 6 has the highest germination rate and plant height, with a germination rate of 80% and a plant height of 7.6 cm.

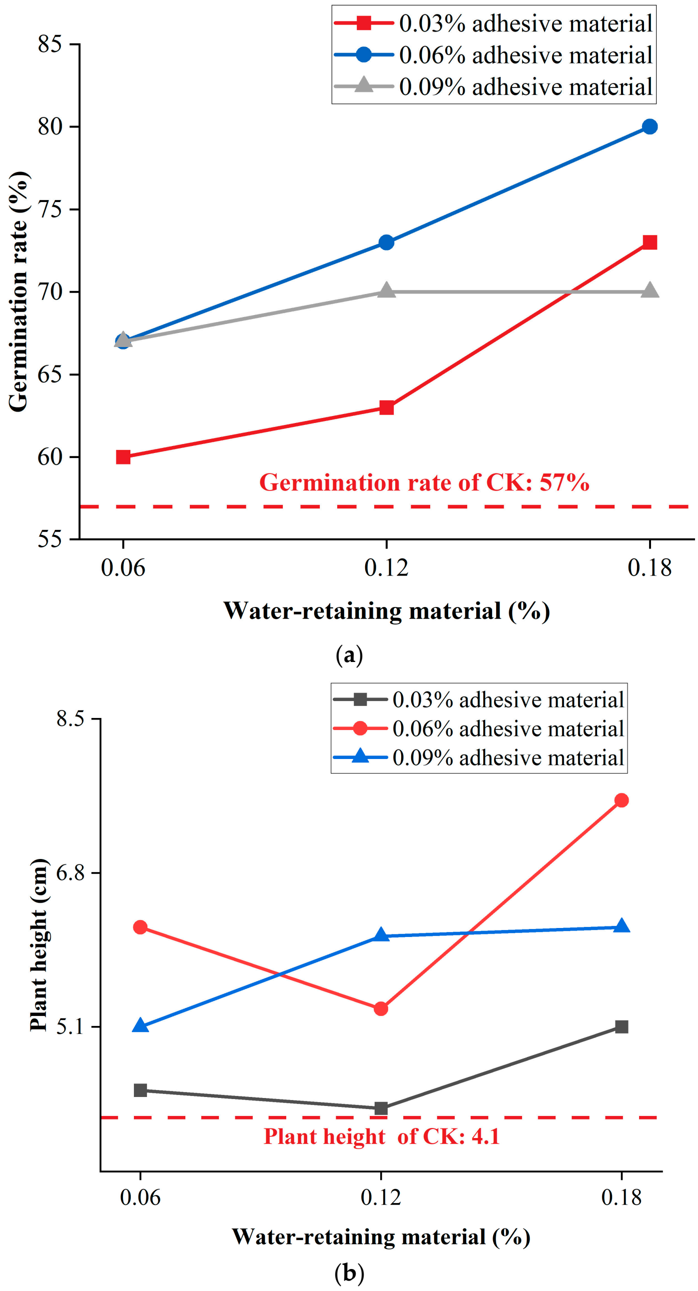
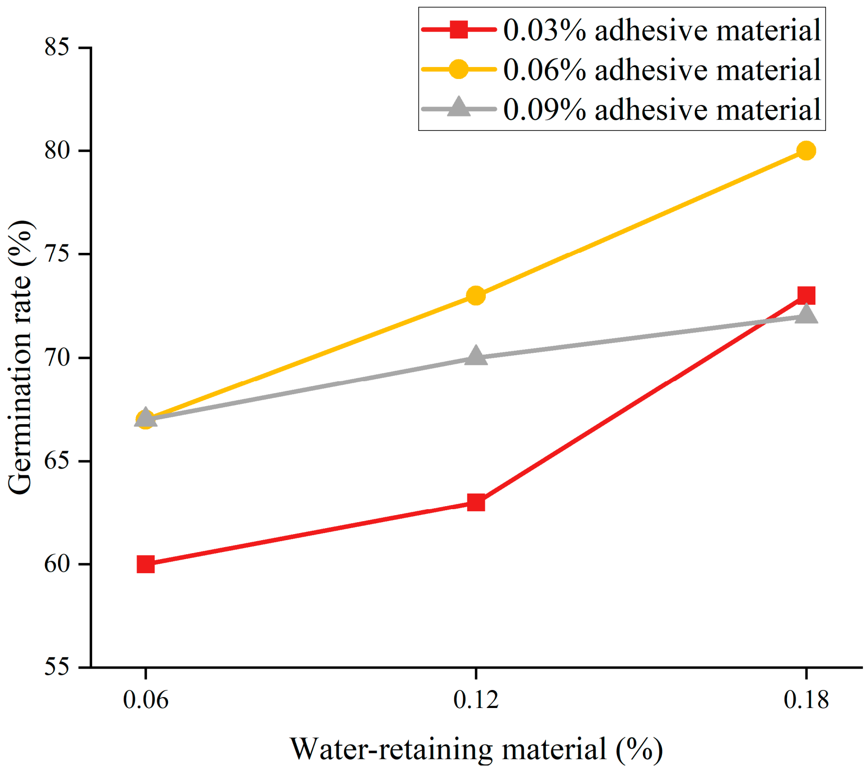


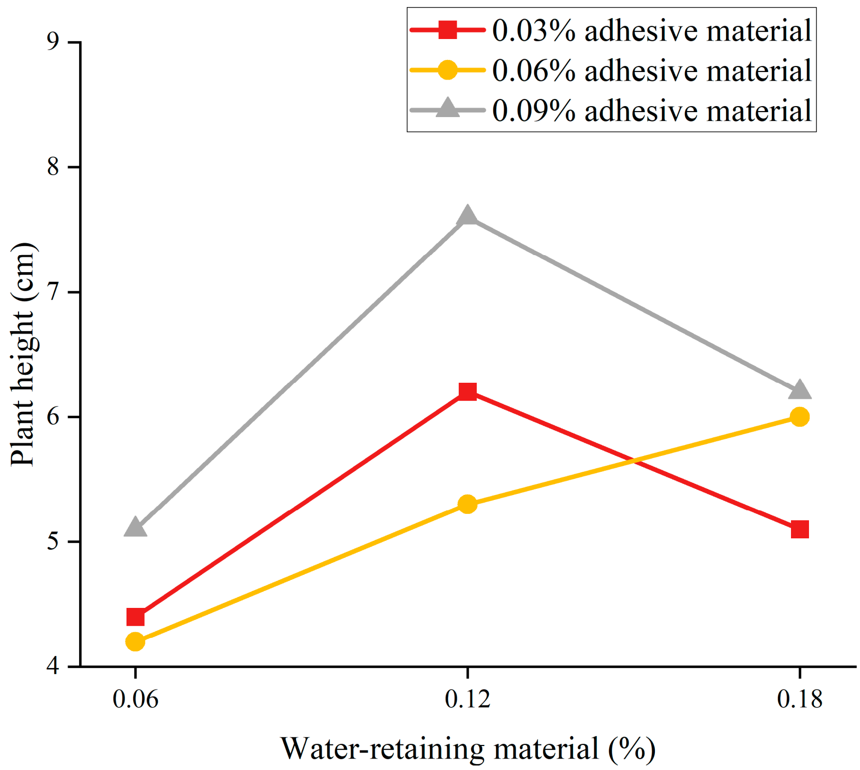
Figure 11. Planting test results of ecological mini-aggregation substrates: (**a**) plant germination rate; (**b**) plant height.

A two-way analysis of variance on the MWD and GMD of aggregates in the plant growth test results was conducted, with the addition of adhesive and water-retaining material as independent variables, and plant germination rate and plant height as dependent variables. In analysis of plant germination rate, for variable addition of water-retaining material, F-test results showed that the significance *p*-value was 0.020 < 0.05, showing that water-retaining material has a significant impact on the germination rate. For variable addition of adhesive material, F-test results showed that the significance *p*-value was 0.048 < 0.05, showing that adhesive material has a significant impact on the germination rate as well. It can be inferred that both materials have a significant impact on plant germination, but water-retaining material has a greater impact. In the analysis of plant height, for variable water-retaining material, F-test results showed that the significance *p*-value was 0.133 > 0.05, which indicates no significant impact on plant height. For variable adhesive material, the F-test showed that the significance *p*-value was 0.047 < 0.05, which indicates a significant impact on plant height. In Figure 12, the mean value comparison of the variance analysis for plant growth test results is presented; combining with Figure 11 and comparing groups 1–9, it can be found that with a fixed amount of adhesive material added, as the amount of polymer water-retaining material increased, the water content of the substrate increased, and the plant germination rate increased. When the amount of water-retaining material was constant, as the amount of adhesive material increased, the plant germination rate mainly showed a trend of first increasing and then decreasing. It can be inferred that adding too much polymer adhesive material may harm plant germination. In terms of plant height, with an increase in water-retaining material, the overall plant height showed a decreasing trend, and excessive water-retaining material was detrimental to plant growth. In sum, an optimal material ratio scheme should be selected to ensure the overall stability of the ecological mini-aggregations, while ensuring that the porosity and water retention of the substrate are suitable for plant growth and that the ecological mini-aggregation can improve the ecological self-repair ability of a slope.



(**a**)

Figure 12. *Cont.*



(**b**)

Figure 12. Mean value comparison of variance analysis for plant growth test results: (**a**) plant germination rate; (**b**) plant height.

From the above tests, it can be concluded that ecological mini-aggregations with polymer composite materials exhibit strong water stability, mechanical stability, good structural stability and erosion resistance, and good ecological performance. Polymer composite materials create good conditions for plant growth.

The adhesion of polymer adhesive material is the reason for the enhanced stability of the ecological mini-aggregation substrate structure. Adhesive material significantly enhances the mechanical properties of an ecological mini-aggregation, while polymer water-retaining material has a certain counterproductive effect on improving their mechanical properties. However, the presence of polymer water-retaining material is the main factor in improving the ecological performance of an ecological mini-aggregation. A new physical and chemical connection (ionic bond, hydrogen bond, or van der Waals force) is generated between the adhesive material molecules and the soil particles [17]. Through these chemical bonds, the long-chain macromolecules of the polymer wrap the surface of the substrate particles to form a stable aggregate composed of a certain number of soil particles, enhancing soil aggregates, and promote plant growth, and these interconnected long-chain macromolecules form an elastic and viscous covering layer on the surface of the substrate aggregate, effectively enhancing the structural stability of the ecological mini-aggregation substrate. Compared to directly applying composite materials to slope soil, this study used a red-bed ecological membrane for slope protection, further reducing soil erosion on slopes [7,17]. Polymer water-retaining material effectively enhances the plant growth environment of the substrate. Water-retaining material can absorb water and expand when moisture is sufficient and release water and contract when the surrounding soil is drier, providing good water conditions for plant growth that are beneficial for the germination of plant seeds, but excessive water may harm the later stages of plant growth. The repeated expansion and contraction of water-retaining material during the process of absorbing and releasing water can lead to an increase in soil voids. During the water absorption process, water-retaining material expands in volume, compresses the surrounding soil, and forces the soil to undergo microdeformation, thereby playing a role in fluffy soil and increasing soil porosity and permeability. Adhesive material establishes new physical and chemical connections between particles, thereby enhancing the overall strength and stability of the ecological mini-aggregation substrate. However, excessive interparticle connectivity may cause soil compaction in the substrate, reducing the porosity and permeability of the ecological mini-aggregation substrate. It can be concluded that adhesive material and water-retaining material interact with each other in the ecological mini-aggregation substrate. An increase in the porosity and permeability of the ecological mini-aggregation substrate means a decrease in structural stability, but the growth and development of plants require the soil to have a certain pore structure and permeability.

Therefore, when developing ecological mini-aggregations based on polymer composite materials, it is necessary to consider the actual situation, the climate of the slope, rainfall erosion, and other conditions; select a suitable ratio; and develop an ecological mini-aggregation that meets sufficient stability requirements while also having good plant growth conditions. As shown in Figure 13, in this study, Group 6 corresponds to the optimal ratio, with strong mechanical stability and good water stability. Overall, Group 6 exhibits strong erosion resistance stability and the best ecological performance.

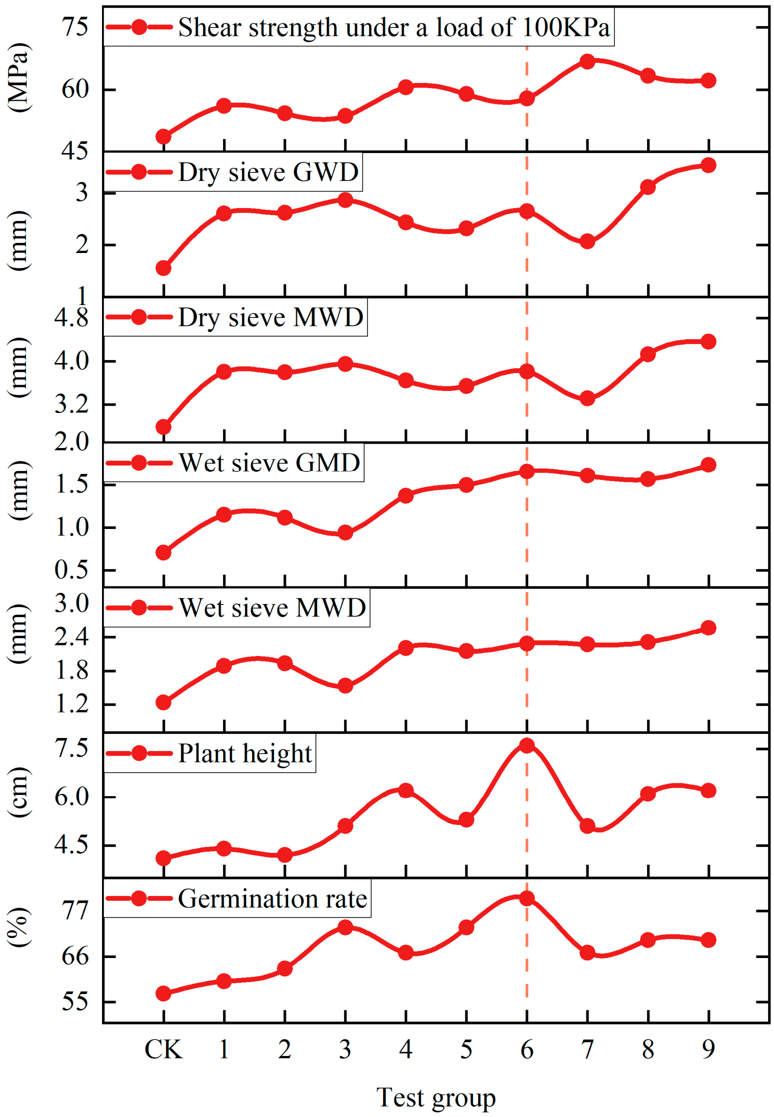


Figure 13. Summary of ecological mini-aggregation substrate mechanics and ecological test results.

4. Conclusions

1. Ecological mini-aggregations developed using eco-friendly polymer composite materials can effectively achieve the ecological restoration of slope soil. Ecological mini-aggregations have excellent erosion resistance, great mechanical properties, strong structural stability, and good ecological performance. The development mechanism for ecological mini-aggregation materials was revealed through tests.
2. Polymer composite materials can provide excellent erosion resistance and stability to ecological mini-aggregation while also possessing good ecological performance, which can improve the plant growth conditions in a planting substrate and promote plant growth. Polymer adhesive material can enhance the structural stability and erosion resistance of ecological mini-aggregations, but can also reduce the porosity of the substrate, leading to excessive hardening that is not conducive to plant growth. Polymer water-retaining material can improve plant growth conditions but is not conducive to the structural stability of ecological mini-aggregations. There is an optimal material ratio for the addition of polymer composites. In this study, the optimal material ratio for the development of ecological mini-aggregations was determined to be 0.18% polymer water-retaining material and 0.06% polymer adhesive material.
3. This paper studied the mechanical and ecological properties of ecological mini-aggregations with different polymer composite material ratios, providing valuable theoretical and data references for the application and promotion of ecological mini-aggregations in ecological slope protection and soil ecological restoration.

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