Application of New Polymer Composite Materials in Rock Slope Ecological

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Abstract. Geological disasters frequently occur in red bed areas. Ecological protection can improve the stability of the rock slope and beautify the environment and reduce soil erosion. The natural red bed weathered soil often has a loose structure and poor water retention, resulting in poor vegetation growth. It is necessary to develop a new material to improve the slope soil and promote plant growth. Therefore, this study employed the self-developed ADNB soil stabilizer to improve the silty clay in the red bed areas. The effects of ADNB on soil physical properties (density, moisture content, and temperature) and ecological properties (germination rate, plant height, and coverage) were analyzed to examine the effects of ADNB on soil improvement. The results show that, compared with natural soil, the density of ADNB treated soil decreased by 9.1%–14.3%, water content increased by 9.3%–19.7%, water holding capacity increased by 20.0%–33.3%, temperature increased by 0.7%–1.8%, germination rates of herbs and shrubs increased by 3.0%–36.0%, and 1.0%–17.0%, respectively, plant height increased by 8.7%–98.6%, and coverage increased by 25%–45%. This study provides theoretical and data support for slope ecological protection and soil erosion control in red bed areas.

1. Introduction

Ecological restoration and soil erosion control in red bed areas are the key contents of China’s ecological civilization construction. However, due to the wide distribution, complex composition, and easy softening of red bed weathered soil [1–3], soil and water conservation of rock slopes in red bed areas face significant technical problems. Currently, the traditional measure in engineering is physical protection [4–6], i.e., using geotextile, wire mesh, and other materials to fix the surface soil and improve the anti-erosion ability of the slope. Although this method can effectively reduce slope erosion, there are problems, such as high costs and environmental pollution, which are not conducive to the ecological restoration of rock slopes. Recently, with the development of material science, research on soil improvement using soil stabilizers has been widely reported [7–9]. How to reasonably select the type and amount of soil stabilizer, maintain the ecological performance of soil while improving stability, and realize the soil and water conservation and rapid ecological restoration of rock slope is one of the research hotspots in slope ecological protection.

As a new functional material, soil curing agent has attracted significant attention worldwide, and it is often used to improve soil structure and reduce soil erosion.
Yuan et al. [10] developed a modified cellulose polymer gel carboxymethyl cellulose sand-fixing agent. The polymer can effectively improve the strength and anti-disintegration of sandy soil and increase the particle size of water-stable aggregates; thus, effectively improving the soil and water conservation effect in sandy soil areas. Pu et al. [11] investigated the improvement effect of a biomass-based polymeric soil stabilizer (CXZ) on loess. The results showed that CXZ stabilizer agglomerated small loess into large aggregates by “coating” and “weaving,” which significantly improved the agglomeration force, water stability and erosion resistance and promoted the growth of alfalfa. Yao et al. [12] found that the use of polymer curing agent with planting grass could effectively prevent, weaken, or slow down the softening of soft rock slope, improve the waterproof, hydrophobic, surface structure of the slope to improve the stability of the slope and achieve a better greening effect.

As a water-retaining agent and soil structure modifier, water-absorbing ester materials can significantly improve soil water storage state and soil structure to improve soil total porosity, enhance soil water holding capacity, and promote plant growth. Bagherifard et al. [13] found that water-absorbing ester materials could effectively alleviate drought stress, promote the growth of Capparis spinosa, increase plant height, yield per hectare, water use efficiency, soil moisture, relative water content, and leaf area. Pereira et al. [14] found that hydrogel could improve soil structure, improve soil aggregate stability, increase porosity, and enhance soil water infiltration capacity. Through three years of a follow-up study, Coello et al. [15] found that a new polyacrylamide-free polymer could effectively improve seedling survival rate, rhizome growth, water status, and soil moisture under drought conditions, which were helpful to solve soil degradation and enhance ecosystem diversity.

Soil curing agent strengthens the soil structure and improves the anti-erosion ability of soil by improving the connection force between soil particles. The water retention agent can adsorb a large amount of water through its special high molecular structure. It also has excellent water storage and retention performance. Combining the two can improve soil’s water storage capacity while improving the anti-erosion ability of slope and creating a more favorable growth environment for plants. Currently, there are many reports on the application of these two materials alone in soil [16–18]. However, there are few reports on the study of soil properties using these two materials simultaneously. Although Huang et al. [19] have conducted some investigations on the common use of the two materials; the main concern is improving the soil. There are few studies on the ecological performance of improved soil, which is not conducive to the wide promotion.

In this study, a new polymer material (ADNB) optimized by adhesive ester materials (polyvinyl acetate) and water-absorbing ester materials (sodium polyacrylate) was selected to improve the red bed weathered soil. The influence of ADNB on the basic properties of the soil is investigated by dividing the changes of density, moisture content, and temperature of the soil. The effects of ADNB on plant growth were studied by comparing plant germination rate, plant height, and coverage. This study provides theoretical and data support for ecological protection and soil erosion control of rock slopes in red beds.

2. Climate conditions and rainfall simulation

2.1. Climate conditions

In South China, the climate is complex and changeable due to the alternating influence of the low-latitude tropical weather system and mid-high-latitude weather system, which belongs to the humid climate zone. However, the rainfall is abundant, and the annual rainfall is 1500–2000 mm, but the spatial and temporal distribution is uneven. More than 70% of the rainfall is concentrated in the rainy season, and the problem of soil erosion is severe. However, intense solar radiation, high temperature, soil evaporation, crop transpiration, annual evaporation of 1352–1876 mm, regional, seasonal drought is frequent [19].

2.2. Rainfall simulation

According to the Chinese Meteorological Administration, the rainy season is from April to September in South China, and the dry season is from October to March the following year. The monthly average temperature is 10°C–25°C, the average air humidity is 50%–70%, the monthly average rainfall is 50–
70 mm, and the monthly evaporation is 55–75 mm. The slope ecological protection project generally starts in spring. Therefore, considering Yangjiang City in South China as an example, climate simulation is conducted using a constant temperature and humidity maintenance instrument. According to the recent analysis of meteorological data, the simulated spring environment temperature is 6:00–18:00; temperature is 20°C, humidity is 50%. The temperature is 15°C, and the humidity is 60% from 18:00 to 6:00 the next day.

The average monthly rainfall in spring is 126.1 mm. Therefore, in the indoor experiment, the rainfall is simulated by artificial watering every five days, which is 25.2 mm each time. During the experiment, the moisture content of each group of samples was monitored and recorded regularly using the drying method (See Table 1).

| Time          | Temperature | Air humidity | Rainfall simulation               |
|---------------|-------------|--------------|----------------------------------|
| 6:00-18:00    | 20°C        | 50%          | Manual watering, 5 days/time, 25.2mm |
| 18:00-6:00 next day | 15°C        | 60%          | each time                        |

3. Test materials and methods

3.1. Test materials

The test materials include soil and new polymer materials (ADNB).

Test soil from Chunwan Town, Yangjiang City, Guangdong Province is common silty clay in South China. It has weathering product of siltstone (red bed) of lower Jurassic. Table 2 presents the physical and mechanical parameters of soil samples; after drying, the soil sample, crushing through a 2-mm sieve spare.

| Parameters of the natural state | Density (g/cm³) | Wet density ρ₀ | Dry density ρₐ | Specific gravity Gs | Water content ω₁ (%) | Void ratio e | Degree of saturation Sr (%) |
|---------------------------------|-----------------|----------------|----------------|---------------------|-----------------------|--------------|-----------------------------|
|                                 | 1.96            | 1.52           |                | 2.7                 | 29                    | 0.781        | 94.4                        |

| Indexes of consistency         | Liquid limit ωₗ (%) | Plasticity limit ωₚ (%) | Liquidity index I_l | Plasticity index I_p | Cohesion C | Internal friction angle φ |
|--------------------------------|---------------------|-------------------------|---------------------|---------------------|------------|--------------------------|
|                                 | 34.1                | 21.5                    | 12.7               | 0.6                 | 9.3        | 23.8                     |

The new polymer composite (ADNB) is optimized using adhesive ester materials and water-absorbing ester materials (Figure 1).

The main component of the adhesive ester materials is polyvinyl acetate. The molecular formula is [CH₂CHCOOCH₃]ₙ. Polyvinyl acetate is a milky white liquid with a pH value of 6–7, density of 1.01 g/cm³, solid content of 41%, and viscosity of 8,000–10,000 mPa·s. It is insoluble in water but with excellent dispersibility. Thus, it can be used as an aqueous solution. This series of materials are used in home decorations, such as wood bonding. Under natural conditions, polyvinyl acetate is degraded within 24 months, and the final products are CO₂ and H₂O, which are harmless to the environment [19–21].

The main component of the resin is sodium polyacrylate, and its molecular formula is C₃H₅NaO₂. Under dry conditions, sodium polyacrylate consists of white particles with a particle size of less than 0.02 mm, moisture content of less than 5%, and a bulk density of 0.8–0.85 g/ml. It is a transparent hydrogel after water absorption and has theoretical water absorption of about 250%. Under natural
conditions, the resin is degraded within 36 months, and the final products are CO₂, H₂O, and sodium salt, which are harmless to the environment [19–21].

![Image](image1.png)

**Figure 1** New polymer composite (ADNB), (a) Adhesive ester materials, (b) Water-absorbing ester materials

The proportion of adhesive ester materials and water-absorbing ester materials in ADNB is reasonably adjusted, and the two materials’ high viscosity and high water absorption are employed. This improved soil structure and water retention while improving soil strength and erosion resistance. It can effectively promote plant growth and improve the ecological protection effect of the slope.

### Table 3 Material ratio

| Material type                        | CK | A  | B  | C  |
|-------------------------------------|----|----|----|----|
| Adhesive ester materials (g/m²)     | 0  | 10 | 15 | 20 |
| Water-absorbing ester materials (g/m²) | 0  | 60 | 60 | 60 |

#### 3.2. Test method

**3.2.1. Soil density.** The soil density of each sample group was periodically measured using the ring knife method. According to test methods of soil (GB/T 50123–1999, i.e., a national criterion for geotechnical tests in China, which was set based on ASTM standards), the ring knife was placed on the balance to weigh the ring knife mass (m₁) (diameter: 61.8 × 20 mm). Then, the soil sample was cut after coating a thin layer of Vaseline on the inner wall of the ring knife, and the ring knife with soil mass (m₂) was weighed. Since the volume of the ring knife was known, the density (ρ) of the soil was calculated according to the following formula:

\[
\rho = \frac{m₂ - m₁}{V}
\]

**3.2.2. Soil water content and temperature.** Soil water content was measured using the drying method recommended using test methods of the soil (GB/T 50123–1999). First, the aluminum box was washed, dried, and weighed (M₁). Then, about 50 g of the soil sample to be tested was put into the aluminum box and weighed (M₂). Afterward, the aluminum box was put into the oven, and the weight of the dry soil plus the aluminum box was weighed (M₃) after 24 h of drying. At this time, the free water in soil moisture is completely lost in the form of steam, and the difference between the two weights is the water quality in the soil. Furthermore, the soil water content can be obtained by dividing the water mass by the dry soil mass as follows:

\[
W_c = \frac{M₂ - M₃}{M₃ - M₁}
\]

Insert the thermometer into the soil for 5 cm to measure the temperature.

**3.2.3. Plant growth.** Seeds were sown in planting boxes with different material ratios, and the germination rate, height, and coverage of plants were monitored. Seed germination rate (Gr) can be obtained by counting the number of budding plants (N) within one month after sowing 50 seeds per planting box.

\[
Gr = \frac{N}{50} \times 100\%.
\]
After germination, plant height and coverage were measured every day to record changes within two months.

4. Results and discussion

4.1. Influence of materials on physical properties of soil

By monitoring soil density, temperature, and humidity, the effect of ADNB on soil physical properties was analyzed.

4.1.1. Soil density. Figure 2 shows the variation of the soil density. On the first day of the experiment, the density of the A, B, and C groups was 1.28, 1.35, and 1.33 g/cm$^3$, respectively; the density of the CK group was 1.46 g/cm$^3$. This is due to the volume expansion of ADNB in the soil after water absorption, decreasing the soil density. Subsequently, the soil is gradually consolidated under the influence of gravity and water evaporation and seepage. Therefore, with an increase in the experimental time, the soil density of each group increases. However, at the same monitoring period, the sample density of ADNB was lower than that of the natural soil (CK). Two months after sowing, the soil density of the material group was 9.1%–14.3% lower than that of the natural soil (CK).

4.1.2. Water content. Figure 3 shows that the initial water content of each test group was 30%. Over time, the soil water content of the three groups of A, B, and C with materials was higher than that of CK without materials, indicating that adding materials could effectively improve soil water retention. Additionally, the average moisture content of the soil treated by the ADNB is 9.3%–19.7% higher than that of CK, indicating that the application of ADNB can effectively improve the water holding capacity of the soil.

Figure 4 compares the changes in the water content of the soil in each group after the first rainfall cycle. The CK group has the most significant decrease in water content and the worst water retention performance. C group decreased the smallest, the best water retention. On the fifth day, the water content of the three sample groups treated with ADNB was 20.0%–33.3% higher than that of the CK group.
4.1.3. Soil temperature. Maximum and minimum soil temperatures on the same day were periodically measured (Figures 5 and 6).

Figures 5 and 6 show that the maximum and minimum temperatures of soil fluctuated near the predetermined temperature range of the test box, and the fluctuation range was less than 2°C. Overall, regardless of the maximum temperature or minimum temperature, the soil temperature of the A, B, and C groups was higher than that of the CK. By calculating the average temperature recorded, the maximum temperature of the ADNB treated group was 1.3%–1.8% higher than that of the CK group, and the minimum temperature was 0.7%–1.3% higher than that of the CK group. Thus, it shows that ADNB can improve the specific heat capacity of the soil, reduce the influence of the external temperature change on the soil and create a better growth environment for plants.

4.2. Effects of materials on plant growth

4.2.1. Germination rate. After seed sowing, the germination number of seeds was recorded and analyzed to obtain the influence of ADNB with different ratios on plant germination rate.

The germination rate of the A, B, and C groups treated with ADNB was higher than that of the CK group (Figure 7 (a)). Among them, the germination rate of herbaceous plants increased from 3.0%–36.0%, and the germination rate of shrubs increased from 1.0%–17.0%. The germination rate of group A was the highest, compared with the CK group, the germination rate increased by 15% of *Medicago Sativa Linn*, 36% of *Melinis minutiflora P. Beauv*, 7.2% of *Dodonaea viscosa (L.) Jacq*, 2.2% of *Leucaena leucocephala (Lam.) de Wit*, and 17% of *Cajanus cajan (Linn.) Mills*

Figures 7 (b–f) show the effect of ADNB on plant germination rate. For herbaceous plants, after ADNB treatment, A, B, and C groups of seeds germinated on the third day after sowing, CK group
germinated on the fifth day after sowing. For shrubs, A, B, and C groups with ADNB germinated on the 9th day after seed sowing, whereas the CK group germinated on the 11–12th day. Therefore, ADNB can promote plant germination and the germination time 2–3 days earlier.

![Graph showing plant germination rate](image)

*Figure 7 Plant germination rate: (a) Effects of different ratios of ADNB on plant germination rate, (b) Medicago Sativa Linn, (c) Melinis minutiflora P. Beauv, (d) Dodonaea viscosa (L.) Jacq, (e) Leucaena leucocephala (Lam.) de Wit, (f) Cajanus cajan (Linn.) Millsp*
4.2.2. **Plant height.** After germination, the plant height was measured manually. The plant height is defined as the highest position from the soil surface to the plant top (Figures 8 and 9).

Figure 8 shows the differences in plant height after one month of ADNB application with different ratios. The plant height difference is evident in the herbaceous plants of *Melinis minutiflora P.Beauv*. Furthermore, the plant height of the CK group was only 3 cm, whereas that of group A was 9.8 cm, which was 227% higher than that of the CK group. However, due to the short growth time, there was no noticeable difference in plant height of shrubs (*Dodonaea viscosa (L.) Jacq*, *Leucaena leucocephala (Lam.) de Wit*, *Cajanus cajan (Linn.) Millsp*).

![Figure 8](image1.png)  
**Figure 8** One month height comparison of plants

![Figure 9](image2.png)  
**Figure 9** Two-month height comparison of plants

Compared with the CK group, the plant height of the A, B, and C groups were higher than that of the CK group. Overall, the highest plant height was in group A. The advantage of ADNB in promoting shrub growth began to be reflected. The plant heights of the A, B, and C groups were higher than that of the CK group. Among them, group A has the largest coverage and the fastest increase. Compared with the CK group, plant coverage increased from 25%–45% after ADNB treatment.

4.2.3. **Coverage.** Vegetation coverage refers to the percentage of the vertical projection area of vegetation (including leaves, stems, and branches) on the ground to the total area of the statistical area. The plant coverage of each test group was obtained using the grid method. Figure 10 compares the differences in plant coverage under different ADNB ratios. A, B, C groups of plant coverage are higher than the CK group. Among them, group A has the largest coverage and the fastest increase. Compared with the CK group, plant coverage increased from 25%–45% after ADNB treatment.
Figure 10 Comparison of plant coverage

Figure 11 shows the plant growth in different periods in the two-month indoor experiment. As shown in the figure, the germination rate, coverage, and growth height of plants in groups A, B, and C at each period are higher than those in the CK group without materials. Among the three groups with materials, the growth effect of plants in group A is the best.
5. Application

Kaichun Expressway is located in South China, in middle-low mountains and hills. The surface water system is developed, and the terrain is complex. It belongs to the rainstorm concentrated area, and soil erosion is severe. This slope is a rock slope consisting of sandstone (Figure 12(a)), with a height of about 50 m, a width of about 100 m, a slope of 40°–60°, and the ADNB treated area is about 3 000 m². The slope bedrock is exposed, the rock mass structure is complete, and the joint fissures are not developed. The slope design scheme is anchor lattice beam + slope grass planting technology; the lattice beam size is 300 cm × 300 cm, plant protection thickness is 10 cm.
(a) Before treatment with new polymer materials  (b) After treatment with new polymer materials

Figure 12 Field application effect

Figure 12(b) shows the effect after seven months of ADNB application. By comparing the plant growth in the test and control areas, ADNB can promote the growth and germination of plants and improve the survival rate of shrubs. It can also improve the soil structure and anti-erosion ability of the slope soil to achieve better ecological protection and soil and water conservation effect.

6. Conclusions

(1) ADNB can effectively improve soil structure by decreasing soil density from 9.1%–14.3%, increasing the water content from 9.3%–19.7%, increasing the water holding capacity from 20.0%–33.3%, and increasing the temperature from 0.7%–1.8%.

(2) ADNB can effectively promote plant growth, with coverage increased from 25%–45%, the germination rate of herbaceous plants increased from 3.0%–36.0%, the germination rate of shrubs increased from 1.0%–17.0%, and plant height increased from 8.7%–98.6%.

(3) There is an optimal ratio for ADNB addition. Additionally, different soil conditions lead to different amounts of adhesive ester materials and water-absorbing ester materials. Finally, the ADNB ratio for different types of soil can be determined through laboratory experiments.

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