Effects of W-OH Water-Blocking Layer on Rainfall Infiltration, Runoff, and Sediment Yield Processes on Coal Gangue Slopes (Postprint)

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Abstract

To address the challenges of water leakage and frozen soil formation on coal gangue slopes in the Muli mining area of Qinghai, water-blocking layers of hydrophilic polyurethane (W-OH) at different concentrations (0%, 1.5%, 2.5%, 3.5%, 4.5%) were constructed on coal gangue slopes. Using artificial simulated rainfall, the characteristic parameters of rainfall infiltration and runoff-sediment yield on the slopes were analyzed to reveal the influence of different W-OH concentrations on the rainfall infiltration and runoff-sediment yield processes on coal gangue slopes. The results show that: (1) Under slope gradients of 5°, 15°, 25° and rainfall intensities of 30–90 $mm \cdot h^{-1}$, the overall trend of slope infiltration rate at different W-OH concentrations exhibits a rapid initial decrease followed by stabilization, with higher W-OH concentrations reaching the stable infiltration stage earlier. (2) The average infiltration rate at different W-OH concentrations is reduced by 4.15%–73.64% compared with the control group (0% W-OH); the water-blocking effects of 1.5%, 2.5%, 3.5%, and 4.5% W-OH slopes are 5.49%–49.98%, 11.96%–65.91%, 16.61%–72.10%, and 22.92%–85.81%, respectively, increasing with W-OH concentration. (3) The initial runoff generation time at different W-OH concentrations is advanced by 1.95%–74.20% compared with the control group slope; the sediment yield effects of 1.5%, 2.5%, 3.5%, and 4.5% W-OH slopes are 7.68%–97.98%, 15.28%–163.00%, 25.44%–261.44%, and 25.61%–260.58%, respectively, which are negatively correlated with rainfall intensity and slope gradient, and positively correlated with W-OH concentration; the runoff effects are 5.20%–83.39%, 12.93%–131.18%, 14.14%–149.11%, and 16.28%–188.86%, respectively. (4) Correlation analysis of relevant indicators reveals that W-OH plays an important role in preventing water infiltration and increasing runoff and sediment yield, while rainfall intensity and slope gradient remain the dominant factors in the slope runoff and sediment yield processes. Overall, constructing a W-OH water-blocking layer on coal gangue slopes can effectively reduce infiltration and block water, but also increases slope runoff and sediment yield; considering the issue of soil and water loss, appropriate soil and water conservation measures should be implemented on the slopes.

Full Text

Impact of W-OH Water-Blocking Layers on Rainfall Infiltration, Runoff and Sediment Yield Processes on Coal Gangue Slopes

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Abstract

Aiming at the problems of water leakage and frozen soil formation on coal gangue slopes in the Muli mining area of Qinghai Province, water-blocking layers with different concentrations of hydrophilic polyurethane (W-OH) were constructed on coal gangue slopes. Using artificial rainfall simulation, characteristic parameters of rainfall infiltration and runoff-sediment yield on the slopes were analyzed to reveal the influence of different W-OH concentrations on rainfall infiltration and runoff-sediment yield processes. The results showed that: (1) Under slopes of 5°, 15°, 25° and rainfall intensities of 30-90 $\mathrm{mm \cdot h^{-1}}$, the overall trend of slope infiltration rate showed a rapid decline initially followed by stabilization, with higher W-OH concentrations reaching stable infiltration earlier. (2) The average infiltration rate under different W-OH concentrations decreased by 4.15%-73.64% compared with the control group (0% W-OH). The water-blocking effects of 1.5%W, 2.5%W, 3.5%W, and 4.5%W were 5.49%-49.98%, 11.96%-65.91%, 16.61%-72.10%, and 22.92%-85.81%, respectively, increasing with W-OH concentration. (3) The initial runoff generation time on W-OH treated slopes was 1.95%-74.20% earlier than the control. Sediment yield effects were 7.68%-97.98% for 1.5%W, 15.28%-163.00% for 2.5%W, 25.44%-261.44% for 3.5%W, and 25.61%-260.58% for 4.5%W, which were negatively correlated with rainfall intensity and slope but positively correlated with W-OH concentration. Runoff yield effects were 5.20%-83.39%, 12.93%-131.18%, 14.14%-149.11%, and 16.28%-188.86%, respectively. (4) Correlation analysis showed that the W-OH water-blocking layer plays an important role in preventing water infiltration and increasing runoff and sediment yield, while rainfall intensity and slope remain the dominant factors in these processes. Overall, constructing a W-OH water-blocking layer on coal gangue slopes can effectively reduce

infiltration and block water, but also increases slope runoff and sediment yield. Considering soil and water loss concerns, appropriate soil and water conservation measures should be implemented on the slopes.

Keywords: coal gangue; rainfall infiltration; runoff and sediment yield; water-blocking layers

Introduction

The Muli mining area is located in the northeastern Qinghai-Tibet Plateau, a typically ecologically fragile region with an average altitude exceeding 4200 m, thin air, and harsh climatic conditions. Rainfall shows uneven spatiotemporal distribution, with annual precipitation between 282–774 mm concentrated mainly in summer due to significant plateau monsoon and topographic influences. In summer, warm moist air masses are uplifted by terrain to produce substantial precipitation, while winter and spring are controlled by continental cold air masses with scarce precipitation. Permafrost thickness in the Muli mining area ranges from 0–7.0 m, with a permafrost upper limit decline rate of 0–20 $cm \cdot a^{-1}$. In recent years, large-scale coal extraction has created gangue hills composed primarily of coal gangue, causing serious ecological damage. Coal gangue, the main solid waste from coal mining, is characterized by low carbon content and high mineral composition, appearing as dark gray rock. However, due to large particle size, numerous macropores, and poor water-holding capacity, gangue hills suffer severe water leakage, making frozen soil formation difficult or impossible during low-temperature seasons. This reduces soil water conservation capacity and affects ecological restoration progress. Water is a key limiting factor in gangue hill ecological restoration, and rainwater represents a primary moisture source in alpine mining areas. During rainfall, substantial water leakage can leach contaminants into surface and groundwater, causing serious environmental damage.

Currently, applying soil directly onto coal gangue surfaces is a main restoration measure. However, in alpine mining areas, soil is scarce and coverable soil thickness is limited, making it ineffective for reducing rainwater leakage. Therefore, this study constructed a water-blocking layer at a suitable depth (20 cm) from the coal gangue slope surface based on project demonstration area conditions to alleviate water leakage. Hydrophilic polyurethane (W-OH) is a modified hydrophilic polyurethane composite that can react with water in any proportion to gel and solidify, forming a solidified body with good elasticity and certain porosity when combined with sand and soil. Related research shows that low-concentration W-OH aqueous solution has low viscosity and good pre-solidification permeability, strong bonding force with sand and soil, and can solidify within minutes to form a porous structural solidification layer with good water retention, thermal insulation, and fertilizer retention properties that effectively reduces soil surface erosion. Zhu Yayun et al. found through slope flume experiments that W-OH can increase bonding force between soil particles and inhibit soil erosion. Related studies demonstrate that W-OH can serve as a water-blocking agent with excellent anti-seepage effects. Furthermore, W-OH has been widely applied in farmland, forest land, slope revegetation, channel anti-seepage, and desertification control. This study constructed a W-OH water-blocking layer at 20 cm depth from the coal gangue slope surface (schematic diagram shown in [Figure 1: see original paper]).

1. Materials and Methods

1.1 Experimental Materials and Apparatus

The coal gangue used in this experiment was obtained from the Juhugeng mining area of the Muli mining area in Qinghai Province. Before the experiment, the coal gangue was air-dried. The basic physical properties of the sampled coal gangue are shown in . The water-blocking agent W-OH is a light yellow viscous liquid at room temperature with a viscosity of 650–700 $Pa \cdot s$ and density of 1.18 $g \cdot cm^{-3}$. It can quickly undergo cross-linking reactions with water to form a solidified body with good mechanical properties that binds with soil.

The artificial rainfall simulation experiment was conducted at the Zhuolu Experimental Base in Hebei Province. The experimental apparatus mainly included a rainfall device and an experimental soil trough. The soil trough was a self-made steel structure with adjustable slope (0°–30°) and dimensions of 1.6 m × 0.5 m × 0.3 m. The rainfall device was a field portable artificial rainfall simulator with rainfall intensity range of 20-240 $mm \cdot h^{-1}$, rainfall area of approximately 3 m × 4 m, adjustable rainfall height up to 6.8 m, and rainfall uniformity >80%. The schematic diagram of the experimental setup is shown in [Figure 1: see original paper].

1.2 Experimental Design

The experiment was conducted from early July to late September. Based on rainfall conditions in the Muli mining area, three rainfall intensities were designed: 30 $mm \cdot h^{-1}$, 60 $mm \cdot h^{-1}$, and 90 $mm \cdot h^{-1}$. According to local conditions, three slope gradients were designed: 5°, 15°, and 25°. Through preliminary experiments, four W-OH concentration gradients were prepared: 1.5%W, 2.5%W, 3.5%W, and 4.5%W, with the 4.5%W slope serving as the control group. Each treatment was replicated three times.

During trough filling, coal gangue water content was controlled to match field conditions in the Muli mining area. To ensure uniform distribution, a layered filling method was adopted, controlling bulk density to 1.62 $g \cdot cm^{-3}$. When filling reached 10 cm depth, the prepared W-OH solution was evenly sprayed on the coal gangue surface. After full contact and reaction, filling continued to 30 cm depth, level with the outflow outlet, and the surface was roughened. The trough was then positioned under the rainfall simulator. At runoff initiation, the initial runoff time was recorded. During the first 10 minutes after runoff began, water-sediment samples were collected at 1-minute intervals, then at 5-minute intervals until the 60-minute rainfall event concluded. Samples were dried and weighed to calculate runoff and sediment yield.

1.3 Calculation Indicators

The sediment yield rate (D, $g \cdot m^{-2} \cdot min^{-1}$) and runoff rate (R, $mm \cdot min^{-1}$) were calculated as:

$$D = \frac{M}{S \cdot t}$$

$$R = \frac{Q}{S \cdot t}$$

where M is dried sediment weight (g), S is slope area (m^2), Q is runoff volume (mm), and t is sampling time (min).

Based on the water balance equation, infiltration rate (I, $mm \cdot min^{-1}$) was calculated as:

$$I = R - Q - \frac{\Delta W}{\Delta t}$$

where R is rainfall amount (mm), Q is runoff amount (mm), and $\Delta W/\Delta t$ is soil water storage change (neglected in this study).

Water-blocking effect (C) was calculated as:

$$C = \frac{I_c - I_t}{I_c} \times 100\%$$

where I_c is infiltration amount of control slope (mm) and I_t is infiltration amount of W-OH treated slope (mm).

Sediment yield effect (S_e) and runoff yield effect (Q_e) were calculated as:

$$S_e = \frac{D_t - D_c}{D_c} \times 100\%$$

$$Q_e = \frac{Q_t - Q_c}{Q_c} \times 100\%$$

where D_t and D_c are sediment yields of W-OH treated and control slopes (g), and Q_t and Q_c are runoff amounts of W-OH treated and control slopes (mm).

Statistical analysis was performed using Excel 2019 and SPSS 27.0, and figures were created using Origin 2023.

2. Results and Analysis

2.1 Initial Runoff Time

Initial runoff time reflects slope infiltration and runoff-sediment yield processes. Under rainfall intensities of 30-90 mm · h^{-1} and slopes of 5°, 15°, and 25°, initial runoff times for different W-OH concentrations are shown in . At 5° slope, initial runoff times for 1.5%W, 2.5%W, 3.5%W, and 4.5%W treatments were 111-1333 s, 90-1262 s, and 66-1015 s under 30, 60, and 90 mm · h^{-1} rainfall intensities, respectively, representing advances of 1.95%-45.73%, 3.53%-69.78%, and 19.77%-74.20% compared with the control. At 15° slope, times were 90-1262 s, 66-1015 s, and 57-769 s (16.16%-28.49%, 28.53%-47.19%, and 33.12%-56.81% advances). At 25° slope, times were 66-1015 s, 57-769 s, and 42-615 s (38.03%-68.87%, 33.87%-57.69%, and 13.69%-41.85% advances). Initial runoff time decreased with increasing rainfall intensity and slope gradient.

2.2 Infiltration Characteristics

2.2.1 Infiltration Rate Variation Rainfall infiltration is the process where water penetrates soil under gravity and suction forces. Both W-OH treated and control slopes showed decreasing infiltration rates over time, with rapid initial decline followed by stabilization. W-OH treated slopes exhibited faster decline rates, with higher concentrations reaching stable infiltration earlier (Fig. 2). Under 30-90 mm · h^{-1} rainfall, average infiltration rates were 0.42-0.60 mm · min^{-1} (1.5%W), 0.38-0.46 mm · min^{-1} (2.5%W), 0.35-0.41 mm · min^{-1} (3.5%W), 0.24-0.33 mm · min^{-1} (4.5%W), and 0.44-0.78 mm · min^{-1} (control). Infiltration rates decreased with W-OH concentration, with reductions of 4.15%-73.64% compared with control, specifically 12.49%-41.40% at 15° slope and 20.33%-47.43% at 25° slope (Fig. 3). Reduction rates accelerated with steeper slopes.

Under constant slope, infiltration rate showed no clear pattern with rainfall intensity, though rates were generally highest at 60 mm · h^{-1} and lowest at 30 mm · h^{-1}. Under constant rainfall intensity, infiltration rate decreased systematically with slope. For example, at 30 mm · h^{-1}, rates declined from 0.38 mm · min^{-1} at 5° to 0.34 mm · min^{-1} at 15° (12.53% reduction) and 0.31 mm · min^{-1} at 25° (25.10% reduction). Similar trends occurred at other intensities.

Water-blocking effects ranged from 5.49%-49.98% (1.5%W), 11.96%-65.91% (2.5%W), 16.61%-72.10% (3.5%W), and 22.92%-85.81% (4.5%W), increasing with both W-OH concentration and slope gradient, reaching a maximum of 85.81% at 60 mm · h^{-1} and 25° slope. No systematic relationship existed between rainfall intensity and water-blocking effect under constant slope.

2.2.2 Cumulative Infiltration Water-blocking effect refers to hindrance of water flow and infiltration. Under 30-90 mm · h^{-1} rainfall, control group cumulative infiltration was 12.54-18.54 L at 5°, 9.85-16.27 L at 15°, and 6.55-14.18 L at 25°. W-OH treatments significantly reduced cumulative infiltration, as shown in . Cumulative infiltration decreased with increasing W-OH concentration and slope gradient, demonstrating effective water-blocking capacity.

2.3 Sediment Yield

2.3.1 Sediment Yield Rate Sediment yield rate reflects sediment production per unit area per unit time. Analysis of sediment yield rate changes (Fig. 4) shows significant early-stage variation, with rapid increase to a maximum at 5-10 minutes, followed by sharp decline and stabilization. The pattern was consistent across slopes. W-OH application exacerbated sediment production, with higher concentrations producing stronger sediment yield rates. Under constant W-OH concentration, sediment yield rate was positively correlated with rainfall intensity and slope gradient.

2.3.2 Cumulative Sediment Yield Sediment yield effect reflects the degree of sediment increase after W-OH application. As shown in , under 30-90 mm · h^{-1} rainfall, average sediment yield rates were 0.15-0.78 g · m^{-2} · min^{-1} (control), 0.22-1.50 g · m^{-2} · min^{-1} (1.5%W), 0.28-2.26 g · m^{-2} · min^{-1} (2.5%W), 0.32-2.56 g · m^{-2} · min^{-1} (3.5%W), and 0.40-3.04 g · m^{-2} · min^{-1} (4.5%W), with higher concentrations producing greater rates. All W-OH treatments exceeded the control, with increases of 30.06%-95.55% (1.5%W), 82.26%-194.36% (2.5%W), 104.30%-233.51% (3.5%W), and 158.07%-295.34% (4.5%W).

Cumulative sediment yields were 4.77-28.33 g (control), 9.29-45.48 g (1.5%W), 12.20-75.81 g (2.5%W), 12.00-87.35 g (3.5%W), and 16.16-93.67 g (4.5%W). Sediment yield effects ranged from 7.68%-97.98% (1.5%W), 15.28%-163.00% (2.5%W), 25.44%-261.44% (3.5%W), and 25.61%-260.58% (4.5%W). The effect was pronounced on coal gangue slopes, increasing markedly with W-OH concentration. Under 90 mm · h^{-1} rainfall, the effect decreased with slope gradient, while under 60 mm · h^{-1}, the effect was most pronounced.

2.4 Runoff Characteristics

2.4.1 Runoff Rate Runoff rate is the volume of runoff per unit area per unit time. Under 30-90 mm · h^{-1} rainfall, average runoff rates were 0.06-0.90 mm · min^{-1} (control), 0.12-1.07 mm · min^{-1} (1.5%W), 0.08-1.05 mm · min^{-1} (2.5%W), 0.15-1.13 mm · min^{-1} (3.5%W), and 0.16-1.25 mm · min^{-1} (4.5%W). Runoff rates increased with rainfall intensity and slope gradient. At 60 mm · h^{-1} and 90 mm · h^{-1}, larger slopes produced greater runoff rates, with increases of 101.93%-121.44%.

2.4.2 Cumulative Runoff Runoff yield effect reflects the percentage increase in runoff after W-OH application. As shown in , under 30-90 mm · h^{-1} rainfall, cumulative runoff was 4.01-51.09 L (control), 5.10-53.75 L (1.5%W), 7.10-59.19 L (2.5%W), 8.68-61.89 L (3.5%W), and 9.73-65.19 L (4.5%W). Runoff yield effects ranged from 5.20%-77.69% (1.5%W), 15.86%-131.18% (2.5%W), 21.13%-149.11% (3.5%W), and 27.59%-188.86% (4.5%W). At 25° slope, effects were 12.93%-99.09% (1.5%W), 14.14%-108.76% (2.5%W), 16.28%-139.23% (3.5%W), and 25.33%-186.78% (4.5%W). Runoff increased significantly on W-OH treated slopes, with effects more pronounced at 60 mm · h^{-1} rainfall intensity.

2.5 Correlation Analysis

Correlation analysis revealed that rainfall intensity was extremely significantly negatively correlated with initial runoff time (r = -0.712) and sediment yield effect (r = -0.568), and extremely significantly positively correlated with water-blocking effect and average sediment yield rate. Slope gradient was significantly negatively correlated with average infiltration rate and sediment yield effect, and significantly positively correlated with water-blocking effect, average sediment yield rate, and runoff yield effect. W-OH concentration was significantly negatively correlated with average infiltration rate, and significantly positively correlated with water-blocking effect (r = 0.452), average sediment yield rate (r = 0.638), sediment yield effect (r = 0.715), and runoff yield effect (r = 0.689). While the W-OH water-blocking layer significantly affects water infiltration and runoff-sediment yield, rainfall intensity and slope gradient remain the dominant factors controlling these processes on coal gangue slopes.

3. Discussion

3.1 Impact on Infiltration Process

This study found that W-OH application on coal gangue slopes produced obvious water-blocking effects, with infiltration rates showing rapid initial decline followed by stabilization, consistent with Li Yuanyuan et al. Water infiltration in coal gangue slopes is determined by water content, mechanical composition, and water-blocking capacity. Coal gangue particles are large, poorly structured, with numerous macropores and poor water-holding capacity. When W-OH solution is sprayed on the surface, its fluidity allows rapid spreading among particles. After physicochemical reactions, W-OH solidifies into an impermeable yet elastic gel that binds loose coal gangue, effectively alleviating infiltration. Higher concentrations produce stronger film structures and greater bonding capacity, enhancing water-blocking ability. Yang Penghui et al. found that higher W-OH concentrations in coal gangue led to lower infiltration rates, aligning with our results.

In early rainfall stages, low water content creates strong infiltration capacity and high rates. In middle and late stages, as water reaches the W-OH layer, downward infiltration slows and most water is retained above the layer, achieving water-blocking effects. Consequently, W-OH treated slopes reached stable infiltration earlier than controls. Average infiltration rate was highest at 90 mm $\cdot$ h^{-1} and second-highest at 60 mm $\cdot$ h^{-1} because high-intensity raindrops have greater kinetic energy that splashes fine particles, clogging pores and affecting infiltration. Studies show that slope gradient influences infiltration because steeper slopes increase the force component along the slope while decreasing the perpendicular component, which is unfavorable for infiltration.

In summary, W-OH reduces water infiltration while increasing runoff and sediment yield. To prevent secondary soil and water loss, soil and water conservation measures should be implemented, such as ecological blankets, geotextile planting, and water storage/drainage projects, to reduce raindrop impact and surface erosion.

3.2 Impact on Runoff and Sediment Yield

According to water balance principles, reduced infiltration converts rainfall to runoff. Constructing a W-OH water-blocking layer weakens infiltration capacity and increases runoff generation, consistent with Zhu Xiudi et al. During rainfall, runoff rate increases with duration before stabilizing as slope water content saturates and infiltration decreases. Initial runoff time serves as an important indicator of water-blocking layer effectiveness. This study found that initial runoff time advanced with increasing rainfall intensity and slope gradient, consistent with Geng Xiaodong et al.

Sediment yield rate over rainfall duration first increased to a peak, then decreased rapidly and stabilized. In early stages, abundant fine materials provide sufficient erosion material. As duration extends, runoff and carried sediment increase to a maximum. Continued runoff reduces fine materials, increases large particles, and improves erosion resistance, causing sediment yield rate to decline after peaking. W-OH reduces infiltration and increases runoff, enhancing coal gangue slope erosion and sediment yield, similar to Li Yuyuan et al.

4. Conclusions

Based on W-OH water-blocking layer construction and artificial rainfall simulation experiments with different rainfall intensities and slopes, this study analyzed rainfall infiltration and runoff-sediment yield parameters, concluding: (1) During rainfall, W-OH treated coal gangue slope infiltration rates showed rapid initial decline followed by stabilization, with higher concentrations producing faster decline rates and earlier stable infiltration. (2) W-OH treatment advanced initial runoff time by 1.95%-74.20% compared with the control. Water-blocking effects were significant, with average infiltration rates reduced by 4.15%-73.64%. Specific water-blocking effects were 5.49%-49.98% (1.5%W), 11.96%-65.91% (2.5%W), 16.61%-72.10% (3.5%W), and 22.92%-85.81% (4.5%W), increasing with both W-OH concentration and slope gradient. (3) Average sediment yield rates increased by 4.92%-295.34% compared with the control. Sediment yield effects were 7.68%-97.98% (1.5%W), 15.28%-163.00% (2.5%W), 25.44%-261.44% (3.5%W), and 25.61%-260.58% (4.5%W).

Runoff yield effects were 5.20%-83.39% (1.5%W), 12.93%-131.18% (2.5%W), 14.14%-149.11% (3.5%W), and 16.28%-188.86% (4.5%W). (4) The W-OH water-blocking layer significantly reduces water infiltration and increases runoff and sediment yield, while rainfall intensity and slope remain the dominant controlling factors.

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Note: Figure translations are in progress. See original paper for figures.