Effects of W-OH Curing Agent on Water Infiltration in Coal Gangue in Alpine Mining Areas and Model Fitting (Postprint)

Authors: Yang Penghui, Yang Hailong, Yang Siyuan, Zhang Wei, Zhang Songyang, Yang Hailong

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Abstract

Indoor simulated ponded infiltration experiments on coal gangue columns were conducted to investigate the effects of spray treatments with different W-OH concentrations (0%, 1.5%, 2.5%, and 3.5%) on water infiltration in coal gangue from alpine mining areas. Simultaneously, three infiltration models (Philip, Kostiakov, and Horton) were employed to fit the infiltration process, a one-dimensional algebraic model was utilized to predict the distribution characteristics of volumetric water content within the coal gangue profile, and model applicability was evaluated. The results indicated: (1) Cumulative infiltration amount and wetting front advance distance increased gradually with infiltration time and exhibited a negative correlation with W-OH concentration. At the same infiltration time, higher W-OH concentrations resulted in lower infiltration rates and wetting front advance velocities. Compared with the control (0% W-OH), the initial infiltration rates for the three W-OH concentration treatments (1.5%, 2.5%, 3.5%) decreased by 1.12%, 3.59%, and 9.64%, respectively; stable infiltration rates decreased by 16.92%, 78.46%, and 89.23%, respectively; and average infiltration rates decreased by 11.35%, 58.26%, and 71.02%, respectively. (2) All three infiltration models satisfactorily fitted the water infiltration process in coal gangue under different W-OH concentrations. The mean coefficient of determination (R^2) values for the Philip, Kostiakov, and Horton models were 0.962, 0.957, and 0.967, respectively, with the Horton model demonstrating the best fitting performance. (3) During the ponded infiltration process, at the same W-OH concentration, greater burial depths required longer times for water to infiltrate to each monitoring point; at the same depth, higher W-OH concentrations also required longer times for water to infiltrate to each monitoring point. (4) The one-dimensional algebraic model satisfactorily simulated the distribution characteristics of volumetric water content in the coal gangue profile after infiltration completion. The root mean square error (RMSE) and mean absolute error (MAE) between simulated and measured values ranged between 2.574%–3.326% and 2.308%–2.707%, respectively, with the agreement index (D) exceeding 0.92. The research findings can provide theoretical guidance for the application of W-OH solidifying agent in the reconstruction of frozen soil profiles within coal gangue dumps in alpine mining areas.

Full Text

Effect of W-OH Stabilizer on Water Infiltration in Coal Gangue from High-Cold Mining Areas and Model Fitting

YANG Penghui, YANG Hailong, YANG Siyuan, ZHANG Wei, ZHANG Songyang

(College of Soil and Water Conservation, Beijing Forestry University, Beijing 100083)

Abstract

A simulation experiment was conducted on water infiltration in coal gangue columns under indoor ponding conditions to investigate the effects of different W-OH concentrations (0%, 1.5%, 2.5%, and 3.5%) on water infiltration in coal gangue from high-cold mining areas. The Philip, Kostiakov, and Horton infiltration models were employed to fit the infiltration process, while a one-dimensional algebraic model was used to predict the distribution characteristics of volumetric water content in coal gangue profiles, and model applicability was evaluated. The results indicate that: (1) Cumulative infiltration and wetting front advance distance gradually increase with infiltration time, showing a negative correlation with W-OH concentration. At the same infiltration time, higher W-OH concentrations result in lower infiltration rates and wetting front advance rates. Compared with the control (0% W-OH), the initial infiltration rates under the three W-OH concentrations (1.5%, 2.5%, 3.5%) decreased by 1.12%, 3.59%, and 9.64%, respectively; stable infiltration rates decreased by 16.92%, 78.46%, and 89.23%, respectively; and average infiltration rates decreased by 11.35%, 58.26%, and 71.02%, respectively. (2) All three infiltration models effectively fitted the water infiltration process in coal gangue under different W-OH concentrations, with mean coefficient of determination (R^2) values of 0.962, 0.957, and 0.967 for the Philip, Kostiakov, and Horton models, respectively, with the Horton model showing particularly good fitting performance. (3) During water infiltration, greater burial depth at the same W-OH concentration required longer times for water to reach each monitoring point; at the same depth, higher W-OH concentration also required longer infiltration times to reach monitoring points. (4) The one-dimensional algebraic model effectively simulated the distribution characteristics of volumetric water content in coal gangue profiles after infiltration, with root mean square error (RMSE) and mean absolute error (MAE) between simulated and measured values ranging from 2.574%–3.326% and 2.308%–2.707%, respectively, and compliance index (D) values above 0.92.

These results provide theoretical guidance for the application of W-OH stabilizer in reconstructing frozen soil profiles in coal gangue mountains in high-cold mining areas.

Keywords: coal gangue; W-OH; cumulative infiltration; infiltration rate; wetting front; model fitting

Introduction

Permafrost is widely distributed across the Qinghai-Tibet Plateau, with poor water permeability that influences surface runoff formation, groundwater transport processes, and groundwater distribution patterns. Permafrost degradation affects water exchange between groundwater and surface water in permafrost regions, leading to the death of short-rooted plants dependent on suprapermafrost water, vegetation degradation, and enhanced desertification trends. Open-pit coal mining exposes and destroys the original permafrost layer, causing the permafrost table to shift downward and laterally, disrupting the original freeze-thaw balance. Mining subsidence also causes surface tensile deformation and crack development, reducing soil compaction and enhancing soil water infiltration and evaporation, thereby decreasing water conservation functions and surface water delivery.

Coal gangue, a solid waste from coal mining, typically consists of minerals such as quartz, mica, clay (illite and kaolinite), pyrite, and calcium, magnesium, and iron carbonates. Weathered coal gangue features large particles, numerous pores, poor water retention, and strong permeability. In high-cold mining areas, coal gangue cannot form frozen soil during low-temperature seasons. The Muli mining area is an important water source conservation area in the upper reaches of the Yellow River, holding extremely important ecological status and significance for ecological protection and high-quality development in the Yellow River basin. Previous mining operations in this area neglected permafrost protection, causing serious environmental problems including permanent permafrost destruction, meadow degradation, and upstream river pollution.

To restore permafrost in high-cold mining areas, this study proposes constructing a water-resisting layer at an appropriate depth in the coal gangue profile. W-OH stabilizer, a modified hydrophilic polyurethane composite material, is a pale yellow oily liquid with a density of approximately 1.18 $g \cdot cm^{-3}$ that can react with water in any proportion and rapidly solidify within minutes. When combined with sand, it forms a porous consolidated layer. When sprayed on coal gangue, W-OH can bond with gangue particles to form a consolidated water-resisting layer that regulates the distribution between infiltration water and surface runoff, alleviating the problem of coal gangue profiles failing to form frozen soil during low-temperature seasons in mining areas.

Polymer consolidation materials demonstrate good consolidation and water retention effects, representing a research hotspot among chemical consolidation materials. Previous studies have investigated high water-absorbent resin consolidation materials such as starch-grafted acrylonitrile, starch-grafted polyacrylic acid, cellulose-based materials, polyacrylates, and vinyl acetate. W-OH is a new type of hydrophilic polyurethane composite material that reacts with water to form an elastic gel with good soil/sand fixation, fertilizer retention, water conservation, and vegetation growth properties. Many scholars have studied W-OH applications in sand consolidation, vegetation restoration, infiltration reduction, seepage prevention, and surface runoff effects. Water infiltration in coal gangue layers is crucial for restoring water conservation functions in mines, with numerous experimental studies investigating infiltration patterns, such as effects of different terrains, biochar and PAM mixed application, and expansive water-resisting layers. However, few studies have examined the effects of W-OH on water infiltration in coal gangue.

Therefore, this study combines W-OH with coal gangue to form a water-resisting layer, conducting simulation experiments on water infiltration in coal gangue columns to investigate the effects of different W-OH concentrations on water infiltration, providing theoretical guidance for reconstructing frozen soil profiles in coal gangue mountains in high-cold mining areas.

1. Materials and Methods

1.1 Test Materials

The coal gangue used in this study was collected from the Juhugeng mining area of the Muli coalfield in Qinghai Province, air-dried and sieved through a 20 mm screen for later use. Dry bulk density was measured using the ring knife method, soil water content by the drying method, and saturated hydraulic conductivity by the constant head method. The particle size composition of the coal gangue is shown in Table 1, with bulk density controlled at 1.65 $\mathrm{g \cdot cm^{-3}}$. The gangue was packed in layers and compacted uniformly with a rammer, with scarification between layers to prevent stratification. Four W-OH concentrations were prepared (0%, 1.5%, 2.5%, and 3.5%) as treatments, with water as the control. After packing coal gangue to a depth of 29 cm, different concentrations of W-OH were sprayed to react fully with the gangue, followed by continued packing to create 60 cm coal gangue columns.

1.2 Test Apparatus

The test apparatus included a Mariotte bottle, acrylic columns, water content sensors, and a data collector. The acrylic columns had an inner diameter of 10 cm, with drainage holes at the bottom and uniformly distributed height markings. A 5 cm layer of permeable sand was placed at the bottom, as shown in [Figure 1: see original paper]. The water content sensor model was SM100, connected to a watchdog1400 data collector that automatically recorded water content data every 1 minute.

1.3 Test Methods

The coal gangue infiltration experiment was conducted in the laboratory of Beijing Forestry University in August 2023, with laboratory temperature maintained at 25$±$2°C. Coal gangue was packed in 5 cm layers, with water content sensors installed at depths of 10 cm, 20 cm, 30 cm, and 40 cm. A mesh cloth was placed on the coal gangue surface with gravel above to prevent scouring and ensure uniform infiltration. The Mariotte bottle supplied water at a constant 5 cm head. After packing, sensors were calibrated until readings stabilized before commencing the constant-head infiltration test. Observations recorded infiltration time, Mariotte bottle water level, and wetting front advance distance at 5-minute intervals until stable water flow emerged from the bottom drainage pipe. Data were processed using Excel 2022 and Origin 2022 software.

1.4 Calculation Methods and Models

1.4.1 Infiltration Rate Calculation Infiltration rate is defined as the volume of water infiltrating per unit area of soil surface per unit time ($\mathrm{cm} \cdot \mathrm{min}^{-1}$), calculated as:

$$I = \frac{Q}{A \cdot t}$$

where I is infiltration rate ($\mathrm{cm} \cdot \mathrm{min}^{-1}$), t is infiltration time (min), A is soil surface area (cm^2), and Q is the volume of infiltrated water (cm^3). The initial infiltration rate is the average rate during 0–5 min; the stable infiltration rate is the rate when water flow stabilizes; and the average infiltration rate is the ratio of cumulative infiltration to time when stable infiltration is reached.

1.4.2 Water Infiltration Models The Philip model is calculated as:

$$I = B + 0.5St^{-0.5}$$

where B is stable infiltration rate ($\mathrm{cm} \cdot \mathrm{min}^{-1}$) and S is initial infiltration rate ($\mathrm{cm} \cdot \mathrm{min}^{-1}$) model parameter.

The Kostiakov model is calculated as:

$$I = at^{-b}$$

where a is initial infiltration rate ($\mathrm{cm} \cdot \mathrm{min}^{-1}$) and b is the rate of infiltration rate decline over time.

The Horton model is calculated as:

$$I = I_f + (I_i - I_f)e^{-kt}$$

where I_i is initial infiltration rate ($\mathrm{cm \cdot min^{-1}}$), I_f is stable infiltration rate ($\mathrm{cm \cdot min^{-1}}$), and k is a model parameter.

1.4.3 Wetting Front Fitting The power function model is widely used due to its simplicity and good fit for describing the relationship between wetting front travel distance and time. Therefore, this study selected the power function to fit wetting front changes in coal gangue:

$$Z_f = mt^n$$

where Z_f is wetting front advance distance (cm), t is infiltration time (min), and m, n are fitting parameters.

1.4.4 Volumetric Water Content Distribution Model The one-dimensional algebraic model can fit water content distribution at different depths after infiltration:

$$\theta = \theta_r + (\theta_s - \theta_r)\left(1 - \frac{Z}{Z_f}\right)^{\alpha}$$

where θ is soil profile volumetric water content ($\mathrm{cm^3 \cdot cm^{-3}}$), Z is any depth (cm), I is cumulative infiltration (cm), θ_s is saturated water content ($\mathrm{cm^3 \cdot cm^{-3}}$), θ_r is residual water content ($\mathrm{cm^3 \cdot cm^{-3}}$), θ_0 is initial water content ($\mathrm{cm^3 \cdot cm^{-3}}$), and α is the comprehensive shape coefficient of unsaturated hydraulic conductivity. Since the coal gangue was naturally air-dried with low initial water content, θ_0 can be assumed as 0, simplifying the formula.

1.4.5 Model Evaluation Model simulation effectiveness was evaluated using root mean square error (RMSE), mean absolute error (MAE), and compliance index (D). Smaller RMSE and MAE indicate higher simulation precision; D values closer to 1 indicate better agreement.

2. Results

2.1 Effects of W-OH Concentration on Cumulative Infiltration and Infiltration Rate

The variation curves of cumulative infiltration and infiltration rate over time for coal gangue under different W-OH concentrations are shown in [Figure 2: see original paper]. Cumulative infiltration increased gradually with infiltration time for all treatments. During the initial infiltration stage, cumulative infiltration increased rapidly with no significant differences among different W-OH concentrations. After approximately 10 min, higher W-OH concentrations resulted in lower cumulative infiltration at the same infiltration time. Compared with the control (0% W-OH), the 1.5% W-OH treatment showed minimal reduction in cumulative infiltration, but as concentration increased to 3.5% W-OH, cumulative infiltration decreased significantly. After 90 min, cumulative infiltration values were 21.19 cm, 19.30 cm, 15.00 cm, and 13.18 cm for 0%, 1.5%, 2.5%, and 3.5% W-OH treatments, respectively. After water began draining from the bottom, the coal gangue became fully saturated, and cumulative infiltration showed a good linear relationship with time, with the slope representing the stable infiltration rate.

Infiltration rates showed a negative correlation with time, being high initially and decreasing rapidly before stabilizing. Infiltration parameters under different W-OH concentrations are presented in Table 2. Initial, stable, and average infiltration rates all decreased with increasing W-OH concentration. The Horton model can intuitively fit both initial and stable infiltration rates, which decreased with increasing concentration, consistent with experimental results. After infiltration, stable infiltration rates were 0.130 $\text{cm} \cdot \text{min}^{-1}$, 0.108 $\text{cm} \cdot \text{min}^{-1}$, 0.028 $\text{cm} \cdot \text{min}^{-1}$, and 0.014 $\text{cm} \cdot \text{min}^{-1}$ for 0%, 1.5%, 2.5%, and 3.5% W-OH treatments, respectively. Stable infiltration was reached at 85 min, 80 min, 185 min, and 260 min, respectively, indicating that higher concentrations prolonged the time to reach stable infiltration.

2.2 Model Fitting of Coal Gangue Water Infiltration Process

The three infiltration models were used to fit the infiltration process of coal gangue under different W-OH concentrations ([Figure 3: see original paper]), with fitting results shown in Table 3. In the Philip model, initial infiltration rates decreased with increasing W-OH concentration. The Kostiakov model's parameter a reflects initial infiltration rate, while b reflects the decay speed of infiltration rate over time. Table 3 shows that larger a values correspond to smaller b values, indicating that initial infiltration rate decreases while infiltration rate decay speed increases with W-OH concentration.

The Horton model's fitted initial and stable infiltration rates showed small errors compared with measured values. All three models achieved high R^2 values (Philip: 0.962, Kostiakov: 0.957, Horton: 0.967), indicating good overall fitting performance, with the Horton model performing best.

2.3 Effects of W-OH Concentration on Wetting Front

The variation curves of wetting front advance distance and rate over time under different W-OH concentrations are shown in [Figure 4: see original paper]. Wetting front advance distance increased continuously with infiltration time, rapidly at first with no significant differences among treatments. After about 10 min, higher W-OH concentrations resulted in smaller wetting front distances at the same infiltration time. The wetting front of the 3.5% W-OH treatment paused at 35 cm depth for about 10 min. After 50 min, wetting front distances were 45.00 cm, 42.25 cm, 29.32 cm, and 19.06 cm for 0%, 1.5%, 2.5%, and 3.5%

W-OH treatments, respectively. Times required to reach 45 cm depth were 50 min, 60 min, 140 min, and 245 min, respectively.

Wetting front advance rates were highest initially, then decreased rapidly and stabilized. In the later infiltration stage, rates stabilized at approximately 0.314 $\mathrm{cm \cdot min^{-1}}$, 0.276 $\mathrm{cm \cdot min^{-1}}$, 0.180 $\mathrm{cm \cdot min^{-1}}$, and 0.124 $\mathrm{cm \cdot min^{-1}}$ for the four treatments. Power function fitting of wetting front distance versus time showed good relationships with $R^2 > 0.96$ for all treatments (Table 4).

2.4 Relationship Between Cumulative Infiltration and Wetting Front

Cumulative infiltration showed a linear relationship with wetting front advance distance. Linear fitting using Equation (7) yielded R^2 values above 0.96 for all W-OH concentrations (Table 5), indicating high precision in the linear relationship. The unsaturated hydraulic conductivity comprehensive shape coefficient α showed relatively high values, reflecting strong water transport capacity in coal gangue.

2.5 Variation Patterns of Profile Volumetric Water Content

Water content sensors monitored temporal changes in volumetric water content at different depths under various W-OH concentrations ([Figure 6: see original paper]). At all depths (10 cm, 20 cm, 30 cm, 40 cm), volumetric water content suddenly increased and eventually stabilized. Before water arrival, water content remained at the initial value (~13.7%). Upon water arrival, water content increased rapidly, after which it remained nearly constant as the gangue approached saturation. Final average water contents stabilized at approximately 56.9%, 58.7%, 59.4%, and 57.5% for the four treatments, close to the measured saturated water content of 58.7%.

Times required for water to reach each monitoring point are shown in Table 6. Greater burial depth required longer infiltration times at the same concentration, and higher W-OH concentrations also required longer times to reach the same depth.

2.6 Model Fitting and Evaluation of Profile Volumetric Water Content

The one-dimensional algebraic model was used to simulate profile volumetric water content after infiltration. Substituting parameters from Table 5 into Equation (6) yielded simulated values for comparison with measured values. Water content decreased gradually with depth for all treatments, with small differences between simulated and measured values indicating high simulation accuracy.

At 10 cm and 20 cm depths, simulated values were slightly lower than measured values, while at 30 cm and 40 cm depths, simulated values were slightly higher. For the 2.5% W-OH treatment, surface water content was overestimated while deeper layers were underestimated. RMSE and MAE ranged from 2.574%–3.326% and 2.308%–2.707%, respectively, with D values above 0.92, demonstrating that the one-dimensional algebraic model can effectively simulate post-infiltration profile water content distribution in coal gangue.

3. Discussion

3.1 Water Infiltration Characteristics and Patterns in Coal Gangue Under Different W-OH Concentrations

Coal gangue water infiltration capacity depends primarily on its inherent properties such as texture, bulk density, structure, and initial water content. As a chemical stabilizer, W-OH forms a consolidated layer with coal gangue, directly affecting its physical structure and consequently influencing water infiltration. To eliminate the influence of initial water content, all coal gangue samples were collected from the same location and time, with water content measured and balanced before testing to ensure consistent initial conditions across treatments.

During initial infiltration, matric potential is the main influencing factor, resulting in rapid increases in cumulative infiltration and wetting front distance with no significant differences among treatments. As infiltration progressed and gangue became wetted, matric suction decreased, slowing the increase in cumulative infiltration and wetting front distance. Differences among W-OH treatments emerged after approximately 10 min, with higher concentrations producing smaller cumulative infiltration and wetting front distances. After 90 min, cumulative infiltration decreased by 8.92%, 29.21%, and 37.80% for 1.5%, 2.5%, and 3.5% W-OH treatments, respectively, while wetting front distances after 50 min decreased by 6.11%, 34.84%, and 57.64%, respectively.

Higher W-OH concentrations create denser consolidated layers with better water resistance, reducing infiltration capacity. The effect is more pronounced at higher concentrations, consistent with previous research. Infiltration rates and wetting front advance rates were highest initially, then decreased rapidly before stabilizing. The presence of more fine particles in lower layers reduced permeability over time. Higher W-OH concentrations resulted in longer times to reach stable infiltration (80 min, 185 min, and 260 min for 1.5%, 2.5%, and 3.5% W-OH, respectively), demonstrating stronger water-blocking effects.

3.2 Applicability of Water Infiltration Models

The Philip model is semi-theoretical and generally suitable for homogeneous soils with uniform initial water content and sufficient water supply. However, its fixed infiltration time assumption makes it difficult to precisely reflect variations in infiltration curves for soils with different initial water contents. In this study, the Philip model produced negative stable infiltration rates for the 2.5% and 3.5% W-OH treatments, indicating poor fitting performance.

The Kostiakov model's infiltration rate approaches infinity as time approaches zero and approaches zero as time increases, which is inconsistent with this study's observation that infiltration rates stabilize at non-zero values. Therefore, the Kostiakov model also showed limitations.

The Horton model fitted initial and stable infiltration rates with small errors and high R^2 values, demonstrating the best overall fitting performance and strongest applicability for simulating coal gangue infiltration processes under different W-OH concentrations.

3.3 Applicability of the One-Dimensional Algebraic Model

Accurate prediction of water content distribution in coal gangue profiles is crucial for permafrost restoration in high-cold mining areas. The one-dimensional algebraic model has clear physical meaning and can describe soil profile water content distribution. In this study, RMSE and MAE averaged 2.95% and 2.51%, respectively, with D values above 0.92, indicating good simulation accuracy.

However, some discrepancies occurred: for the 2.5% W-OH treatment, measured values exceeded simulated values at all depths, with the lowest D value of 0.921. These discrepancies may result from model parameter requirements for correction or from W-OH altering coal gangue structure and affecting water movement. Previous studies have shown the model's applicability to gravel-mulched and saline-alkali soils, and this study further demonstrates its effectiveness for simulating post-infiltration water content distribution in coal gangue.

4. Conclusions

(1) Comparison of water infiltration processes under different W-OH concentrations revealed that at the same infiltration time, higher W-OH concentrations resulted in smaller cumulative infiltration and wetting front advance distances, as well as lower initial, stable, and average infiltration rates.

(2) The Philip, Kostiakov, and Horton models all effectively fitted water infiltration processes in coal gangue under different W-OH concentrations, with mean R^2 values of 0.962, 0.957, and 0.967, respectively. The Horton model demonstrated particularly good fitting performance.

(3) During water infiltration, greater burial depth at the same W-OH concentration required longer times for water to reach monitoring points; at the same depth, higher W-OH concentration also required longer infiltration times.

(4) The one-dimensional algebraic model effectively simulated post-infiltration profile volumetric water content distribution in coal gangue, with RMSE and MAE between simulated and measured values of 2.574%–3.326% and 2.308%–2.707%, respectively, and D values above 0.92.

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