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Research Article

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Mechanistic Study on the Filtration Behavior Simulation of Suspended Solids in Mine Water by Coal Mine Goaf

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Abstract: Coal and water resources are inversely distributed in western China, and the resource utilization of mine water is recognized as one of the key pathways for the green development of coal. In underground coal mine reservoirs, gangue from mined-out areas is utilized as the core purification medium; however, the removal characteristics and synergistic mechanisms for suspended solids are not yet fully clarified.Gangue and suspended solids from the Daliuta mining area are selected as research subjects. Dynamic circulation simulation tests, XRD, SEM, and laser particle size analysis are employed to systematically investigate the purification effects of gangue on suspended solids in mine water under varying concentrations, settling times, settling heights, and settling distances, and the underlying mechanisms are elucidated.The turbidity of mine water is reduced from 77.43 NTU to 11.41 NTU by gangue, with a total removal rate of 85.26%, which is nearly 20 percentage points higher than that of natural sedimentation. A higher initial concentration of suspended solids results in a faster initial removal rate, and 750 mg/L is identified as the optimal purification concentration. The main removal process is completed within 15 minutes, and an increase in settling height significantly enhances the purification effect. Suspended solids are removed through the synergistic actions of physical interception, gravitational sedimentation, and surface adsorption by gangue. Coarse particles of 150–180 μm are effectively intercepted, while most residual particles are smaller than 60 μm.The regulatory patterns of gangue particle size gradation, hydraulic retention time, and settling conditions on suspended solids sedimentation efficiency are clarified. A theoretical basis and technical support are thereby provided for the structural optimization of mined-out areas in underground coal mine reservoirs and the in-situ, low-cost purification of mine water.

Keywords: Coal mine underground reservoir; Coal gangue; Mine water; Suspended solids; Dynamic circulation test; Purification mechanism

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1Introduction

According to data from the National Bureau of Statistics, China's raw coal output reached 4.83 billion tonnes in 2025, a year-on-year increase of 1.2%, demonstrating robust energy supply security (Anonymous 2026). However, the issue of mine water generated as a byproduct of coal mining is becoming increasingly severe. The annual volume of mine water generated nationwide is approximately 9.66 billion tonnes, and there is a pronounced inverse distribution between major coal-producing regions and water resources: western China accounts for 70% of the nation's coal reserves but only 4.6% of its water resources(Anonymous 2026). Direct discharge of mine water not only causes environmental pollution but also exacerbates resource constraints in these already water-scarce western regions. Furthermore, coal mining processes generate various types of mine water characterized by high suspended solids, acidity, high salinity, elevated sulfate levels, and fluoride content, making it complex in composition and difficult to treat(Xu et al. 2026). Therefore, exploring technologies for the beneficial reuse of mine water is of great significance for achieving green coal development and regional sustainable development.

In addition, coal mining generates substantial quantities of coal gangue. Characterized by low carbon content, high hardness, and low calorific value, coal gangue is difficult to utilize comprehensively; consequently, it is predominantly stockpiled in open air or discarded nearby, having already encroached upon over 10,000 mu of arable land(Cui et al. 2025). Current utilization strategies for coal gangue and mine water primarily rely on targeted treatments based on their specific properties: for instance, extracting valuable components from coal gangue or repurposing it as construction material, while different types of mine water require complex purification and filtration processes(Gao et al. 2024; Cui et al. 2025; He et al. 2024; Li et al. 2021).

To address the aforementioned challenges, Gu Dazhao et al. (Cun et al. 2021; Gu 2015; Gu et al. 2021a; Gu et al. 2021b) proposed the technology of underground reservoirs in coal mines in 2015, offering an innovative approach to mine water management. This technology utilizes collapsed rock masses in mined-out areas to construct a high-porosity "rock accumulation filter." Driven by gravity, mine water containing suspended solids flows through the pore spaces of the rock strata, achieving purification through synergistic mechanisms including filtration, adsorption, and sedimentation(Fang et al. 2022). Successfully applied in the Shendong Mining Area, this technology has resulted in the construction of 35 underground reservoirs, supplying over 95% of the mining area’s total annual water demand. It has not only effectively alleviated water scarcity in this 200-million-tonne-scale coal base but also served as a model for green coal mining by storing water to sustain local ecosystems. Existing studies have demonstrated that underground reservoirs significantly remove suspended solids, organic matter, and heavy metal ions: Jiang Binbin et al. (Jiang et al. 2022; Jiang et al. 2023; Jiang 2023; Jiang et al. 2024; Jiang et al. 2023; Jiang et al. 2020) monitored that when influent suspended solid concentrations ranged from 560 to 2,500 mg/L, effluent turbidity was reduced to 114-182 NTU, with removal rates reaching up to 93%; Han Jiaming et al.(Han et al. 2020) confirmed that rock masses in mined-out areas can effectively reduce dissolved organic matter (DOM) concentrations; and Yu Yan et al.(Yu et al. 2018), using three-dimensional excitation-emission

matrix fluorescence spectroscopy to analyze TOC and UV_{254} in both influent and effluent, found that this technology also exhibits strong performance in removing organic compounds from mine water.

Although the purification efficacy of underground reservoirs has been widely validated, the underlying water–rock interaction mechanisms—the core medium of this technology—require further investigation. Existing studies have predominantly focused on macroscopic purification performance, while insufficient attention has been paid to the relationship between coal gangue characteristics and suspended solids removal efficiency. In fact, as the primary accumulation material in mined-out areas, coal gangue's particle size distribution directly governs pore structure, flow pathways, and pollutant retention capacity. Dynamic leaching experiments by Yao Qiangling(Yao et al. 2024; Yao et al. 2020) demonstrated that smaller gangue particle sizes yield superior adsorption of ions such as Ca^{2+} and Mn^{2+}; Li et al.(Li and Wang 2019) similarly found a negative correlation between gangue particle size and the removal rate of high-salinity ions; and Guo et al. (Guo et al. 2021) and reported that modifying natural gangue with NaOH, NaCl, and HCl enables low-cost treatment of acidic mine water. Through batch adsorption experiments using mined-out area gangue, Zhao(Zhao et al. 2025) investigated the effects of initial Ca^{2+} concentration, contact time, pH, temperature, and particle size on Ca^{2+} removal, thereby deepening the understanding of gangue-based water purification mechanisms. This work provides a theoretical basis for the application of underground reservoirs in coal mines and offers a novel technical approach to mitigating membrane scaling caused by Ca^{2+} during mine water treatment. Furthermore, Tan Yingming(Tan 2017) examined the adsorption and desorption characteristics of heavy metal ions across different lithologies, including silty mudstone, sandy mudstone, and fine sandstone; Zhao Li et al.(Zhao et al. 2018) studied the removal of organic matter and ammonia nitrogen from mine water by coal gangue, identifying illite and kaolinite as key mineral components responsible for ammonia nitrogen adsorption; and Zhu et al.(Zhu et al. 2023) found that coal gangue can stabilize the pH of mine water within the range of 7.5–8.5 under varying initial pH conditions. Under both acidic and alkaline environments, increased porosity enhances the adsorption capacity of coal gangue, with adsorption rates ranging from 3% to 5%. Calcium ion reduction rates reached 75% under static leaching conditions and 70% under dynamic leaching conditions, with medium-grained coarse sandstone exhibiting stronger adsorption capacity than argillaceous siltstone. Nevertheless, for mine water with high suspended solids, given fixed gangue particle size and composition, the filtration mechanisms and long-term purification stability remain unclear, hindering further improvement in the purification efficiency of underground reservoirs.

To this end, this study designed a simulated underground reservoir experimental apparatus filled with coal gangue to systematically investigate the sedimentation behavior of suspended solids in mine water under gangue-filled conditions. Specifically, it examines the variation patterns of turbidity in high-concentration mine water under different initial suspended solid concentrations, settling times, and settling distances, and elucidates the purification mechanisms by which coal gangue removes suspended solids. The findings aim to provide a theoretical basis for optimizing the design of mined-out areas in underground reservoirs and enhancing the utilization efficiency of mine water as a resource, thereby supporting coal mining regions in achieving green development goals centered on "treating pollution with waste and promoting resource recycling."

2 Materials and Methods

2.1Materials and Equipment

2.1.1Experimental Materials

Coal gangue samples were collected from the Daliuta Mining Area. Suspended solids used in the experiments were derived from mine water sourced from the same mining area; they were obtained through collection, filtration, and drying, and subsequently employed to prepare simulated mine water at varying concentrations for the experimental tests.

2.1.2 Experimental Methods

An LS320 laser particle size analyzer was employed to determine the changes in particle size distribution of suspended solids before and after dynamic circulation of the mine water. A WZS-188E turbidimeter was used to measure the turbidity of water samples before and after the experiments to evaluate the removal efficiency of suspended solids. The surface morphology evolution of the coal gangue particles before and after the tests was observed using a ZEISS Sigma 360 field-emission scanning electron microscope (SEM). Additionally, an XRD-7000S X-ray diffractometer (XRD) was utilized to analyze the primary mineral compositions of both the coal gangue and the suspended solids in the mine water.

2.2Experimental Design

2.2.1Construction of the Dynamic Circulation Apparatus for Mine Water

Based on the actual engineering scale of goaf areas in coal mine underground reservoirs, and following the similarity principle as well as relevant literature [6, 7], a scaled-down laboratory simulation apparatus was independently designed and constructed for this study. The main body of the apparatus consists of four plexiglass tanks connected in series, each measuring 60 cm in length, 10 cm in width, and 30 cm in height. The overall dimensions of the assembled system are 240 cm × 40 cm × 30 cm, which is intended to simulate a coal mine underground reservoir system composed of multiple interconnected goaf areas.

The experimental apparatus primarily comprises three components: a simulated roadway system, a peristaltic pump, and a mechanical stirrer. To prevent coal gangue particles from clogging the tubing of the peristaltic pump during circulation, a protective metal mesh with an aperture size of 0.5 mm was installed at the outlet of the device. The structural configuration of the simulation apparatus is illustrated in Fig. 1.

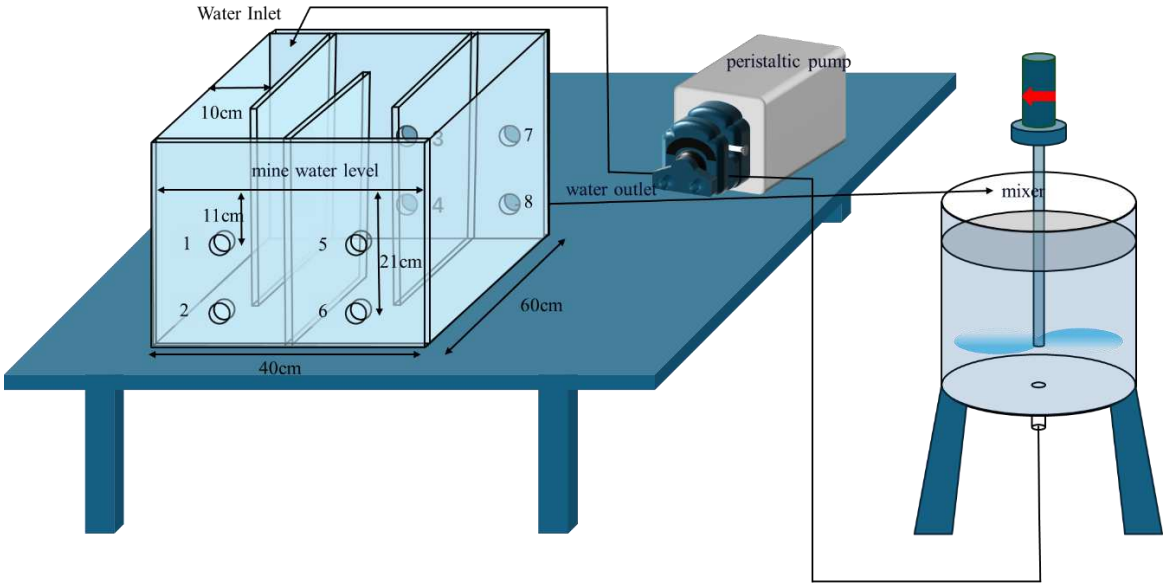


Fig.1 Mine water dynamic circulation system

2.2.2 Arrangement of Sampling Points

Along the flow direction of the apparatus, sampling cross-sections were established at distances of 60, 120, 160, and 240 cm from the inlet. At each cross-section, two sampling points were positioned at depths of 11 cm and 21 cm below the water surface, resulting in a total of eight sampling ports. The specific numbering of these ports is shown in Fig. 1.

2.2.3 Preparation of Simulated Mine Water

Suspended solids derived from mine water in the Daliuta mining area were collected, filtered, and dried. Different masses of these solids were then added to 40 L of tap water to prepare simulated mine water with five distinct concentration gradients: 250, 500, 750, 1000, and 1250 mg/L.

2.2.4Preparation of Coal Gangue Backfill Samples

Bulk coal gangue collected from the Daliuta mining area was crushed and sieved to prepare samples in five particle size fractions: 50–25, 25–13, 13–6, 6–3, and 3–0.5 mm. The coal gangue in the simulation apparatus was packed according to the gradation proportions listed in Table 1.

Table 1 Coal gangue particle size gradation and filling mass

size fraction/mm	50-25	25-13	13-6	6-3	3-0.5
Average Particle Size /mm	37.5	19	9.5	4.5	1.75
Proportion	15	5	22	18	40
Mass/kg	10.08	3.36	14.78	12.10	26.88

2.2.5 Dynamic Circulation Experiment of Mine Water

(1) The prepared simulated mine water of varying concentrations was rapidly injected into the experimental apparatus until the water level reached a height of 26 cm. A peristaltic pump was then activated at a rotational speed of 210 r/min to establish dynamic circulation within the system.

(2) At Sampling Port No. 8 (located at the 240 cm mark and 5 cm below the water surface), 10 mL water samples were collected at 5, 10, 15, 20, 30, 40, 50, 60, and 70 min after the initiation of circulation. Turbidity was measured to analyze its temporal variation during the circulation process.

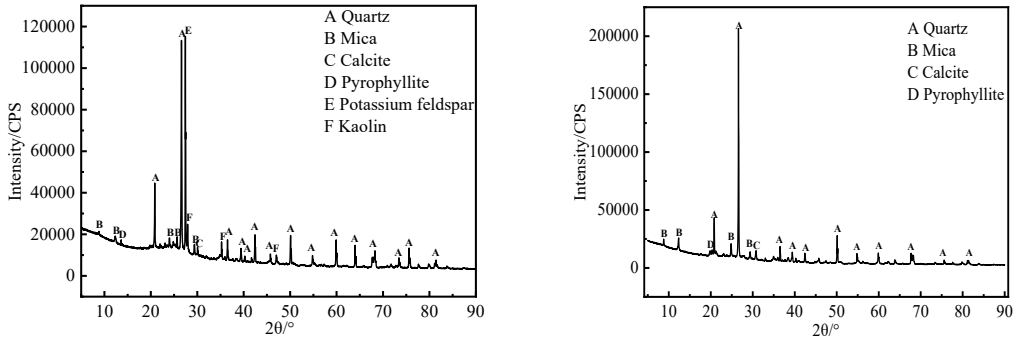
(3) Once the turbidity at Sampling Port No. 8 stabilized, water samples were collected to determine the particle size distribution of the suspended solids.

To evaluate the effect of coal gangue backfill on suspended solid sedimentation, a control group without gangue backfill was established under identical operating conditions to observe the natural settling behavior of suspended solids in the mine water.

3Analysis of Results from Dynamic Circulation Simulation Experiments of Mine Water

3.1Analysis of Suspended Solids in Mine Water and Coal Gangue Composition

The material composition of the collected mine water suspended solids and coal gangue was analyzed, with the results presented in Fig. 2.



(a) (b)

Fig.2 XRD phase composition analysis (a) Mine water suspended solids (b) Coal gangue

Fig. 2(a) presents the XRD pattern of the suspended solids in mine water. As shown, the strongest diffraction peak appears at $2\theta \approx 26°$, corresponding to the primary characteristic peak of quartz. Diffraction peaks in the 2θ range of 10°–20° are attributed to mica, kaolinite, and pyrophyllite, while those near 28°–30° correspond to the characteristic peaks of calcite and K-feldspar. Overall, quartz is the dominant mineral in the suspended solids, accompanied by calcite, mica, K-feldspar, kaolinite, and pyrophyllite, indicating a complex mineralogical composition.

Fig. 2(b) shows the XRD pattern of the coal gangue sample. The results indicate that the strong diffraction peak at $2\theta \approx 26.6°$ is also characteristic of quartz. Diffraction peaks at $2\theta \approx 10°$, 25°, and 28° are attributed to mica; the peak at $2\theta \approx 20°$ corresponds to pyrophyllite; and the peak at $2\theta \approx 29.5°$ is identified as calcite. These findings demonstrate that quartz is the primary mineral constituent of the coal gangue, with mica, calcite, and pyrophyllite present as secondary minerals.

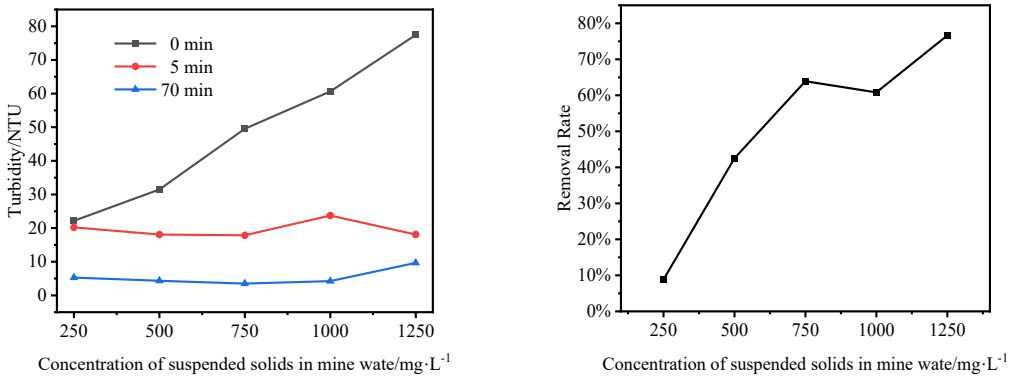
Based on the comprehensive XRD phase analysis, the suspended solids in mine water and coal gangue exhibit similar mineralogical compositions, both being dominated by quartz and enriched in mica, with associated calcite and pyrophyllite. From the perspective of mineral functionality, the layered structures of mica and pyrophyllite, possessing lattice charges and interlayer pores, can

provide sites for ion exchange and physical adsorption. Quartz, as the primary framework mineral, facilitates the construction of a porous structure, thereby optimizing flow channels and particle interception pathways. Furthermore, calcite may undergo dissolution under weakly acidic conditions, further enhancing interfacial adsorption effects. These mineralogical characteristics indicate that the coal gangue inherently possesses synergistic purification capabilities involving physical filtration, ion exchange, and composite adsorption, suggesting its potential as an in-situ adsorptive filter medium for purifying suspended solids in underground coal mine reservoirs.

3.2Effect of Coal Gangue Accumulation on Water Quality in Simulated Goaf Underground Reservoirs

3.2.1Removal Patterns of Suspended Solids at Different Influent Concentrations

Fig. 3(a) illustrates the temporal variation of mine water turbidity at a fixed sampling point (Sampling Port No. 8) during dynamic circulation tests conducted under different initial suspended solid concentrations.



（a） （b）

Fig.3 Relationship between turbidity and time at different mine water concentrations (a) Variation pattern of mine water turbidity under different suspended solids concentrations (b) Turbidity change rate during the first 5 minutes under different suspended solids concentrations

Fig. 3(a) depicts the variation of effluent turbidity with circulation time under different initial suspended solid concentrations. Overall, higher influent suspended solid concentrations correspond to greater initial turbidity. Given identical coal gangue filling gradation and packing conditions, the purification of mine water with high suspended solid concentrations becomes significantly more challenging, resulting in correspondingly higher effluent turbidity after treatment.

As indicated by the turbidity change rate in Fig. 3(b), when the suspended solid concentration of mine water ranges from 250 to 1000 mg/L, the rate of turbidity reduction gradually slows with prolonged circulation time. After 70 min of circulation, the effluent turbidity across all concentration groups converges to similar levels. This is likely attributed to the fact that, under fixed coal gangue filling volume and gradation, the number of suspended particles increases with higher initial concentrations. Consequently, the physical interception capacity of internal pores and surface adsorption sites within the coal gangue accumulation gradually approach saturation, leading to a progressive decline in turbidity removal efficiency per unit time and ultimately narrowing the differences in effluent turbidity among different concentration groups. However, when the initial concentration increases to 1250 mg/L, the effluent turbidity after 70 min of circulation remains

significantly higher than that of other groups, suggesting that this concentration may have exceeded the effective purification threshold of the coal gangue under the current filling conditions.

The removal efficiency of coal gangue for suspended solids in mine water is evaluated using the turbidity change rate, denoted as *C*. Let *B* represent the turbidity at time *t*, and *A* represent the turbidity at the previous time step. The turbidity change rate *C* is defined as:

$$C = \frac{A-B}{A} \times 100\% \quad (1)$$

Under all tested concentration conditions, the mine water turbidity exhibited a characteristic trend of "rapid decline in the initial stage followed by a gradual plateau in the later stage," with the reduction being particularly pronounced within the first 5 minutes. To quantify the purification efficiency during this initial phase, the turbidity change rate at 5 min of circulation was adopted as the evaluation index. The results under different initial concentrations are presented in Fig. 3(b).

As shown in Fig. 3(b), with the increase in the initial suspended solid concentration of mine water, the turbidity change rate within the first 5 min exhibits a continuous upward trend. At an initial concentration of 250 mg/L, the turbidity change rate is only 8.80%; as the concentration increases, the rate rises rapidly, reaching a maximum value of 76.66% at 1250 mg/L. This indicates that high-concentration suspended solids possess greater potential for turbidity reduction during the initial stage of circulation, and the physical interception and adsorption effects of the coal gangue filling layer are fully exerted during this period.

Notably, although the 1250 mg/L group exhibited the highest turbidity change rate during the initial stage, its effluent turbidity remained significantly higher than that of other concentration groups after 70 min of circulation when a relatively stable state was reached (Fig. 3(a)). This suggests that this concentration may have exceeded the effective treatment range of the coal gangue purification capacity under the current filling conditions. Considering that the interaction between suspended solids and coal gangue is more intensive under high-concentration conditions, which is more conducive to elucidating the purification mechanisms and saturation behavior of the coal gangue filling layer, 1250 mg/L was selected as the experimental concentration for subsequent tests.

3.2.2 Effect of Settling Time on Mine Water Turbidity

Taking the mine water with a suspended solid concentration of 1250 mg/L as an example, the effect of different settling times on the treatment efficiency was analyzed, and the results are shown in Fig. 4.

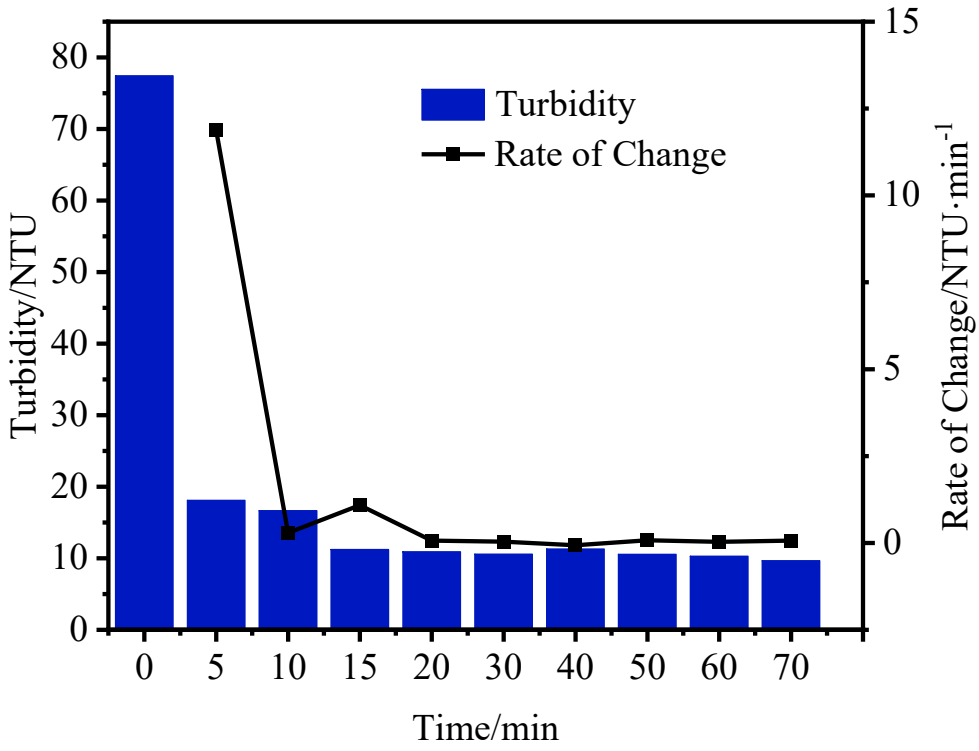


Fig.4 Variation of turbidity and turbidity change rate over time for 1250 mg/L mine water

The efficiency of the coal gangue's effect on mine water turbidity is evaluated using the turbidity change rate, D. The turbidity change rate D (NTU/min) is defined as follows: let n be the turbidity at time t, and N be the turbidity at the previous time point T; then the turbidity change rate D is calculated as:

$$D = \frac{N-n}{T-t} \qquad (2)$$

As shown in Fig. 4, the turbidity of the mine water decreased significantly within the first 0–10 min, dropping from 77.43 NTU to 11.21 NTU, with a turbidity change rate reaching 85.52%. After 20 min, the turbidity stabilized at approximately 10 NTU, achieving an overall reduction of 87% compared to the initial value. In the dynamic water circulation system, the turbidity declined rapidly before leveling off. Furthermore, it is evident from Fig. 4 that as the circulation time increased, the turbidity change rate approached zero, suggesting that the removal capacity of the coal gangue for mine water at this concentration had nearly reached saturation.

3.2.3 Effect of Settling Height on Mine Water Turbidity

To investigate the effect of coal gangue accumulation height on the purification efficiency of suspended solids in mine water, sampling points were established at various settling heights within the apparatus to analyze the variation pattern of turbidity with respect to settling height. The results are presented in Fig. 5.

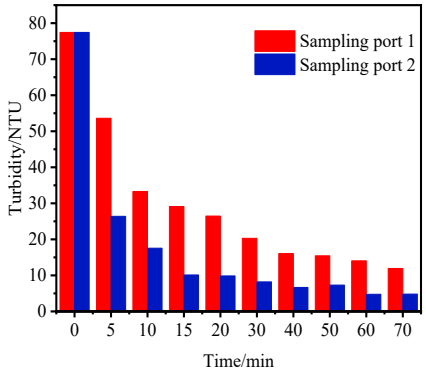
The apparatus was equipped with eight sampling ports, among which the odd-numbered ports (1, 3, 5, and 7) were located at a settling height of 11 cm from the liquid surface, while the even-numbered ports (2, 4, 6, and 8) were positioned at a settling height of 21 cm. As illustrated in Fig.

5, at the same cross-section, the turbidity measured at most odd-numbered sampling ports was higher than that at the corresponding even-numbered ports. This indicates that a greater settling height facilitates both the gravitational settling of suspended solids and their interception by the coal gangue layer. Taking sampling ports 1 and 2 in Fig. 5(a) as an example, the turbidity at port 1 (settling height of 11 cm) was significantly higher than that at port 2 (settling height of 21 cm), which is consistent with the aforementioned trend.

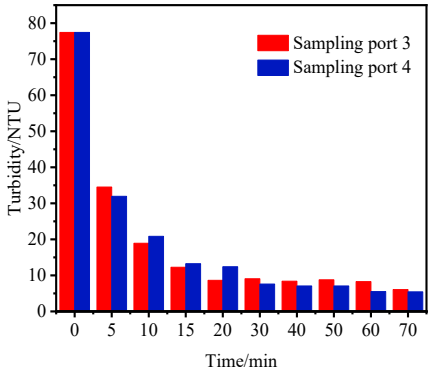
Notably, the turbidity variation patterns at sampling ports 3 and 4 during the initial stage of circulation were contrary to the overall trend described above. This anomaly is hypothesized to result from local heterogeneity in the coal gangue accumulation morphology, which likely caused differences in flow paths and pore distribution during the early phase. However, as circulation time increased, the combined effects of hydraulic scouring and the gradual filling of pores by suspended particles led to a convergence in turbidity trends between ports 3 and 4. Eventually, the pattern reverted to the general rule wherein greater settling height corresponds to lower turbidity.

Furthermore, the turbidity at sampling port 7 (settling height of 11 cm, located near the outlet) was slightly higher than the initial value after 5 min of circulation. This is attributed to significant local flow disturbance near the discharge end, which likely transported and accumulated suspended particles that had not yet settled. After 5 min, however, the turbidity at this port decreased rapidly and stabilized from 40 min onward, with the effluent turbidity maintained at approximately 10 NTU. In contrast, although sampling port 8 was also situated near the outlet, its greater settling height (21 cm) allowed the turbidity to reach a stable level earlier, essentially stabilizing after 15 min, with a steady-state turbidity similarly around 10 NTU.

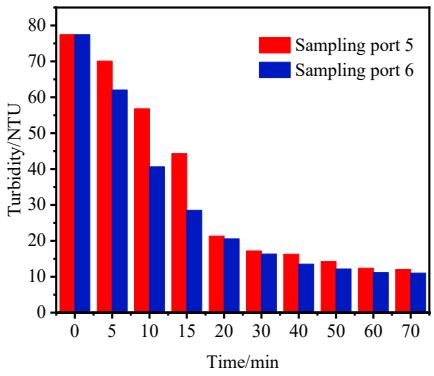
In summary, under identical circulation durations, settling height exerts a significant influence on the removal efficiency of suspended solids in mine water, with greater settling heights facilitating a more rapid reduction in turbidity. However, as circulation time extends and the system approaches equilibrium, the effluent turbidity at different settling heights converges to essentially comparable levels.

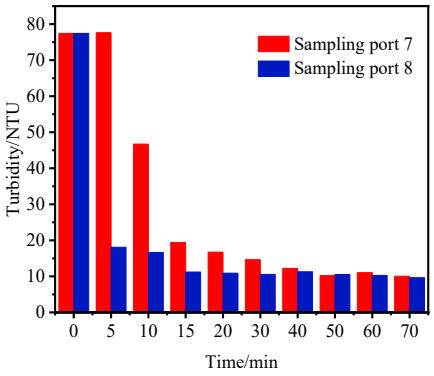


(a)



(b)





(c) (d)

Fig.5 (a) Sampling ports 1 and 2(b) Sampling ports 3 and 4(c) Sampling ports 5 and 6(d) Sampling ports 7 and 8 Relationship between mine water turbidity and height

3.3Discussion

3.3.1Effect of Coal Gangue Accumulation on Suspended Solids Removal Efficiency in Mine Water

To investigate the effect of coal gangue on the removal efficiency of suspended solids in mine water, a comparative experiment without coal gangue filling was conducted. The test results from sampling port 8 at various settling times, using mine water with an initial concentration of 1250 mg/L, are compared and illustrated in Fig. 6.

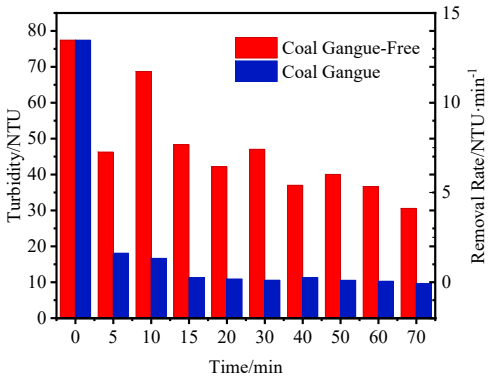


Fig.6 Comparison between conditions with and without coal gangue

To clarify the contribution of the coal gangue filling layer to the purification of suspended solids in mine water, comparative experiments with and without coal gangue filling were conducted under identical operating conditions. The results are presented in Fig. 6.

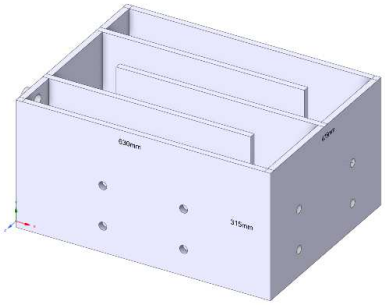
As shown in Fig. 6, with coal gangue filling, the turbidity of mine water decreased sharply within the first 5 min of circulation and essentially stabilized after 10 min, demonstrating rapid and efficient purification. In contrast, without coal gangue filling, the turbidity exhibited significant fluctuations throughout the circulation process. This instability is attributed to continuous flow disturbance within the apparatus in the absence of a filling medium; suspended particles continuously entering the sampling zone interfered with turbidity measurements, resulting in an erratic decline. After 50 min of circulation, the turbidity in the blank control group showed only a slight reduction from the initial concentration due to the combined effects of gravitational settling

and flow-induced particle transport, stabilizing at approximately 30 NTU, corresponding to a removal efficiency of about 66.02%.

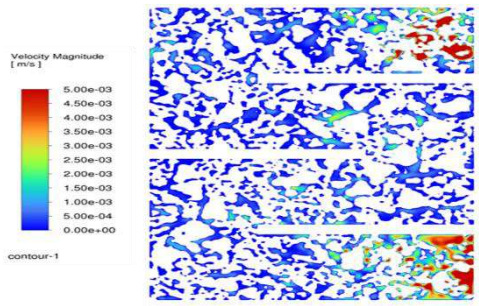
A comparison of the two experimental results reveals that without coal gangue filling, mine water purification relies solely on gravitational settling, resulting in low efficiency and an unstable process. In contrast, with coal gangue filling, the rate of turbidity reduction is significantly enhanced, yielding lower effluent turbidity and greater stability. These findings demonstrate that the coal gangue filling layer effectively accelerates the settling and removal of suspended solids in mine water, indicating its significant potential for in-situ purification within underground coal mine reservoirs.

3.3.2Influence of Flow Field Characteristics in the Simulated Experimental Apparatus on the Settling Process

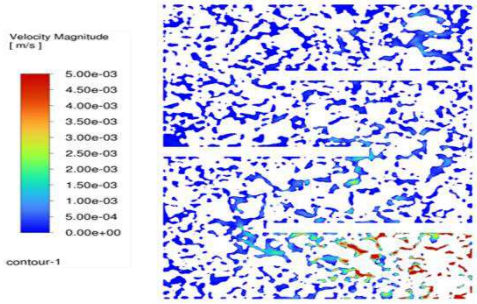
To investigate the influence of flow field characteristics on the settling process, a custom-built fluid tank model was developed, and ANSYS CFD-Post software was employed to simulate mine water flow within the apparatus. The numerical model adopted is illustrated in Fig. 7(a). Random spherical particles, with properties similar to those of coal gangue, were introduced into the model as filling media. The resulting flow field contour maps of the apparatus are presented in Fig. 7(b) and (c).



（a） Equipment Drawing (Including Wall Thickness)



（b） Top view of the flow field contour map at sampling port 7 of the experimental setup



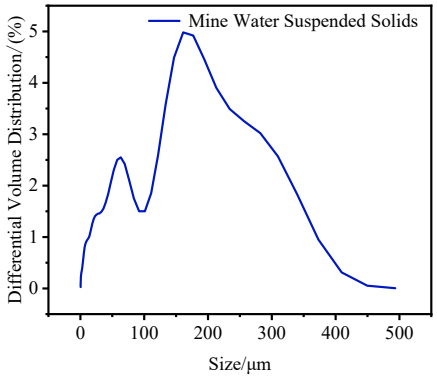
（c） Top view of the flow field contour map at sampling port 8 of the experimental setup

Fig.7 Simulation test setup and its simulated flow field contour plot

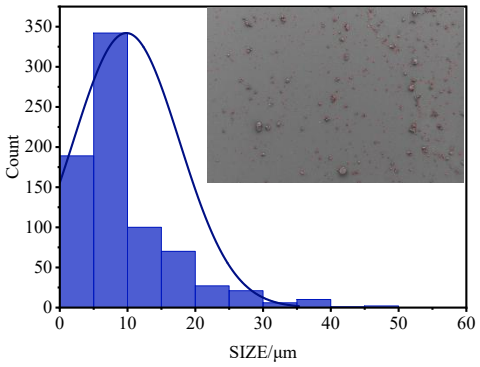
Fig. 7(b) and (c) present the overall flow field contour maps of the experimental apparatus model. The mine water exhibits high flow velocities at both the inlet and outlet, with particularly rapid flow observed in the upper liquid layer. This fast-moving water entrains fine suspended particles, thereby influencing the turbidity variations observed at sampling ports No. 7 and No. 8, as shown in Fig. 5(d). Specifically, the turbidity at sampling port No. 7, located near the outlet, remains relatively high due to the strong flow carrying suspended solids. In contrast, sampling port No. 8 benefits from a greater settling height; here, the coal gangue medium effectively intercepts and adsorbs suspended particles, which, combined with gravitational settling, results in significantly lower turbidity at this location.

3.3.3Effect of the Simulated Experiment on Particle Size Distribution of Suspended Solids in Mine Water

To investigate the effect of coal gangue on suspended particles in mine water, particle size analysis of the raw mine water sample was conducted prior to the experiment using a laser particle size analyzer, with results shown in Fig. 8(a). After the experiment, the collected mine water was filtered, and the retained particles were examined via scanning electron microscopy (SEM); particle sizes were manually annotated and statistically analyzed, as presented in Fig. 8(b).



(a)



(b)

Fig.8 Particle size distribution of suspended solids (a) pre-test mine water (b) post-test mine water

As illustrated by the particle size distribution characteristics in Fig. 8(a), the sample exhibits a

distinct bimodal distribution pattern. The dominant particle size fraction ranges from 150 to 180 μm, followed by a secondary peak at 60–80 μm, indicating a broad overall particle size range.

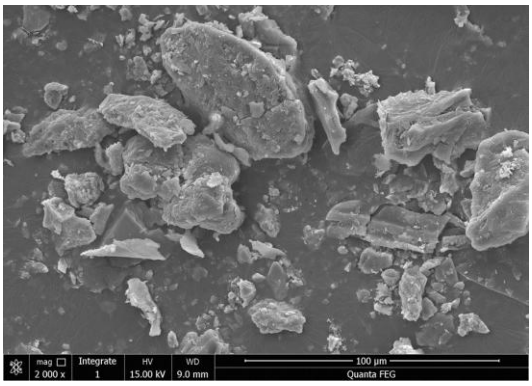
Fig. 8(b) shows the particle size distribution of the sample collected at sampling port No. 8 at 70 min, with particle diameters measured and annotated using ImageJ; the red-labeled particles represent the suspended solids retained after the experiment. The results indicate that the residual suspended particles in the mine water are sparse and predominantly fine-grained, with most particles concentrated around 10 μm. The largest detected particle measures approximately 66.107 μm, confirming significant particle removal and size reduction—likely attributable to interception, adsorption, and gravitational settling by the coal gangue medium.

As evidenced by the comparison between Fig. 8(a) and 8(b), the particle size of suspended solids in mine water is significantly reduced following treatment with coal gangue backfill. Compared to the original particle size distribution, the dominant coarse fraction (150–180 μm) is completely absent in the treated effluent. This suggests that these coarse particles are readily retained by the interstitial voids formed within the coal gangue accumulation and the surface pores of the gangue itself, demonstrating excellent physical interception efficiency for larger particles.

Regarding the 60–80 μm fraction, only trace amounts remain, indicating a slight decrease in retention efficiency for this size range. However, for particles smaller than 60 μm—and particularly ultrafine particles—the removal performance relying solely on mechanical interception or adsorption by coal gangue is considerably weaker. To effectively reduce these micro-fine particles, it is necessary to employ deep-bed filtration or pre-flocculation to promote particle agglomeration and increase effective particle size, thereby enhancing overall removal efficiency.

3.3.4 Adsorption of Mine Water Contaminants onto Coal Gangue: The Role of Surface Morphology

Scanning electron microscopy (SEM) characterization was performed on the coal gangue prior to the experiment, as shown in Fig. 9(a). Following the experiment, the sample was characterized again, with the results presented in Fig. 9(b), allowing for a comparative analysis of the surface morphology before and after treatment.



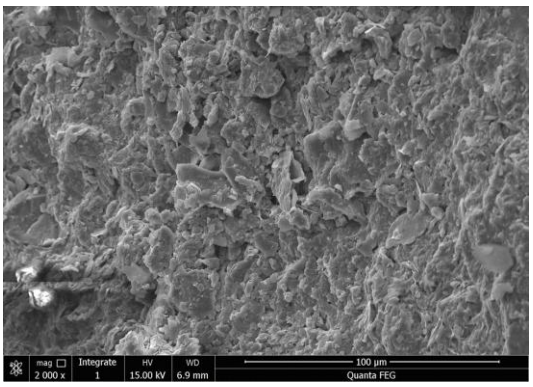


Fig.9 Surface morphology of coal gangue (a) pre-test (b) post-test

As shown in Fig. 9, the coal gangue surface exhibited relatively few attached substances prior to the experiment. In contrast, after treatment, a substantial amount of suspended particles was observed adhering to the gangue surface, resulting in significantly increased surface roughness. Combined with material analysis of both the coal gangue and mine water suspended solids, kaolinite-type clay minerals were identified in both samples. These minerals possess inherent adsorption capacity, which facilitates the adhesion of suspended particles from the mine water onto the coal gangue surface.

4 Conclusions

(1) Coal gangue backfill demonstrates a significant purification effect on suspended solids in mine water. Under dynamic circulation conditions, turbidity decreased from 77.43 NTU to 11.41 NTU, achieving a removal rate of 85.26%. This represents an improvement of nearly 20 percentage points compared to the 66.02% removal observed without gangue backfill, indicating significantly superior stability and efficiency over natural sedimentation.

(2) The removal pattern of suspended solids is jointly influenced by the initial concentration of mine water, settling time, and settling height. Higher initial concentrations result in more pronounced rapid removal during the early stage; when the mine water concentration ranges from 750 to 1000 mg/L, the turbidity reduction rate with gangue backfill essentially reaches saturation. Turbidity decreases significantly with extended settling time and increased settling height, with the majority of removal accomplished within 15 minutes and stable deep purification achieved at a height of 21 cm.

(3) The coal gangue accumulation achieves purification through the synergistic mechanisms of physical interception, gravitational sedimentation, and surface adsorption.

(4) For operational control, a hydraulic retention time of 15–20 minutes is recommended as the baseline to achieve efficient and stable removal of suspended solids, providing theoretical and technical support for low-cost in-situ purification in underground mines.

CRediT authorship contribution statement

Binbin Jiang: Writing - review & editing, Writing - original draft, Supervision, Project administration, Funding acquisition. **Bo Hu**: Writing - original draft, Investigation, Data curation,Conceptualization. **Zhao Zhao**: Writing - original draft, Conceptualization. **Yuexian Yu**: Writing - review & editing. **Lijun Liu**: Writing - review & editing, Supervision. **Wei Yu**: Writing - review & editing. **Haiqin Zhang**:Writing - review & editing. **Jingwei Hao**: Writing - review

&editing.**Yutian Hu**: Writing - review &editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data will be made available on request

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