Experimental Study on the Damage Mechanism of Coal Pillars in Abandoned Mines under Immersion Conditions

Xu, Zhimin[1,2]; Yuan, Huiqing[1]; Lu, Weining[1,3]; Han, Yuhang[1]; Xiong, Shijie[1]

[1]*China University of Mining and Technology, School of Resources and Geosciences, Xuzhou 221116, China.*

[2]*Fundamental Research Laboratory for Mine Water Hazards Prevention and Controlling Technology, Xuzhou 221116, China.*

[3]*China Railway Liuyuan Group Co., Ltd., Tianjin 300308, China.*

Abstract

Coal mining often leaves large abandoned spaces where acidic mine water accumulates, threatening the stability of boundary coal pillars. Rising water levels and corrosive mine water can severely weaken these pillars, risking water inrush disasters. Understanding the damage mechanisms is crucial for enhancing mine safety and preventing environmental hazards. This study assesses the long-term effects of immersion on coal pillar strength, with implications for mine safety and water management.

A new high-pressure mine water-rock coupling test device simulated immersion conditions under varying pressures and solutions. The study introduced the "damage coefficient" to quantify the reduction in compressive and tensile strength of coal pillars due to prolonged immersion. CT scanning provided insights into internal structural changes, such as crack expansion and mineral dissolution.

Results show that after 150 days of immersion in synthetic acidic solutions, the tensile strength of coal samples was most affected, with a damage coefficient of 0.775. CT scans revealed significant crack growth and dissolution of minerals like calcite and feldspar, further weakening the pillars. These findings highlight the substantial impact of prolonged immersion in corrosive solutions on coal pillar strength and stability.

The results are important for designing and evaluating water-proof coal pillars in abandoned mines, especially in reducing the risk of water inrush disasters. This work guides future efforts to protect both active and abandoned mines from water-related risks.

Keywords: Water-rock interaction, damage mechanism, damage coefficient, coal pillar stability, immersion test

Introduction

Abandoned mines can have a negative effect on regional groundwater systems and threaten adjacent operating mines with water inrush. Under high water flow pressure, the boundary coal pillars and waterproof walls between abandoned and operating mines suffer long-term damage from aggressive mine water(as shown in Fig. 1), severely affecting their mechanical stability and resistance to failure(Sun *et al.* 2020; Andrews *et al.* 2020). This leads to reduced water resistance of coal pillars and increased risk of water inrush accidents. Cases of water inrush from abandoned mines or old workings have shown that the water-coal (rock) interaction under high water flow pressure and the long-term influence of aggressive mine water can significantly weaken the mechanical properties of rocks. Under water-saturated conditions, the chemical dissolution and leaching of mineral components in coal (rock) intensify, intergranular bonding strength decreases, and stress corrosion accelerates the expansion of pores and growth of fractures. Although scholars have made achievements, research on the erosion and destruction of boundary coal rock pillars due to rising water levels in abandoned mine spaces, water flow conditions, and resulting water inrush disasters is relatively insufficient. The lack of quantitative studies has become the main reason for the frequent occurrence of such water-related accidents(Duan *et al.* 2012; Wu *et al.* 2022; Zhu *et al.* 2024). Existing research mostly focuses on theoretical analysis and numerical simulation, with insufficient study on the stability impact of actual coal rock bodies under long-term water immersion, especially in the damage evolution and deterioration mechanisms under aggressive water solutions(Chen *et al.* 2025).

This paper shows how we conducted simulated pressurized water immersion tests on coal and mine water samples from Mine A in the Xuzhou Mining District of the North China Carboniferous-Permian coalfield. Through laboratory analyses and theoretical analysis, we comprehensively analyzed the structural evolution and mechanical damage of coal samples under long-term water immersion and clarified the physicochemical mechanisms. This provides a theoretical basis and parameters for quantitatively evaluating water-induced "damage" to boundary water-proof coal pillars.

Sampling and Methods

Coal and mine water samples were collected from Mine A in the Xuzhou Mining District of the North China Carboniferous-Permian coalfield. A total of 350 kg of coal blocks were extracted from the main 9# coal seam. The samples were processed into standard cylindrical coal samples according to the ISRM standards(Ulusay 2015), with an end-face non-parallelism of less than 0.02 mm. Cylindrical coal samples with dimensions of Φ50×100 mm were used for uniaxial compression tests, and those with dimensions of Φ50 mm×25 mm were used for Brazilian splitting tests. A whole-rock analysis was conducted on the coal samples before soaking to determine their mineral composition. The main minerals in the initial coal samples were quartz (4.3%), albite (12.5%), muscovite (30.9%), kaolinite (24.5%), calcite (17%), gypsum (4.3%), and hematite (6.5%).

We sampled 350 L of water from the abandoned goaf area of Mine A, with the pH of the abandoned mine water measured at 5.8. To assess the erosive effects of acidic mine water, we prepared simulated mine water (pH = 3.0) and deionized water (pH = 7.0) as controls. Specimens were immersed for 150 days under two pressure conditions:

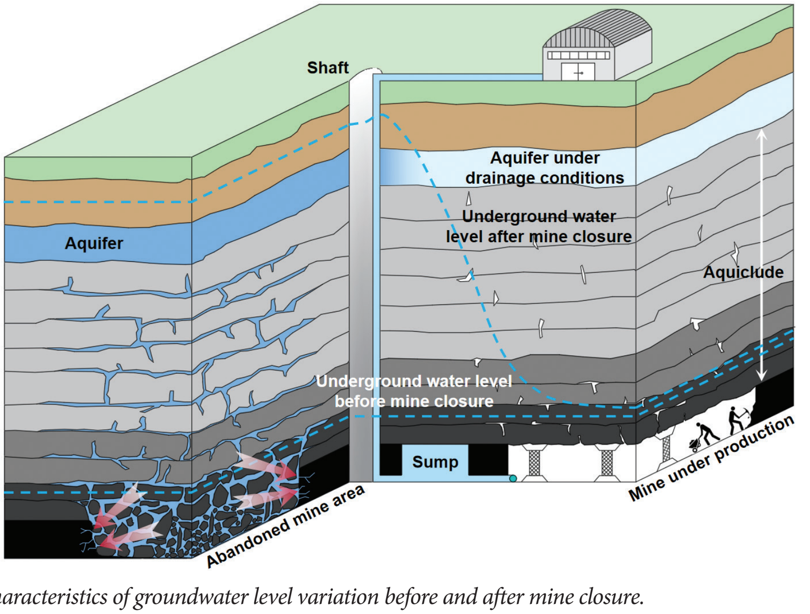

Figure 1 *Characteristics of groundwater level variation before and after mine closure.*

atmospheric pressure (0.1 MPa) and elevated pressure (0.8 MPa).

The experimental scheme, detailed in Table 1, included 74 groups. To assess the impact of water immersion on coal properties, we conducted uniaxial compression and Brazilian splitting tests on each group(Packulak *et al.* 2024). We analyzed the mineral composition of coal samples after different immersion durations and the changes in cations and anions in the soaking water.

Uniaxial compression and Brazilian splitting tests on coal samples were conducted using a high-pressure servo-compression system. In the uniaxial test, axial load was applied at 0.2 MPa/s until failure. In the Brazilian test, a linear load was applied at 0.05 MPa/s in the diameter direction until the sample fractured due to horizontal tension.

Before X-ray diffraction (XRD) analysis, coal samples were ashed and etched using a low-temperature plasma ashing instrument (LTA, Quorum K1050X) to oxidize organic matter. Mineral composition of the ashed samples was then analyzed using XRD (ThermoFisher ARL EQUINOX 3000). Jade 6.0 software was used for qualitative mineral identification, and the Rietveld method for quantitative analysis of mineral components. The pH of the soaking solution was measured using a pH30 meter.

Results and Discussion

CT scanning produced high-resolution 2D slice images of the coal samples in their original dry state and after 45 and 150 days of soaking in simulated mine water, as shown in Fig. 2. These slices were reconstructed into 3D models using VGSTUDIO MAX and AVIZO software, including detailed models of pores and fractures.

Fig. 3(a) shows that the number of pores and fractures in the coal samples increased over time, while the area, volume, and average size of individual pores and fractures initially increased and then decreased. In the acidic environment, the evolution of pore and fracture structure exhibited nonlinear characteristics, possibly due to substance dissolution and pore filling/reorganization. Compared with the initial samples, the porosity of the coal samples significantly increased from 0.25% to 1.2% after soaking in simulated mine water for 45 and 150 days. As the water-coal reaction continued, the pores inside the coal samples gradually transformed from fewer and larger to more and smaller. Although the porosity continued to increase, the rate of increase decreased with soaking time, indicating a slowdown in the water-coal reaction. The pores and fractures were categorized into 14 size ranges from less than 100 μm to greater than 5000 μm, with statistical parameters presented in Table 2. Overall, the coal samples were predominantly characterized by micro-pores with a diameter of less than 400 μm, accounting for over 95%, while the distribution of pores and fractures with a diameter greater than 3000 μm was minimal.

In the simulated mine water environment, as soaking time increased, porosity rose in initially low-porosity areas of the coal samples, while porosity in dense areas, especially the centers, changed little. Chemical reactions promoted new pore formation and expansion of existing small pores in loose areas, increasing porosity. This was seen as: (1) new pores and fractures

Table 1 *Table of preparation scheme of immersed coal sample.*

Immersion pressure MPa	Immersion solution pH	Immersion time of coal sample Day
0	3 (Simulated mine water)	5
		10
	5.8 (Abandoned mine water)	20
		45
0.8	7(Deionized water)	90
		150

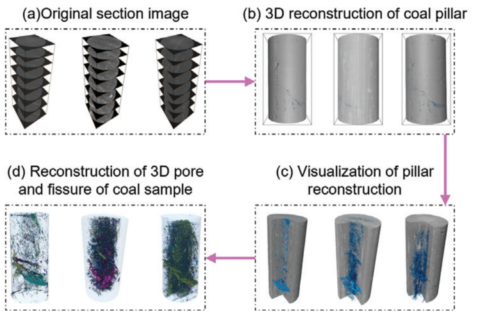

***Figure 2** Flowchart of 3D pore reconstruction using CT.*

forming, possibly due to mineral dissolution or organic matter decomposition; (2) irregular pore and fracture shapes, especially where acidic solution eroded unevenly; (3) more uneven pore distribution, with varying reaction involvement; (4) more complex pore and fracture structures, including more types; (5) increased specific surface area due to more pores and fractures, enhancing surface activity.

XRD results showed that the mineral composition of coal samples changed over time (Fig. 3b). From 0 to 150 days, the main minerals were quartz, albite, muscovite, kaolinite, calcite, gypsum, and hematite. In unsoaked samples, muscovite, kaolinite, and calcite were dominant, making up 72.4% of total content. As soaking time increased, their relative content dropped to 53.7%. After 150 days, albite, calcite, and hematite decreased from initial 12.5%, 17%, and 6.5% to 9.6%, 10.9%, and 4.9%, while quartz increased from 4.3% to 29.1%.

In the acidic solution, water-coal interaction was key to the initial increase in most mineral components. As soaking time increased, albite, calcite, and hematite content decreased, while quartz content rose. This was due to chemical reactions between these minerals and H+ ions in the solution, forming new substances and reducing their content. Quartz, being chemically stable, did not easily react with acid and generated additional SiO_2 during albite's reaction with H^+ ions, increasing its overall content.

***Table 3** Main mineral reaction equations during coal sample soaking.*

Mineral	Chemical equation
albite	$NaAlSi_3O_8 + 4H^+ = 3SiO_2 + 2H_2O + Al^{3+} + Na^+$
calcite	$CaCO_3 + 2H^+ = Ca^{2+} + H_2O + CO_2$
hematite	$Fe_2O_3 + 6H^+ = 2Fe^{3+} + 3H_2O$
kaolinite	$Al_4[Si_4O_{10}](OH)_4 + 4H_2O = Al_4[Si_4O_{10}](OH)_4 \cdot 4H_2O$

Clay minerals show more water absorption and swelling than other minerals when interacting with aqueous solutions(Ju *et al.* 2019). In this experiment, kaolinite exhibited significant water absorption and swelling, occurring more rapidly than new substance formation. This led to a notable impact of clay minerals in coal fractures early in soaking and increased their mineral content. The pH trends of the three soaking solutions from 0 to 150 days are shown in Fig. 3(c). pH values rose significantly initially as coal minerals reacted with H^+ ions, consuming them and causing the solution pH to increase rapidly. Over time, pH stabilized around 8.

Dry coal samples had a compressive strength of 27.21 MPa and tensile strength of 1.42 MPa. Mechanical properties decreased significantly with soaking time, especially in simulated mine water. After 150 days, compressive strength dropped by 69.9-72.9% and tensile strength by 70.4-77.5%. This shows that solution acidity, soaking time, and pressure all affect coal strength, with acidic water causing the most damage. Thus, we propose a "damage coefficient," defined as the ratio of the reduction in physical and mechanical parameters after soaking to dry state strength. As illustrated in Fig. 3(d) the growth rate of the damage

***Table 2** Distribution of pore fracture parameters in coal samples under different soaking duration.*

Diameter range µm	0d	45d Counts	150d
<400	106158	263718	500441
400–3000	5584	5380	20850
>3000	3	2	2

coefficient exhibits a progressive deceleration over time. The damage coefficient reaches its maximum in simulated mine water and minimum in deionized water, demonstrating significant environmental sensitivity. Pressurized soaking generally caused higher damage coefficients. As coal moisture neared saturation, the soaking effect transitioned to a water-coal coupling reaction stage. Aggressive solutions interacted physically and chemically with coal minerals, dissolving clay minerals and increasing porosity, leading to mechanical damage.

$$d = \frac{s_{dry} - s_i}{s_{dry}} \times 100\% \qquad (1)$$

Coal samples were soaked in three solutions for 5–150 days, with ion concentration trends shown in Fig. 3(e). Initially, most ions in abandoned mine water showed no significant change, likely due to coal adsorbing ions, indicating ion exchange capacity. In simulated mine water, high initial H^+ concentration caused frequent reactions between coal minerals and H+, rapidly increasing metal cation concentrations. Among the solutions, K^+, Na^+, Cl^-, and SO_4^{2-} concentrations initially decreased then increased, while Ca^{2+} and Mg^{2+} concentrations rose continuously. Coal samples, containing abundant albite and calcite, reacted with H^+, increasing Ca^{2+} and Na^+ concentrations. In deionized water, low initial H^+ concentration limited reactions, with Ca^{2+} and Na^+ increases mainly due to coal surface dissolution.

Water-induced damage to abandon mine coal pillars results from multiple factors. Aggressive water solutions with different pH values affect coal pores and fractures, directly influencing their development. Clay, feldspar, and carbonate minerals in coal react

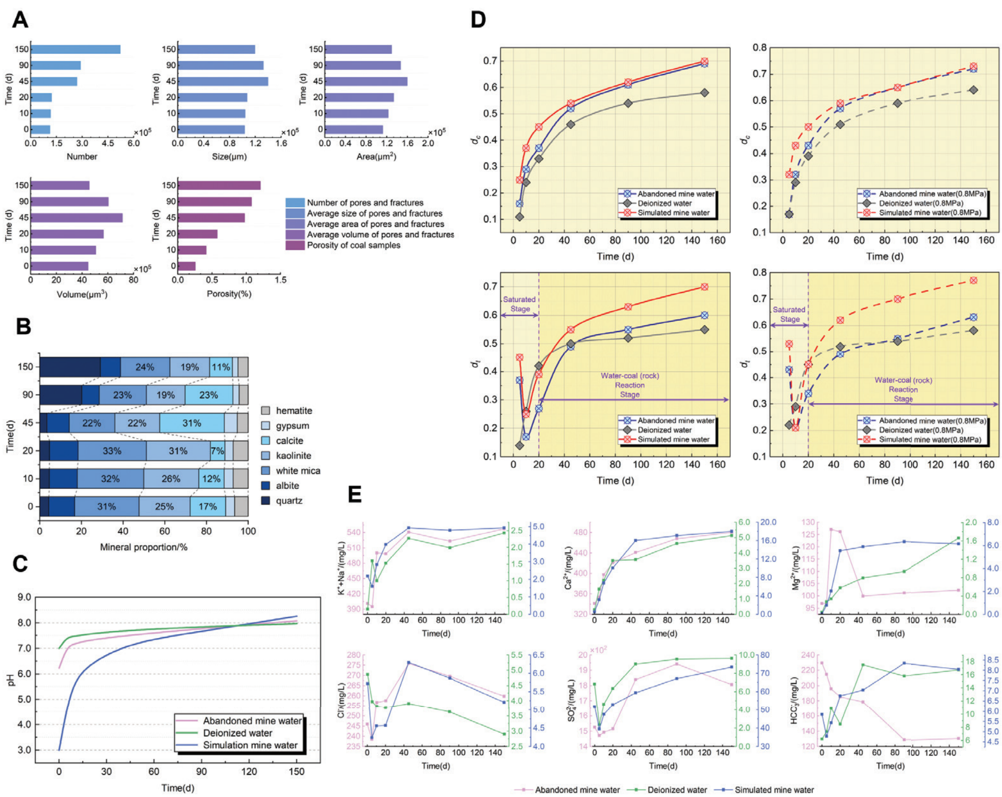

Figure 3 Soaking test results,(a) data of pore fracture parameters of coal sample un-der different soaking duration;(b) mineral composition ratios of coal samples at different soaking time;(c) pH value of soaking solution changed with different soaking time;(d) mechanical damage coefficient under different soaking conditions;(e) The ion concentrations in different soaking solutions change with different time, respectively.

differently in various pH solutions, causing coal edge dissolution, clay swelling, and particle migration, exacerbating fractures and weakening coal structure, leading to strength loss. In acidic environments, pronounced H^+ reactions with coal minerals generate CO_2, potentially causing coal dissolution and further damage.

Main Conclusions

Long-term soaking and XRD/CT scans showed that aggressive mine water caused significant internal pores and fractures in coal pillars from Mine A, increasing porosity from 0.25% to 1.2%. Pore development heterogeneity decreased over time. Coal samples' strength dropped significantly, with compressive strength falling 58−72.9% and tensile strength 54.9%–77.5% from 0 to 150 days. Soaking time, pressure, and solution pH affected the coal samples' strength, with soaking time being especially influential.

The study clarified the physicochemical mechanisms of structural evolution and damage in boundary coal pillars in abandoned goaf areas under high water flow pressure and long-term aggressive mine water influence. Pressurized water immersion has two key stages: initial water saturation, marked by physical water absorption and expansion, causing compressive strength to drop and tensile strength to initially decrease then increase; and water-coal coupling reaction, characterized by combined physical and chemical effects, where clay mineral dissolution and increased porosity lead to mechanical damage. As coal pillars transition from water saturation to water-coal reaction, water chemistry changes, with K^+, Na^+, Ca^{2+}, and SO_4^{2-} concentrations in the solution first decreasing then increasing, and pH becoming weakly alkaline.

The "damage coefficient" was defined as the ratio of the reduction in physical and mechanical parameters after soaking to the dry-state mechanical strength. Empirical values of the "damage coefficient" for water-soaked coal pillars were determined, providing a new quantitative indicator for the mechanical performance evaluation of coal rock pillars in abandoned mines or goaf areas.

Acknowledgments

The authors thank all co-organisers for hosting the IMWA 2025 Conference.

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