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Evolution of the Structure of Different-Rank Coals under Acidic Conditions

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Abstract

Acidic mine drainage (AMD) present in coal seam roof and floor strata significantly modifies coal structure. To investigate the modification patterns of AMD on different coal ranks, coal samples of varying ranks (lignite, bituminous coal, anthracite) were selected. Changes in elemental content, molecular structure, functional groups, pore structure, and microcrystalline structure of the coal samples after immersion in acidic water (pH=4, 35°C) were studied. Fourier Transform Infrared (FTIR) spectroscopy analysis revealed that under the influence of acidic water, the coal samples exhibited a decrease in aromatic structures, disappearance of aliphatic structures, transformation of hydroxyl structures, and redistribution of oxygen-containing functional groups. However, these effects weakened with increasing coal rank. X-ray Photoelectron Spectroscopy (XPS) results indicated a significant reduction of oxygen-containing functional groups (e.g., C-O and C=O) in low-rank coal, while in high-rank coal, the content of C=O groups (such as carbonyl and carboxyl) decreased. BET adsorption experiments showed that the impact of acidic water on the specific surface area and openness of pores in low-rank coal was far greater than in high-rank coal. X-ray Diffraction (XRD) analysis results indicated that the Full Width at Half Maximum (FWHM) of the coal samples gradually increased under acidic water influence, suggesting a decrease in crystallite size. The interlayer spacing (d_{002}) of aromatic layers decreased, and the molecular structure of the coal exhibited higher condensation and orderliness. All findings consistently demonstrate that the influence of acidic water weakens with increasing coal rank, although functional group transformation and structural reorganization still occur. Through the aforementioned characterization techniques, the modifying effects of acidic mine drainage on coal quality and structure were clarified, providing a reference for understanding the transformation mechanism of acidic water on coal reservoir physical properties.

Keywords

Acidic Water, pH, Temperature, Coal Structure, Different Coal Ranks.

1. Introduction

Coal, as a crucial component of the global energy mix, has played a key role in driving societal development. It is widely used for power generation and industrial manufacturing, and has historically underpinned the process of global industrialization, providing stable energy support for economic growth in many countries [1-3]. During coal mining, the exposure of underground coal seams to air and groundwater triggers a series of complex chemical reactions [4-6]. Particularly when coal seams interact with groundwater, these reactions can lead to the formation of Acidic Mine Drainage (AMD) [7]. Sulfide minerals (e.g., pyrite) oxidize upon contact with oxygen and water, forming sulfuric acid (H_2SO_4) and iron ions, thereby lowering the water pH and dissolving other metal ions. AMD not only affects the physicochemical properties of coal but can also lead to coal oxidation, swelling, and disintegration, consequently reducing its mechanical strength and combustion performance [8]. Nie Baisheng et al., using Scanning Electron Microscopy (SEM) on 11 coal samples of different metamorphic stages, found that with increasing coalification degree, the surface pore morphology and the proportion of open pores showed significant differentiation. Tan et al. characterized via SEM that with increasing coal rank, coal surface morphology tends to become more complex, specifically manifested as increased wrinkling structures, increased pore density but decreased pore size, resulting in more compact nanopore structures in anthracite and bituminous coal compared to lignite. Zhang Wei et al. [9] treated Yulin coal with hydrochloric and phosphoric acids, finding that acid treatment disrupted the carbon microcrystalline structure of the coal, leading to structural disintegration, a decrease in hydroxyl group content, and an increase in the proportion of absorption peaks for carboxylic acid and phenolic C-O. This indicates the transformation of functional groups and structural reorganization in coal under acidic conditions. Zhu Xiaoqian et al. [10] studied lignite from Eastern Mongolia treated with hydrochloric and nitric acid solutions of varying concentrations. Results showed that increasing acid concentration caused the specific surface area and total pore volume of the lignite to first increase and then decrease, with an increase in average pore diameter. The ratios of C-C and C-O groups decreased, while C=O groups increased, revealing the impact of acid treatment on coal pore structure and chemical composition [11]. C.A. Strydom et al. [12] subjected South African inertinite-rich medium-rank bituminous coal to different combinations of acid treatments. Results indicated increased CO_2 reactivity and coal surface area post-treatment, demonstrating a certain impact on coal structure. Mengyao Xing et al. [13-14] investigated the effects of different multi-component acid solutions on coal pore structure, finding that different acid components led to the formation of different types of corrosion pores and significantly altered coal pore connectivity [15]. Currently, research primarily focuses on the mechanisms of AMD generation. Studies on the interaction between AMD and coal structure remain insufficient. Systematic research on the specific effects of AMD on the structure of different coal ranks and the ion exchange mechanisms between water and coal is still lacking. This study aims to investigate the effects of acidic water (pH=4, 35°C) on the structural evolution of coal samples of different ranks [16-18]. On one hand, acidic water under these conditions can reasonably simulate the actual conditions of most mine AMD in China, offering strong representativeness. On the other hand, under these conditions, the impact of acidic water on coal structure is most significant, allowing clear observation of its effects on coal chemical and physical structure, while the experimental conditions are easily controllable, facilitating operation and data collection. The experiment comprehensively utilized techniques such as low-temperature nitrogen adsorption, Scanning Electron Microscopy (SEM), and Infrared Spectroscopy (FTIR) to analyze in detail the specific effects of acidic water on coal chemical and physical structure. The results are expected to reveal the evolutionary patterns of coal resources in acidic environments, providing scientific theoretical support for safe mining, efficient utilization, and environmental protection in the coal industry [19-22].

2. Experimental Section

2.1. Coal Samples and Pretreatment

2.1.1. Coal Sample Collection

Coal samples of three typical ranks were selected: Lignite (HM, from Huolinhe Mine, Inner Mongolia), Bituminous Coal (FM, from Gujiao Mine, Shanxi), and Anthracite (WYM, from Rujigou Mine, Ningxia). The industrial analysis parameters and mean maximum vitrinite reflectance (R_0) of the coal samples are shown in Table 1.

Table 1. Basic Properties of the Experimental Coal Samples

Sample	Mad/%	Aad/%	Vdaf/%	Ro/%
HM	12.3	8.7	45.2	0.38
FM	1.5	11.4	28.6	1.12
WYM	0.8	9.2	5.3	3.05

2.1.2. Coal Sample Pretreatment

Raw coal was crushed to 60-80 mesh (aperture 0.25-0.18 mm) using a QM-3SP2 planetary ball mill and sieved to remove impurities. It was then sterilized with high-pressure steam at 121℃ for 30 minutes to eliminate microbial interference. Finally, the samples were dried under vacuum at 60°C for 24 hours to constant weight and stored sealed for later use.

2.2. Simulation System for Acidic Mine Drainage

To simulate the AMD environment, this study used a mixture of pyrite (FeS_2, purity ≥95%) and calcium carbonate ($CaCO_3$, analytical grade) at a mass ratio of 3:1 to prepare the acidic solution. Pyrite oxidation generates sulfuric acid, providing the acidic environment; calcium carbonate buffers the acidity, stabilizing the solution pH, making the experimental conditions closer to actual situations and easier to control. Deionized water was added to prepare an initial acidic solution with pH=2.0. The target pH of 4.0 ± 0.1 was achieved by dropwise addition of 0.1 mol/L NaOH (pH meter: Mettler FE28). The solution was kept static in a constant temperature water bath at 35°C (accuracy ±0.5°C) for 72 hours, then filtered to obtain the simulated AMD.

2.3. Acid Etching Experiment and Characterization Methods

1.Acid Treatment:The pretreated coal samples were immersed in the simulated acidic mine drainage at a solid-to-liquid ratio of 1:10 (g/mL) to simulate conditions of weak runoff intensity during the normal water period. This was followed by constant-temperature oscillatory treatment at 35°C and 150 rpm for 72 hours. Three parallel samples (n=3) were set up for each experimental group.

2.Monitoring of Solution Chemical Parameters: The pH, Oxidation-Reduction Potential (Eh), Total Dissolved Solids (TDS), Conductivity (COND), and Salinity (SAL) of the soaking solution were measured every 24 hours using a Multi3430 multi-parameter analyzer (WTW, Germany).

2.4. Multi-scale Characterization of Coal Samples

1)Functional Group Analysis: Performed using an IRTracer-100 Fourier Transform Infrared Spectrometer (Shimadzu, Japan) with the KBr pellet method. The scanning range was 4000–400 cm^{-1}, with a resolution of 4 cm^{-1} and 32 scans accumulated.

2)Microcrystalline Structure Characterization: Conducted using a D8 Advance X-ray Diffractometer (Bruker, Germany) with Cu-Kα radiation ($\lambda = 1.5406$ Å). The scanning range was 5°–80° (2θ) with a step size of 0.02° and a scanning speed of 4°/min. Microcrystalline parameters (La, Lc, d_{002}) were calculated using the Scherrer equation.

3)Pore Structure Analysis: Carried out using a JW-BK100B low-temperature nitrogen adsorption instrument (JWGB, China). The relative pressure (P/P_0) range was 0.01–0.99. The specific surface area was calculated using the BET model, and the pore size distribution was analyzed using the BJH model.

4)Surface Chemical State Analysis: Performed using an ESCALAB 250Xi X-ray Photoelectron Spectrometer (Thermo Fisher Scientific, USA) with a monochromatic Al-Kα source (1486.6 eV). The binding energy was calibrated using the C 1s peak at 284.8 eV, with a step size of 0.1 eV.

2.5. Data Analysis

Experimental data were processed using Origin software. Differences between groups were tested by one-way analysis of variance (ANOVA), with the significance level set at $p < 0.05$.

3. Results and Discussion

3.1. Changes in Liquid Phase Parameters of Acidic Water

The pH, Eh, TDS, SAL, and COND of the liquid phase were measured every two days during the immersion process. The profiles of these parameters for each coal sample at 35°C are shown in Figure 1.

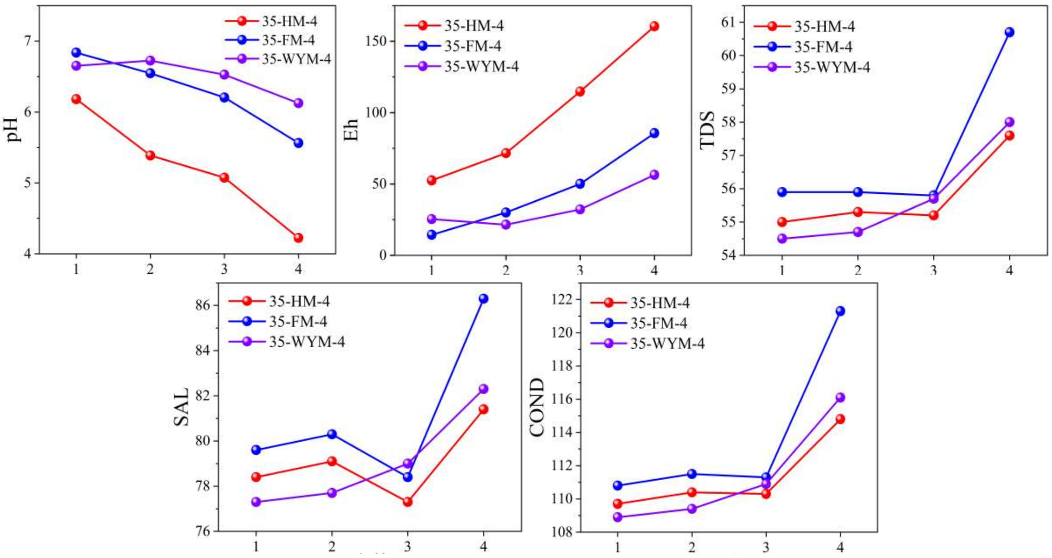


Figure 1. Profiles of pH, Eh, TDS, SAL, and COND for the different coal samples at 35°C.

Figure 1 illustrates the variations in liquid phase parameters for the three coal samples (lignite, HM; bituminous coal, FM; anthracite, WYM) during immersion in acidic water (pH=4). The following trends were observed:

During the initial immersion stage (0–24 h), the solution pH increased significantly—from 4.0 to 6.18 (ΔpH = 2.18) for HM, to 6.83 (ΔpH = 2.83) for FM, and to 6.65 (ΔpH = 2.65) for WYM. This rise is primarily attributed to the rapid dissolution of alkaline minerals (e.g., carbonates, metal oxides) in the coal, which partially neutralized H^+ ions. As immersion continued (24–72 h), the pH gradually decreased toward the initial value, reaching 4.22 for HM, 5.56 for FM, and 6.12 for WYM, indicating that acid hydrolysis of organic components (e.g., oxygen-containing functional groups) began to dominate, releasing H^+.

The oxidation-reduction potential (Eh) consistently increased over 72 h, by 160.5 mV for HM, 85.6 mV for FM, and 56.4 mV for WYM, suggesting that the interaction between acidic water and coal involved significant oxidation processes. These are closely associated with pyrite oxidation and the oxidative cleavage of organic components in coal. Furthermore, the degree of oxidation decreased with increasing coal rank.

Total dissolved solids (TDS), salinity (SAL), and conductivity (COND) exhibited linear increasing trends with immersion time, with HM showing the most pronounced increases—TDS increased by 8.6 mg/L, and COND increased by 18.1 mS/cm. This phenomenon was jointly driven by the dissolution of alkaline minerals and the release of organic matter. H^+ ions released from pyrite oxidation reacted with carbonates to form soluble ions, leading to synchronous increases in TDS and SAL. Simultaneously, the acidic water promoted the dissociation of small organic molecules, such as carboxylic acids and phenols, further elevating the ion concentration. Coal rank significantly influenced the dissolution kinetics: due to its high porosity and proportion of active components, HM demonstrated the fastest ion release rate, with a COND increase 2.5 times that of WYM. In contrast, the dense aromatic structure of WYM suppressed the dissolution process, resulting in a TDS increase only 40% of that observed for HM

3.2. Characteristics of Elemental Content Variation

Elemental analysis (EA) was performed on all coal samples before and after the experiment to determine the changes in elemental content. The results are presented in Figure 2.

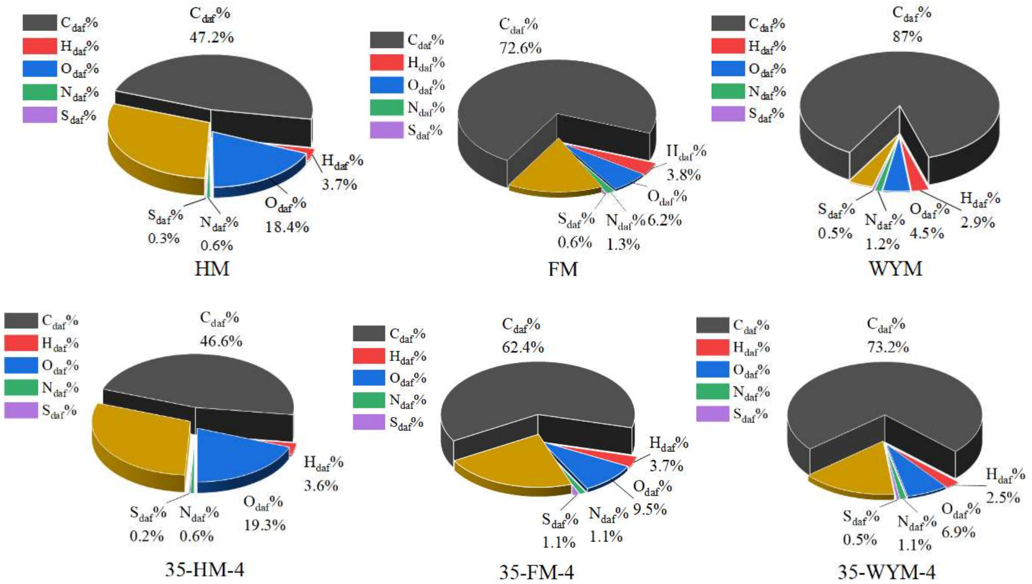


Figure 2. Changes in the elemental content of coal samples before and after the experiment

As shown in Figure 2, the variation trends of elemental contents in the experimental coal samples align with those observed in the raw coal samples as the degree of coal metamorphism increases. In the raw coal samples, the contents of carbon (C) and nitrogen (N) show an increasing trend, while the contents of hydrogen (H) and oxygen (O) gradually decrease. The sulfur (S) content, despite minor fluctuations, remains relatively stable overall.

In the chemical structure of coal, carbon (C), hydrogen (H), and oxygen (O) primarily constitute aromatic and aliphatic compounds. A portion of carbon also exists in the form of carbonates, while small amounts of hydrogen and oxygen can occur as water of crystallization. Nitrogen (N) mainly exists in the form of organic nitrogen and nitrogen-containing functional groups, sometimes embedded in heterocyclic structures, particularly in lignite where nitrogen often manifests as amino acids and their derivatives. Sulfur (S) is predominantly present in sulfur-containing functional groups.

As the carbon content increases, the proportions of aromatic and aliphatic compounds correspondingly rise. Concurrently, with increasing coal rank, oxygen-containing functional groups gradually diminish or even disappear, leading to a continuous decline in oxygen content. Since carbon is the primary component of coal, the extent of acidic water's impact on samples of different ranks can be assessed by observing changes in carbon content. The experimental results indicate that after immersion in acidic water, the carbon content of the HM, FM, and WYM coal samples decreased by 1.08%, 14.01%, and 15.81%, respectively. This suggests that the higher the coal rank, the greater the percentage change in elemental content affected by acidic water.

3.3. Characteristics of Functional Group Changes

Fourier transform infrared (FTIR) spectroscopy was employed to analyze both the raw coal samples and those of different ranks after treatment, aiming to investigate the alterations in functional groups induced by acidic water. The raw data obtained were processed using Origin software, and the infrared absorption spectra for each coal sample were plotted, as shown in Figure 3.

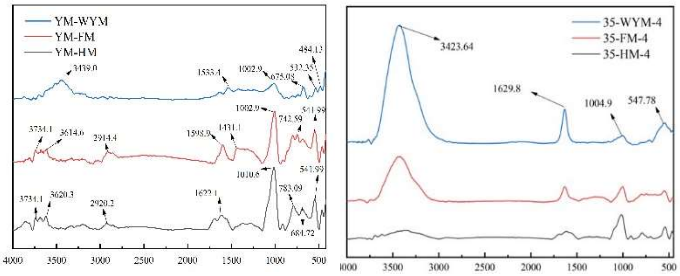
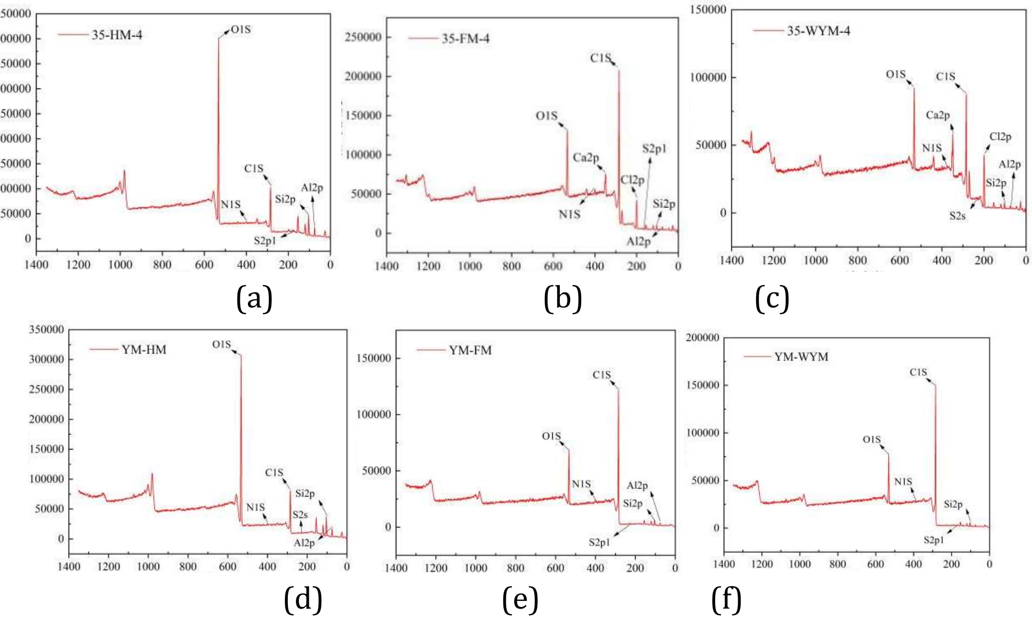


Figure 3. FTIR spectra of the coal samples

FTIR analysis reveals significant differences in the transformation of functional groups among coal samples of different ranks under acidic water treatment. In the 700–1000 cm^{-1} region, the lignite spectrum exhibits characteristic peaks at 684.72 cm^{-1} (alkane vibrations), 783.09 cm^{-1} (aromatic C–H deformation), and 1010.6 cm^{-1} (Si–O vibration). The intensity of these peaks decreases with increasing coal rank, with the absorption peak intensities in anthracite being only 35–42% of those in lignite. Analysis of the oxygen-containing functional group region (1000–1800 cm^{-1}) shows that the absorption intensities of carboxyl groups (~1720 cm^{-1}) and hydroxyl groups (~1260 cm^{-1}) decrease by 42% and 28%, respectively. This trend is consistent with the observed reduction in oxygen content and confirms the hydrolysis reaction of oxygen-containing functional groups ($R{-}COOH + H^+ \rightarrow R{-}OH + CO_2\uparrow$). In the aliphatic structure region (2800–3000 cm^{-1}), the disappearance of the CH_2 vibration peak in lignite, coupled with a 0.32% decrease in hydrogen content, indicates the cleavage of aliphatic chains. Changes in the hydroxyl region (3000–3600 cm^{-1}) suggest hydroxyl reorganization in lignite (free hydroxyl decreased by 18%) and hydroxyl removal in anthracite (intensity decreased by 9%). The study demonstrates that the changes in coal molecular structure under acidic water are distinctly rank-dependent: low-rank coals primarily undergo transformation of active functional groups, while high-rank coals mainly exhibit selective surface oxidation.

3.4. X-ray Photoelectron Spectroscopy (XPS) Analysis



(a) (b) (c)

(d) (e) (f)

Figure 4. XPS survey spectra of the coal samples.

The XPS survey spectra of the coal samples before and after acidic water treatment are presented in Figure 4. The corresponding changes in the relative content of chemical states of elements, derived from the high-resolution spectra, are summarized in Table 2.

The relative contents of carbon, oxygen, and nitrogen in the survey spectra of the coal samples are consistent with the trends shown in Figure 2 (Elemental Analysis) and are therefore not presented again here. The focus of this study is to analyze the changes in the relative contents of these elements to reveal the molecular structural differences among coal samples of different ranks under the influence of acidic water.

Table 2. Changes in the relative content of chemical species from high-resolution XPS spectra.

Sample Name	C 1s Relative Content /%				O 1s Relative Content /%		
	C-C/C-H	C-O	C=O	COO-	C=O	C-O	COO-
35-HM-4	60.35	29.91	9.4	0.35	80.17	19.12	0.71
35-FM-4	75.97	16.69	4.73	2.61	62.25	36.97	0.96
35-WYM-4	70.51	19.79	3.82	6.78	63.18	32.25	4.57
HM	62.30	23.42	10.77	3.50	62.83	33.07	4.10
FM	73.16	18.69	1.11	6.58	44.90	40.37	14.73
WYM	89.53	5.39	1.2	2.98	48.49	49.03	2.78

As shown in Figure 4 and Table 1, in the raw coal samples, lignite (HM) exhibits relatively high proportions of C-O and C=O molecular structures due to its low degree of coalification, reflecting its rich content of oxygen-containing functional groups. As the coal rank increases (from bituminous coal FM to anthracite WYM), carbon progressively becomes dominated by C-C/C-H bonds, indicating an increase in aromaticity. This suggests the coal molecular structure evolves towards a more stable and condensed aromatic hydrocarbon configuration. Furthermore, with increasing coalification, a transformation from C=O to C-O is observed. This indicates a reorganization of the types of oxygen-containing functional groups present, with the high-rank stages dominated by more stable alcohol/ether (C-O) structures, while the content of C=O groups (e.g., carbonyl, carboxyl) decreases.

The abundant oxygen-containing functional groups (C-O, C=O) in lignite make it more susceptible to hydrolysis, dissolution, or chemical reactions with ions like H^+ or SO_4^{2-} under acidic water conditions. The observed shift from C=O to C-O in bituminous coal and anthracite is likely a result of the redistribution of oxygen-containing functional groups induced by ions (e.g., H^+ or SO_4^{2-}) in the acidic water, although the overall magnitude of change is relatively small. Therefore, it can be concluded that the degree of coalification significantly influences the chemical reactivity of coal samples towards acidic water: lignite reacts most vigorously, bituminous coal moderately, and anthracite remains relatively stable.

4. Conclusion

This study investigated the effects of acidic water (pH=4, 35°C) on the structural evolution of coal samples of different ranks. Techniques including low-temperature nitrogen adsorption, scanning electron microscopy (SEM), and Fourier transform infrared spectroscopy (FTIR) were employed to analyze in detail the specific impacts of acidic water on the chemical and physical structure of coal. The results are expected to elucidate the evolutionary behavior of coal resources in acidic environments. The main conclusions are summarized as follows:

(1) Lignite undergoes vigorous reactions under acidic water conditions, evidenced by significant transformation of its oxygen-containing functional groups. Its structure tends

towards higher aromaticity and stability. The pore structure expands considerably, indicating substantial physical alterations and strong chemical reactivity.

(2) Bituminous coal reacts more slowly with acidic water compared to lignite. The transformation of oxygen-containing functional groups is relatively moderate, and changes in pore structure are less pronounced. However, a gradual increase in aromaticity and structural ordering is observed.

(3) Anthracite exhibits the weakest response to acidic water, primarily characterized by slight transformations of oxygen-containing functional groups and further stabilization of its molecular structure. The pore structure remains relatively stable, with minimal physical changes.

(4) The degree of coalification is a critical factor determining the structural evolution of coal under acidic water influence. Low-rank coals experience more intense reactions, demonstrating substantial chemical changes and structural adjustments. In contrast, high-rank coals are relatively stable, showing less susceptibility to acidic water, which manifests mainly as minor transformations of functional groups and slight physical modifications.

References

[1] Cong, Z., Zhao, F., Zheng, X. Research progress on acidic mine drainage from coal mines [J]. Coal Mine Environmental Protection, 2002(05): 8-12. (in Chinese)

[2] GB/T 37764-2019, Technical guideline for treatment and reuse of acidic mine water [S]. (in Chinese)

[3] Hu, L. Causes and treatment methods of acidic mine water in coal mines [C]// China Coal Society. Proceedings of the 2005 Academic Exchange Conference of the Mine Geology Professional Committee of the China Coal Society and the Water Damage Prevention Professional Committee of the China Coal Industry Labor Protection Science and Technology Society. Department of Resources and Environmental Engineering, Anhui University of Science and Technology. 2005: 68-70. (in Chinese)

[4] Song, S. Experimental Study on the Influence of Water Immersion on Coal Structure and Spontaneous Combustion Characteristics [D]. China University of Mining and Technology, 2019. (in Chinese)

[5] Hu, H. Study on Changes in Structure and Spontaneous Combustion Characteristics of Non-caking Coal During Water Immersion Process [D]. China University of Mining and Technology, 2021. DOI:10.27623/d.cnki.gzkyu.2021.002002. (in Chinese)

[6] Zheng, Z., Cai, C. Research progress on the formation mechanism of acidic coal mine water [J]. Resources Environment & Engineering, 2007(03): 323-327. DOI:10.16536/j.cnki.issn.1671-1211.2007.03.026. (in Chinese)

[7] Sun, L. Hazards and prevention of acidic mine water [J]. Coal Technology, 2007(12): 53-54. (in Chinese)

[8] Li, F., Gao, S., Xue, T., et al. Research progress on treatment technology of acidic mine water from coal mines [C]// Professional Committee of Environmental Protection of China Coal Society, CCTEG Hangzhou Research Institute, Editorial Department of Energy Environmental Protection. Proceedings of the 2021 National Energy Environmental Protection Technology Forum. School of Energy and Environmental Engineering, Hebei University of Engineering; 2021: 6. DOI:10.26914/c.cnkihy.2021.022358. (in Chinese)

[9] Zhang, W., Song, Q., Zhang, F., et al. Effect of acid washing on mineral removal, chemical composition, and wettability of coal [J]. Coal Conversion, 2019, 42(03): 1-9. DOI:10.19726/j.cnki.ebcc.201903001. (in Chinese)

[10] Zhu, X., Tian, J., Liu, Y., et al. Effect of acid treatment on the structure of lignite from East Mongolia [J]. Coal Engineering, 2018, 50(07): 137-141. (in Chinese)

[11] Wang, M., Fu, C., Chang, L., et al. Effect of sequential acid treatment on the structure and pyrolysis characteristics of Ximeng lignite [J]. Journal of Fuel Chemistry and Technology, 2012, 40(08): 906-911. (in Chinese)

[12] Xu, Q., Liu, R., Ramakrishna, S. Comparative experimental study on the effects of organic and inorganic acids on coal dissolution [J]. Journal of Molecular Liquids, 2021, 339, 116730.

[13] Strydom, C.A., Bunt, J.R., Schobert, H.H., Raghoo, M. Changes to the organic functional groups of an inertinite rich medium rank bituminous coal during acid treatment processes [J]. Fuel Processing Technology, 2011, 92(4): 764-770.

[14] Xing, M., Xu, C., Zhou, G., Sun, L., Du, W. Experimental investigation for effect of multicomponent inorganic-organic acid solution on pore structure of lignite [J]. Powder Technology, 2021, 392: 503-513.

[15] Sun, X. Study on Dissolved Substances from Long-term Water-immersed Coal and Their Effects on Spontaneous Combustion Characteristics [D]. China University of Mining and Technology, 2015. (in Chinese)

[16] Song, S. Experimental Study on the Influence of Water Immersion on Coal Structure and Spontaneous Combustion Characteristics [D]. China University of Mining and Technology, 2019. (in Chinese)

[17] Li, X., Zeng, Q. Progress of spectral analysis in coal structure research [J]. Spectroscopy and Spectral Analysis, 2022, 42(02): 350-357. (in Chinese)

[18] Qin, R., Gan, Y. Study on the influence of moisture content on functional groups in coal [J]. Journal of Jiujiang University (Natural Sciences Edition), 2021, 36(04): 18-21. DOI:10.19717/j.cnki.jjun.2021.04.005. (in Chinese)

[19] Zhu, X., Zhu, Z., Han, C., Zhang, C. Quantitative analysis of oxygen-containing functional groups in coal by FTIR [J]. Journal of Fuel Chemistry and Technology, 1999(04): 335-339. (in Chinese)

[20] Han, F., Zhang, Y., Meng, A., Li, Q. FTIR analysis of Yunnan lignite structure [J]. Journal of China Coal Society, 2014, 39(11): 2293-2299. DOI:10.13225/j.cnki.jccs.2013.1661. (in Chinese)

[21] Wang, L., Zhang, P. XRD structural analysis of coal [J]. Coal Conversion, 1997(01): 50-53. (in Chinese)

[22] Tian, C., Zeng, F. Preliminary XRD analysis of the structure of vitrain and fusain [J]. Journal of Taiyuan University of Technology, 2001(02): 102-105. DOI:10.16355/j.cnki.issn1007-9432tyut.2001.02.002. (in Chinese)