International Journal of Energy
ISSN: 2957-9473 | Vol. 9, No. 3, 2026

Preparation of Coal Slag-Based Zeolite Molecular Sieves and Their Adsorption Performance for Carbon Dioxide

Wenqin Zeng [1], Zhen Li [2], Chen Xie [3], Jintao Wang [3]

[1] YongZhou Vocational Technical College, Yongzhou, Hunan, China
[2] Jinduicheng Molybdenum Co., LTD, Xi'an, Shaanxi, China
[3] Rocket Force University of Engineering, Xi'an, Shaanxi, China

Abstract: Anthropogenic carbon dioxide (CO_2) over-emission has been identified as a dominant driving factor for a series of global ecological problems, including global warming and sea level elevation. Accordingly, exploiting cost-effective and high-performance CO_2 adsorption materials has become a research topic with prominent practical application value. As a class of well-established high-efficiency adsorbents, zeolite molecular sieves have shown remarkable application prospects in the field of CO_2 capture. Nevertheless, traditional synthesis routes for zeolites generally suffer from drawbacks such as high raw material cost and cumbersome preparation procedures. To tackle the above limitations, this work selected bulk industrial solid waste coal slag as the primary feedstock. Sieving and acid leaching pretreatment procedures were implemented to effectively enrich the active silicon and aluminum components in the raw slag. With sodium hydroxide (NaOH) and sodium aluminate ($NaAlO_2$) as auxiliary reagents, sodalite (SOD) zeolite molecular sieves were successfully fabricated via an alkali fusion coupled with hydrothermal synthesis approach. The influences of varying synthesis parameters on the crystalline structure, microscopic morphology and CO_2 adsorption capacity of the as-synthesized zeolites were systematically explored. Experimental results confirm that the proposed route can realize the high-value resource conversion of solid waste, and the obtained zeolite molecular sieves possess satisfactory CO_2 adsorption performance. This study provides a novel technical strategy and reference for the development of low-cost and sustainable carbon capture materials.

Keywords: Zeolite Molecular Sieves; CO_2; Adsorption Performance; Desorption Regeneration.

1. Introduction

Coal slag, also known as cinder, is a typical solid byproduct discharged from coal-fired industrial boilers and power plants after high-temperature combustion processes. Silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3) are the main chemical components contained in this waste residue[1]. As an inevitable byproduct of coal resource utilization, the annual output of coal slag is highly correlated with the overall scale of coal consumption. According to relevant statistics, China's annual coal consumption has long stayed at the level of billions of tons, among which power generation and industrial boiler combustion account for the largest proportion. This situation has led to the continuous accumulation of massive coal slag solid waste across the country[2]. If proper disposal and resource utilization measures are not taken, the stockpiled coal slag will not only occupy a large amount of precious land resources, but also change the physical and chemical properties of the surrounding soil, causing problems such as soil alkalization and vegetation degradation, which will bring long-term negative impacts on the local ecological environment.

Under such background, promoting the high value-added resource utilization of coal slag has gradually become a key research direction in the fields of environmental science and material engineering[3]. Among numerous resource utilization approaches, preparing zeolite molecular sieves from coal slag for CO_2 capture application is considered a highly promising technical route, which can take into account both environmental benefits and economic benefits. At present, relevant research work in this field is still relatively insufficient. In-depth exploration in this direction can not only effectively cut down the production cost of zeolite adsorption materials and promote the conversion of solid waste into high-value functional materials, but also conform to the development concepts of circular economy and waste resource recovery, thus possessing important theoretical research value and engineering application prospects[4].

This research focuses on the preparation technology of coal slag-based zeolite molecular sieves and their CO_2 adsorption performance, and systematically analyzes the key influencing factors and internal action mechanisms involved in the synthesis and adsorption processes[5]. The relevant research conclusions are expected to provide useful theoretical reference and technical support for the resource utilization of industrial solid waste and the technological progress of carbon capture. In this work, chemically pretreated coal slag was adopted as the raw material, and zeolite molecular sieve samples with specific crystalline structures and pore structure characteristics were prepared through a systematic alkali fusion-hydrothermal synthesis process. Scanning electron microscopy (SEM) was used to observe and analyze the microscopic morphology of the as-prepared products. The structural parameters such as specific surface area, pore volume and pore size distribution of the samples were comprehensively characterized via Brunauer-Emmett-Teller (BET) test method. On this basis, the CO_2 adsorption performance of the synthesized zeolite samples was tested and evaluated with a dedicated CO_2 adsorption test device.

2. Experimental Section

2.1. Experimental Materials, Reagents and Equipment

(1) Coal Slag Pretreatment Process: The coal slag raw material used in the experiment was collected from Yongzhou

Dong'an Power Plant. Considering that the raw coal slag has a complex chemical composition, containing a certain amount of organic impurities and soluble alkaline oxide components, an acid washing pretreatment process was adopted in this study to purify the raw material and activate its active components, so as to make it more suitable for the subsequent zeolite synthesis reaction. The specific operation steps are described as follows: First, the raw coal slag was crushed and fully ground, then sieved to collect the powder sample with particle size between 38 μm and 74 μm (i.e., 200–400 mesh). After that, 10.0 g of the sieved slag powder was weighed and mixed with 100 mL of 7 mol/L hydrochloric acid solution. The mixed solution was placed in a constant temperature water bath device, and continuously stirred at 95 °C for 4.5 h to ensure sufficient acid leaching reaction. After the reaction was completed, vacuum filtration was performed on the mixed system, and the filtered solid residue was washed repeatedly with deionized water until the pH value of the filtrate was close to neutral. Finally, the washed solid sample was placed in a drying oven and dried at 105 °C to constant weight. The obtained sample was recorded as pretreated coal slag, which was used as the raw material for the subsequent zeolite synthesis experiments.

(2) Zeolite Molecular Sieve Preparation Process: Pretreated coal slag, sodium aluminate ($NaAlO_2$) and sodium hydroxide (NaOH) were accurately weighed according to the preset material ratio, then fully ground and mixed uniformly in an agate mortar. The evenly mixed powder sample was transferred to a muffle furnace and calcined at 600 °C for 2 h to complete the alkali fusion activation process. After the calcination was finished and the sample was cooled down, the alkali fusion product was mixed with a certain amount of deionized water according to the set liquid-solid ratio, and then mechanically stirred continuously at room temperature for 10 h to fully promote the hydrolysis and activation of silicon and aluminum components in the system. After the stirring activation step, the mixed slurry was transferred to a stainless steel hydrothermal autoclave lined with polytetrafluoroethylene, and hydrothermal crystallization reaction was carried out at the preset reaction temperature. After the hydrothermal reaction was completed, the autoclave was taken out and cooled naturally to room temperature. The solid product was collected by vacuum filtration, and washed repeatedly with deionized water until the pH of the filtrate reached neutral. Finally, the washed solid sample was placed in a constant temperature drying oven and dried at the set temperature to constant weight, and the target zeolite molecular sieve sample was obtained.

2.2. CO_2 Static Adsorption Test Method

The CO_2 adsorption performance of the samples was tested and evaluated by a fully automatic specific surface area and pore size analyzer (model: 3H-2000PS2), and the test principle was based on the static volumetric method. The specific experimental operation process is as follows:

(1) Sample Degassing Pretreatment: Before the formal adsorption test, the sample needs to be degassed to remove the impurities adsorbed on the surface and in the pores. First, the mass of a clean and empty sample tube was weighed and recorded as m_1. Then an appropriate amount of sample was loaded into the sample tube, and the total mass of the sample tube with the sample was weighed and recorded as m_2. After that, the sample tube containing the sample was installed on the degassing station of the analyzer. Under a pure helium atmosphere, the temperature was raised to the preset degassing temperature at a constant heating rate and kept for a set period of time to complete the degassing treatment. After the degassing was finished and the sample tube was cooled to room temperature, the sample tube with the degassed sample was weighed again, and the obtained mass was recorded as m_3.

(2) CO_2 Isothermal Adsorption Test: The actual mass of the test sample was calculated according to the formula $m = m_3 - m_1$. Before the test, helium gas was introduced to purge the gas pipeline of the analyzer, and the inlet pressure of CO_2 gas was controlled at the set value (0.34 MPa±0.02 MPa). The isothermal CO_2 adsorption test was carried out under constant temperature conditions, and the adsorption capacity of the sample at different pressure points within the range of 0–1 bar was recorded, so as to obtain the CO_2 adsorption isotherm curve of each sample.

3. Results and Discussion

3.1. Microscopic Morphology Analysis of the As-synthesized SOD Zeolite

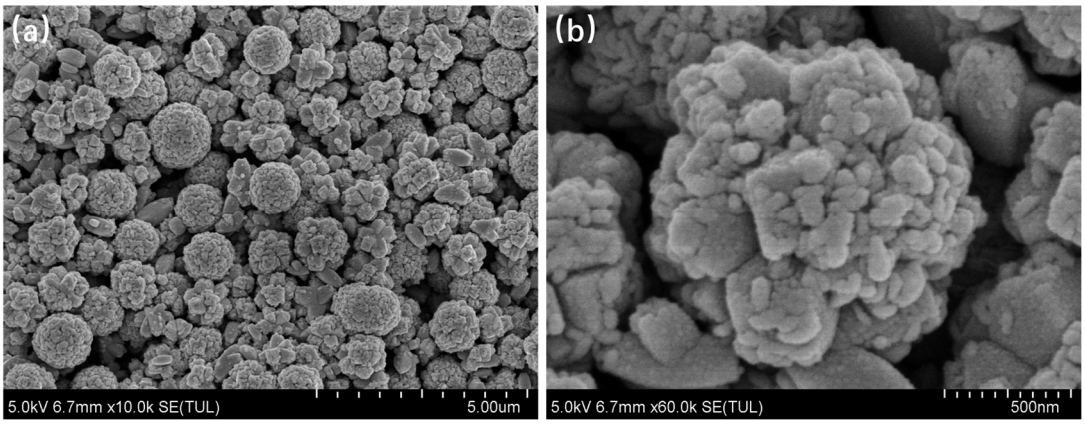


Fig 1. SEM of SOD zeolite molecular sieve prepared from coal-fired slag

The microscopic morphology characteristics of the raw coal slag and the prepared SOD zeolite molecular sieve are shown in Fig. 1. Through observation and analysis, it can be found that the raw coal slag material mainly presents irregular spherical microbead structures, accompanied by some larger irregular polyhedral particles.

After the alkali fusion-hydrothermal synthesis reaction, the microscopic morphology of the obtained molecular sieve sample has changed significantly. The sample is composed of crystalline particles with a particle size distribution of 1–3 μm,

the overall particle size is relatively uniform, and the crystals present a regular cubic morphology, which is consistent with the typical morphological characteristics of SOD zeolite crystals.

3.2. Pore Structure Characterization Based on Nitrogen Adsorption-Desorption Test

Nitrogen adsorption-desorption tests were carried out on the synthesized zeolite molecular sieve samples at 77 K, and the obtained adsorption-desorption isotherm curves are shown in Fig. 2. According to the adsorption isotherm classification standard formulated by the International Union of Pure and Applied Chemistry (IUPAC), the nitrogen adsorption-desorption isotherm of the sample in this study belongs to the typical Type I isotherm. The isotherm shows a rapid rise in adsorption capacity in the low relative pressure region, and then enters a plateau stage where the adsorption amount basically remains unchanged with the further increase of relative pressure. This adsorption characteristic indicates that nitrogen molecules are rapidly adsorbed and saturated in the microporous structure of the sample, which confirms that the prepared zeolite molecular sieve is mainly dominated by microporous structure. The narrow micropore channels can strengthen the interaction force between adsorbate molecules and the pore wall, which is conducive to the adsorption of gas molecules. It is worth noting that an obvious hysteresis loop can be observed in the high relative pressure region of the isotherm, which indicates that there are a certain number of mesoporous structures in the sample. Combined with the sample morphology analysis, these mesopores are mainly formed by the stacking gaps between zeolite crystal particles, and may also be related to the partial pore expansion effect during the synthesis process.

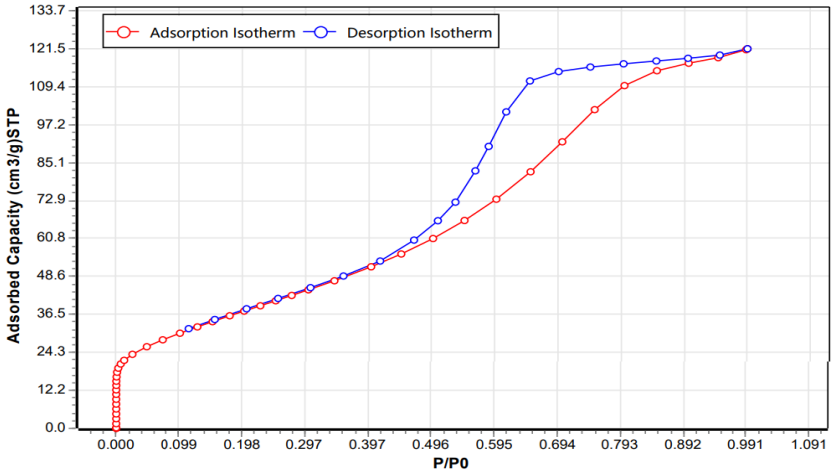


Fig 2. Nitrogen adsorption-desorption isotherm

The BJH pore size distribution curve of the sample is shown in Fig. 3. It can be seen from the pore size distribution results that the synthesized zeolite molecular sieve has clear pore structure characteristics. The pore size of the sample is mainly concentrated in the range of 3–10 nm, and the pore size distribution shows good uniformity. This pore size range is much larger than the kinetic diameter of conventional gas molecules, especially for CO_2 molecules with a kinetic diameter of about 0.33 nm. Therefore, during the CO_2 adsorption process, the pore structure of the molecular sieve can provide unobstructed diffusion channels and abundant physical adsorption sites for CO_2 molecules, which creates favorable structural conditions for efficient gas adsorption from a theoretical perspective. Based on the uniform pore size distribution of the sample and the high matching degree between pore size and target adsorbate molecular size, it can be reasonably inferred that the prepared zeolite molecular sieve material has excellent CO_2 adsorption capacity and structural adaptability, which lays a solid material foundation for its application in the field of carbon capture.

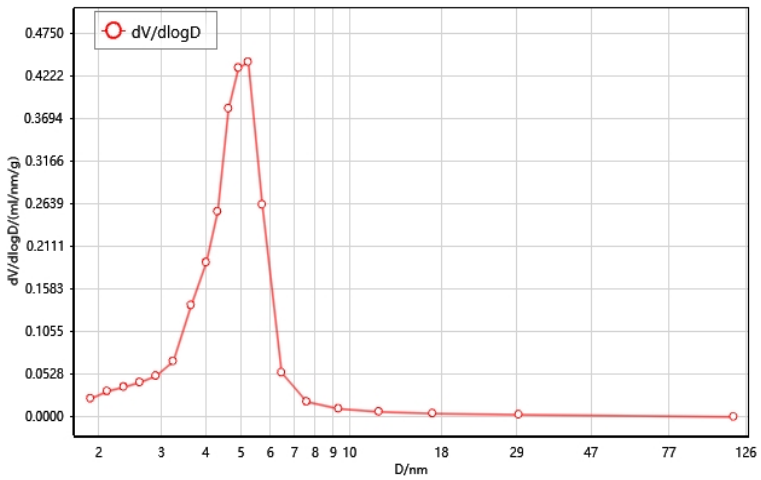


Fig 3. BJH pore size distribution

3.3. CO_2 Adsorption Performance and Cycle Stability Analysis

The CO_2 static adsorption performance of the synthesized zeolite molecular sieve adsorbent was systematically tested by a high-pressure gas adsorption analysis system. The test was carried out under isothermal condition of 303 K, and the test pressure range was 0–3 MPa. The obtained adsorption isotherm curves are shown in Fig. 4, in which Fig. 4a shows the result of the initial adsorption test, and Fig. 4b shows the test result after 10 consecutive adsorption-high temperature desorption cycles under the same experimental conditions. The experimental results show that the CO_2 adsorption capacity of the zeolite molecular sieve increases monotonically with the increase of adsorption pressure, which is consistent with the typical physical adsorption mechanism. The initial CO_2 adsorption capacity of the sample was measured to be 175.2 cm^3/g. After 10 adsorption-desorption cycles, the adsorption capacity of the sample remained at 173.5 cm^3/g, with only a very small attenuation, which indicates that the sample has stable adsorption performance and good cycle regeneration performance. The slight change in adsorption capacity during the cycle process may be caused by the removal of residual impurities in the pore channels, the further optimization of pore structure and the more sufficient exposure of adsorption active sites during the repeated adsorption-desorption process. The above results fully prove that the prepared zeolite molecular sieve material has excellent structural stability under repeated adsorption-desorption operation conditions, and has good application potential in the field of cyclic adsorption separation of CO_2.

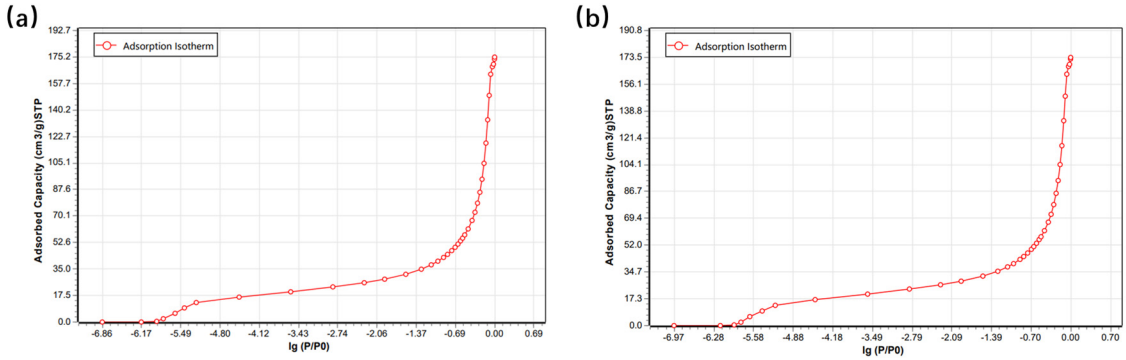


Fig 4. Carbon dioxide adsorption isotherm

4. Conclusion

In this study, industrial solid waste coal slag was used as the raw material. After purification and enrichment of effective components through pretreatment process, SOD-type zeolite molecular sieve materials were successfully prepared by alkali fusion-hydrothermal synthesis method, and their CO_2 adsorption performance was systematically studied. The effects of synthesis process conditions on the microstructure and pore structure characteristics of the materials were characterized by SEM, BET and other test methods. The experimental results show that the prepared zeolite molecular sieve has good CO_2 adsorption performance. The initial CO_2 adsorption capacity of the sample reaches 175.2 cm^3/g. After 10 adsorption-desorption cycles, the adsorption capacity still remains 173.5 cm^3/g, which reflects the excellent cycle stability and adsorption regeneration performance of the material. This research provides a feasible technical approach for the high-value resource utilization of industrial solid waste, and also provides a new material option for the development of low-cost carbon capture adsorption materials.

Acknowledgments

Fund Project: 2025 Institutional Research Project, Yongzhou Vocational and Technical University **(YZ25QN06).**

References

[1] Yan, W., & Yu, J. (2023). Our journey in zeolite science. *Microporous and Mesoporous Materials*, 358, 112368. https:// doi. org/10.1016/j.micromeso.2023.112368.

[2] Collins, F., Rozhkovskaya, A., Outram, J. G., et al. (2020). A critical review of waste resources, synthesis, and applications for Zeolite LTA. *Microporous and Mesoporous Materials*, 291, 109667. https://doi.org/10.1016/j.micromeso.2019.109667.

[3] Wei, L., Li, S., Noguera, D. R., et al. (2015). Dissolved organic matter removal during coal slag additive soil aquifer treatment for secondary effluent recharging: Contribution of aerobic biodegradation. *Journal of Environmental Management*, 156, 158–166. https://doi.org/10.1016/j.jenvman.2015.03.024.

[4] Li, J. Z., Wang, R. K., Xu, J. F., et al. (2014). Pilot-scale investigation on slurrying, combustion, and slagging characteristics of coal slurry fuel prepared using industrial waste liquid. *Applied Energy*, 115, 309–319. https://doi.org/10. 1016/ j. apenergy.2013.10.043.

[5] Zou, J., Guo, C., Jiang, Y., et al. (2016). Structure, morphology and mechanism research on synthesizing xonotlite fiber from acid-extracting residues of coal fly ash and carbide slag. *Materials Chemistry and Physics*, 172, 121–128. https:// doi. org/ 10.1016/j.matchemphys.2016.01.004.