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Review Paper

Research Progress on CO_2 Capture Materials and Mineral Carbonation Technologies from Coal Gasification Slag

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Abstract. Coal gasification slag (CGS), an important by-product of the coal chemical industry, is rich in elements such as silicon, carbon, calcium and magnesium with a unique mineral composition, and has become an important raw material for CO_2 capture and mineralization. Utilization of CGS as a precursor for CO_2 capture material synthesis and CO_2 mineralization can significantly reduce the costs of traditional technologies, achieve the high-value utilization of CGS, and promote the synergistic reduction of pollution and CO_2 emissions in the coal chemical industry. Herein, a comprehensive review on the research progress regarding CO_2 capture and mineralization using CGS was provided. The synthetic strategies and mechanisms of silicon-based, carbon-based, and carbon-ash composite adsorbents derived from CGS for CO_2 capture were presented in detail, while the effects of different treatments on the structural properties and CO_2 capture capacity of adsorbents were summarized and compared. In addition, the mechanisms and the research progress on different technologies using CGS for CO_2 mineral carbonation were introduced. Finally, the problems existing in the application research of CGS in CO_2 capture and mineralization were discussed. It was recommended that more in-depth studies should be conducted focusing on performance enhancement, preparation process optimization, coupling technology development for the preparation of CO_2 capture materials and mineralization from CGS, as well as economic feasibility evaluations.

Keywords: *coal gasification slag; CO_2 capture; silicon-based adsorbents; carbon-ash composite adsorbents; mineralization*

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1 Introduction

Coal remains the predominant energy resource and industrial feedstock in China, consistently representing in excess of 55% of national energy consumption. Amid escalating global energy requirements, coal combustion has emerged as the foremost contributor to worldwide CO_2 discharges. Empirical data indicate that carbon dioxide emissions attributable to coal utilization constitute over 75% of China's aggregate carbon footprint. therefore, reducing CO_2 emissions from the coal industry has become the key to China’s carbon reduction efforts[1-2]. Although the cost of developing and utilizing renewable energy sources such as solar and wind power has gradually decreased and their economic benefits have steadily improved, they still cannot meet the huge energy demand[3]. Under the circumstance that fossil fuels cannot be completely abandoned in the short term, carbon capture, utilization and storage (CCUS) technology is an important implementation pathway to achieve large-scale carbon emission reduction in the coal industry in the medium and short term, while ensuring energy security and sustainable utilization[4]. According to the International Energy Agency, by the mid-21st century, the application of CCUS technology will cumulatively contribute approximately 15% of global carbon emission reductions and 3%–25% of China’s carbon emission reductions[5]. Meanwhile, captured CO_2 can be converted into high-value-added products such as chemicals, biofuels, and fertilizers through physical, chemical, and biological processes, generating additional economic benefits. However, constrained by high costs, technical safety, and reliability concerns, CCUS technology has not yet been deployed on a large scale. As the key component of CCUS technology and the main source of cost and energy consumption, CO_2 capture accounts for 65%–85% of the total project cost[6]. Developing low-cost, high-performance CO_2 capture materials and high-value-added CO_2 utilization technologies has always been a research focus.

Coal gasification technology, as the cornerstone of clean coal conversion and coal-to-chemicals process industries, consumes approximately 250 million tons of raw coal annually[7]. However, incomplete combustion of coal with oxidants during the gasification process results in the co-production of about 30% coal gasification slag per ton of processed coal, with an annual average output exceeding 33 million tons[8-9]. Coal gasification slag obtained via high-temperature quenching processes typically contains abundant inorganic minerals such as SiO_2 (mass fraction 28%–52%), Al_2O_3 (mass fraction 8%–28%), CaO (mass fraction 4.3%–28.0%), and MgO (mass fraction 0.7%–4.3%), as well as residual carbon (mass fraction 20%–50%), providing necessary conditions for its resource utilization and high-value-added applications[10].

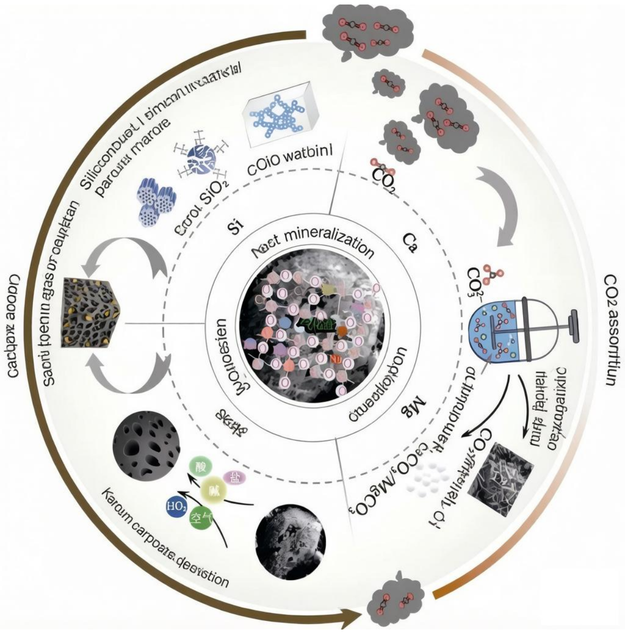

Figure 1 CO_2 capture and mineral carbonation technologies from coal gasification slag

Nevertheless, the elevated residual carbon fraction in gasification slag precludes compliance with ignition loss specifications mandated for construction and building material applications. Furthermore, the inherent phenomenon of carbon-ash fusion and encapsulation constrains its broad-scale valorization within resource recovery frameworks. Currently, most coal gasification slag is still disposed of via open-air stacking or landfilling, with only approximately 8% by mass being utilized as a resource. This situation not only leads to resource squandering but also consumes extensive land area, elevates ecological contamination risks, and potentially endangers public health [11-12]. In alignment with the "Dual Carbon" objectives and advancing CCUS technology research, leveraging the residual carbon, silicon, calcium, magnesium, and other elemental constituents within gasification slag as feedstock for CO_2 capture material synthesis and mineral carbonation sequestration offers an innovative avenue for slag valorization. The substantial SiO_2 content and residual carbon fraction, characterized by preserved porous architectures, expansive specific surface areas, and elevated pore volumes, can function as economically viable silicon and carbon precursors, respectively. Through physical and chemical treatments and acid leaching for impurity removal (Ca, Mg, etc.) as pre-/post-treatment processes, mesoporous SiO_2, activated carbon, and other silicon-based, carbon-based, and carbon-ash composite adsorbents can be prepared for CO_2 capture. The captured CO_2 can then react with CaO, MgO, and other alkaline earth metal oxides in gasification slag, or with the Ca- and Mg-rich acid leachate generated during the preparation of gasification slag-based CO_2 capture materials via carbonation reactions, to produce high-value-added carbonate products. This further realizes CO_2 utilization and sequestration and recovers valuable resources such as Ca and Mg from gasification slag. As two major pollutants in the coal chemical sector, CO_2 and gasification slag offer advantages such as large output, wide availability, and low cost compared with commonly used raw materials such as coal, peat, and natural minerals when used as precursors for CO_2 capture material preparation and CO_2 mineralization. Moreover, gasification slag is abundantly produced in industrial parks near coal chemical CO_2 emission sources, enabling on-site utilization, greatly reducing the costs of slag transfer, treatment, disposal, and CO_2 mineralization transportation. This effectively achieves “pollution control with pollutants" in the coal chemical field, alleviates environmental pollution caused by improper gasification slag disposal, promotes synergistic pollution reduction and carbon emission mitigation in the coal chemical industry, and delivers dual economic and environmental benefits. In recent years, research has reported on the application of gasification slag in construction and building materials, ecological environment remediation, residual carbon utilization, and preparation of high-value-added materials[10,13-14]. With the proposal of China's "Dual Carbon" goals, research on utilizing gasification slag for CO_2 capture and mineralization has attracted increasing attention.

This paper systematically summarizes and analyzes the current preparation methods, reaction mechanisms, advantages, disadvantages, and application prospects of silicon-based, carbon-based, and carbon-ash composite CO_2 capture materials derived from gasification slag. It conducts a comparative evaluation of how diverse fabrication methodologies influence the structural attributes and CO_2 sequestration performance of the resulting adsorbents, while also reviewing and critically examining the contemporary research landscape concerning coal gasification slag utilization in post-capture CO_2 mineralization and long-term storage applications. On this basis, the main problems existing in the application of gasification slag for CO_2 capture and mineralization are pointed out, and future research directions are proposed. A novel concept of utilizing the acid leachate by-produced during the preparation of gasification slag-based CO_2 capture materials for mineralization is put forward, aiming to realize the coupling of gasification slag-based CO_2 capture material preparation and mineralization technologies and the synchronous recovery and utilization of multiple valuable resources. This advancement will facilitate the deployment of gasification slag within carbon capture, utilization, and storage frameworks, while furnishing theoretical foundations and empirical evidence to broaden slag resource valorization and advance the environmentally sustainable evolution of the coal sector.

2 Gasification Slag-Based CO_2 Capture Materials and Their Capture Performance

Carbon dioxide capture denotes the separation and enrichment of CO_2 from emission streams through diverse gas separation methodologies. Presently, prevalent CO_2 capture routes primarily encompass pre-combustion separation, oxy-fuel combustion, and post-combustion recovery. Pre-combustion capture technology isolates CO_2 from fuel or shifted syngas prior to the combustion of carbonaceous or hydrogenous fuels. This approach offers elevated CO_2 partial pressure in the processed gas stream, reduced contaminant levels, and diminished energy penalties, though its current deployment remains largely confined to integrated gasification combined cycle power generation facilities [15]. Oxy-fuel combustion technology substitutes pure oxygen for atmospheric air in fossil fuel combustion, yielding flue gas with substantially elevated CO_2 concentration. A portion of the flue gas is recycled and mixed with oxygen to prevent excessive combustion temperatures, while the remaining portion undergoes cooling, compression, and other processes to separate CO_2. This technology effectively reduces pollutant emissions from traditional fuel combustion processes but increases the energy consumption of the oxygen production system and the total investment[16]. Post-combustion capture technology separates and recovers CO_2 from blast furnace flue gas. Its operational protocol is comparatively straightforward, the underlying technology is well-established, and capital investment requirements are modest, rendering it the most extensively deployed carbon capture methodology currently [17]. Conventional post-combustion capture approaches encompass liquid amine absorption, solid-phase adsorption, membrane separation, and cryogenic fractionation [18]. Among these, the liquid amine scrubbing technique represents the most mature and industrially prevalent technology, distinguished by robust CO_2 absorption capacity and rapid uptake kinetics. Nevertheless, this method is encumbered by substantial regenerative energy demands, pronounced corrosive behavior, and considerable absorbent degradation and volatilization losses. Solid adsorption methods, owing to their high adsorption efficiency, simple operation, low regeneration cost and energy consumption, absence of corrosion, high configuration flexibility, and wide applicability, are the most commercially promising carbon emission reduction strategies[19]. As the core of adsorption-based CO_2 capture technology, porous carbon capture materials are generally required to possess high CO_2 adsorption capacity and selectivity, fast adsorption/desorption kinetics, chemical and thermal stability, and reversible regenerability. In recent years, extensive research has been conducted on the development of various types of solid adsorbents, such as carbon-based adsorbents (activated carbon, carbon nanotubes, etc.), silicon-based adsorbents (zeolites, SiO_2, etc.), and metal-organic frameworks. The abundant silicon and carbon elements in gasification slag can serve as cost-effective silicon and carbon sources for preparing various silicon-based, carbon-based, and carbon-ash composite CO_2 capture materials. The types and preparation schematic of these materials are shown in Figure 2.

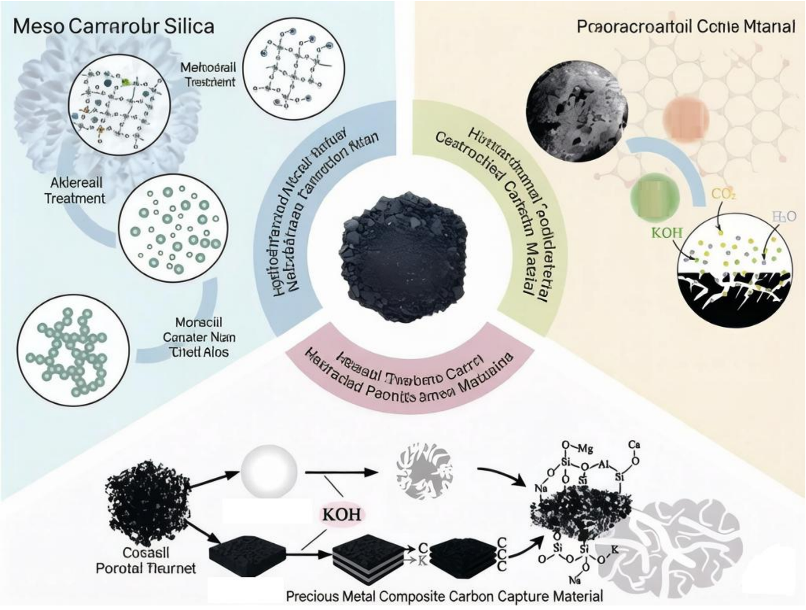

Figure 2 Schematic diagram of types and preparation methods of carbon capture materials based on gasification slag

2.1 Silicon-Based CO_2 Capture Materials

Currently, commonly used silicon-based CO_2 capture materials mainly include mesoporous SiO_2, zeolites, silica gel, lithium silicate, etc.[20]. Among these, mesoporous silica has garnered extensive application in CO_2 sequestration owing to its adjustable pore architecture, expansive specific surface area, profuse surface silanol functionalities (Si–OH), and favorable thermal and mechanical robustness [21]. Traditional mesoporous SiO_2 is mainly prepared by using organic molecules as templates, leveraging the synergistic interaction between inorganic silicon sources and template interfaces or supramolecular self-assembly to form assemblies, followed by removal of the organic matter via high-temperature calcination or extraction to retain the inorganic framework. This process is usually costly and difficult to scale up for mass production[22]. The SiO_2 rich in coal gasification slag can serve as a silicon source precursor for preparing mesoporous SiO_2 CO_2 capture materials, thereby reducing the production cost of mesoporous SiO_2. Since most of the silicon in gasification slag exists in the form of amorphous silicate glass phases with low reactivity, pretreatment via acid leaching to dissolve acid-soluble metals and alkali activation is required to obtain soluble sodium silicate as the silicon source precursor. During acidic leaching, cationic species in solution disrupt the chemically inert Si–O–M linkages (M = Al, Ca, Fe) within the gasification slag matrix, inducing bond scission and generating reactive Si–O and Al–O termini. This process triggers depolymerization of amorphous aluminosilicate frameworks and concurrent dissolution of contaminant elements including aluminum, calcium, iron, and magnesium. The resultant activated Si–O–H functionalities subsequently undergo condensation polymerization, yielding amorphous silica precursors characterized by relatively weak Si–O–Si connectivity [Eqs. (1)–(4)]. Under alkaline activation conditions, Si–O–Si bonds undergo hydrolytic cleavage and transform into Si–O–Na linkages, producing soluble sodium silicate intermediates [Eqs. (5)–(9)] [23]. Then, using a certain template agent, mesoporous SiO_2 CO_2 capture materials are prepared via a hydrothermal self-assembly process.

≡Si−O−Al≡+H+→≡Si−O−H++−Al≡=Si(−O−Al≡)2 +2H+→=Si(−O−H)2 +2+−Al≡=Si(−O−H)2 +≡Si(−O−H)2 → ≡Si−O−Si≡+2H2 O≡Si−O−H+≡Si−O−H→≡Si−O−Si≡+H2 O≡Si−O−+NaOH→≡Si−OH+≡Si−O−Na≡Si−O−+2NaOH→ =Si−(OH)2 +≡Si(−O−Na)2 ≡Si−O−+3NaOH→−Si−(OH)3 +≡Si(−O−Na)3 ≡Si−O−+4NaOH→Si−(OH)4 +Si(−O −Na)4 NaOH+NaAl(OH)4 +Na2 SiO3 →Na(AlO2)b (SiO2)c · NaOH · H2 O (1)(2)(3)(4)(5)(6)(7)(8)(9)

In recent years, to improve the capture capacity of silicon-based CO_2 capture materials, a series of hierarchical porous SiO_2 CO_2 capture materials with micropores, mesopores, and macropores have been developed using gasification slag as a raw material. The hierarchical porous architecture incorporating diverse pore dimensions not only amplifies the specific surface area and pore volume of silicon-based CO_2 adsorbents, thereby furnishing additional active sorption sites, but also attenuates CO_2 diffusion mass transfer resistance through the presence of mesoporous and macroporous channels, consequently enhancing overall CO_2 capture capacity. Wei et al. [23] employed sodium silicate solution derived from sequential acid leaching and alkaline dissolution of gasification fine slag as the silicon precursor, utilizing Pluronic triblock copolymer (PEO_{20}-PPO_{70}-PEO_{20}) as the organic structure-directing agent. Self-assembly was carried out in a ternary hydrothermal system of Pluronic polymer, HCl, and H_2O, followed by high-temperature calcination to remove the organic template, preparing a hierarchical porous nano-silica adsorbent (CGFS, Figure 3a). When the alkali-to-slag mass ratio was 0.6, the prepared adsorbent (CGFS-0.6) had a specific surface area of 457.17 m²/g and a pore volume of 2.34 cm³/g. At 20 °C, 0.1 MPa, and a CO_2 volume fraction of 15%, it reached adsorption equilibrium within only 10 min, with a CO_2 adsorption capacity of 2.87 mmol/g. After 20 adsorption-desorption cycles, it retained 89.90%–96.47% of its adsorption capacity, demonstrating high adsorption-desorption cyclic stability (Figures 3b–e). GAO et al.[24] used pre-decarbonized gasification fine slag (ash mass fraction 99.82%) as a raw material. After alkali dissolution to obtain a silicon-containing precursor, acidification with HCl caused Si^{4+} in the solution to re-polymerize into nanoscale SiO_2 particles, which gradually bonded and cross-linked via condensation reactions to form a three-dimensional network structured SiO_2 wet gel. Drying at 105 °C under atmospheric pressure yielded hierarchical porous SiO_2 aerogels, avoiding the complexity and risks associated with the traditional supercritical drying method for SiO_2 wet gels. Under optimized process parameters, the synthesized material exhibited a specific surface area of 643.48 m²/g and total pore volume of 0.88 cm³/g. The CO_2 sorption capacity at 273 K attained 1.53 mmol/g, with merely 5.22% capacity attenuation following five consecutive adsorption-desorption cycles, demonstrating excellent regenerative stability. However, the aforementioned porous SiO_2 CO_2 capture materials mainly capture CO_2 through the physical adsorption mechanism of the microporous structure. Under actual flue gas conditions with higher temperatures and lower CO_2 partial pressures, their CO_2 capture capacity is poor, limiting their practical application.

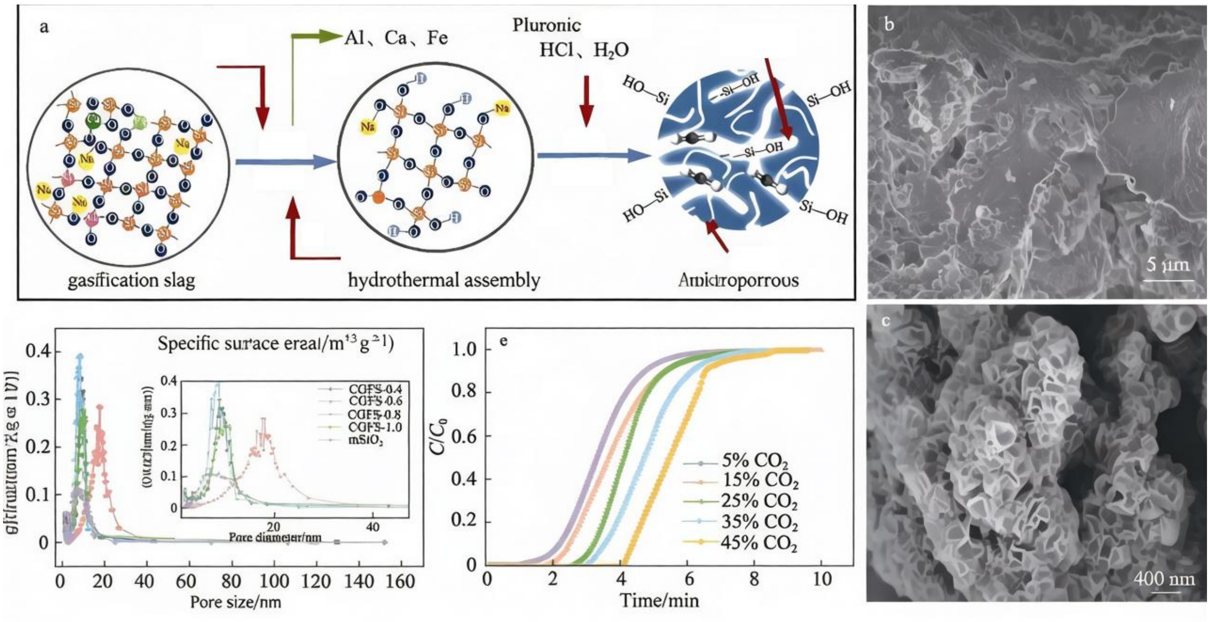

Figure 3 Schematic diagram of preparation process of hierarchical porous silica nanoparticles from coal gasification slag(a), SEM images of CGFS(b) and CGFS-0.6(c), pore size distribution curves of different samples(d) and breakthrough curves of CGFS-0.6 at different CO_2 volume fractions(e)[23]

At higher adsorption temperatures, the CO_2 capture performance of carbon capture materials relies more on surface chemical properties rather than micropore structure. Studies have shown that amine-functionalized modification of silicon-based CO_2 capture materials via physical impregnation, chemical grafting, and in-situ polymerization can effectively increase the surface basicity and electron density of the materials. This enhances the Lewis acid-base interaction between CO_2 and the modified basic groups. The surface-loaded amino groups can react reversibly with adsorbed CO_2 to form ammonium carbamate or ammonium bicarbonate, effectively improving the CO_2 capture capacity and selectivity of the carbon capture materials through chemical adsorption[25]. To elucidate the influence of organic amine identity and loading level on the CO_2 capture performance of silicon-based adsorbents derived from gasification slag, Zhang et al. [26] employed acid-leached, impurity-removed gasification slag (FSA) as the precursor material and synthesized a series of amino-functionalized FSA sorbents through physical impregnation using ethylenediamine, diethylenetriamine, triethylenetetramine, and tetraethylenepentamine. The fabrication protocol and CO_2 sorption characteristics are illustrated in Figure 4.

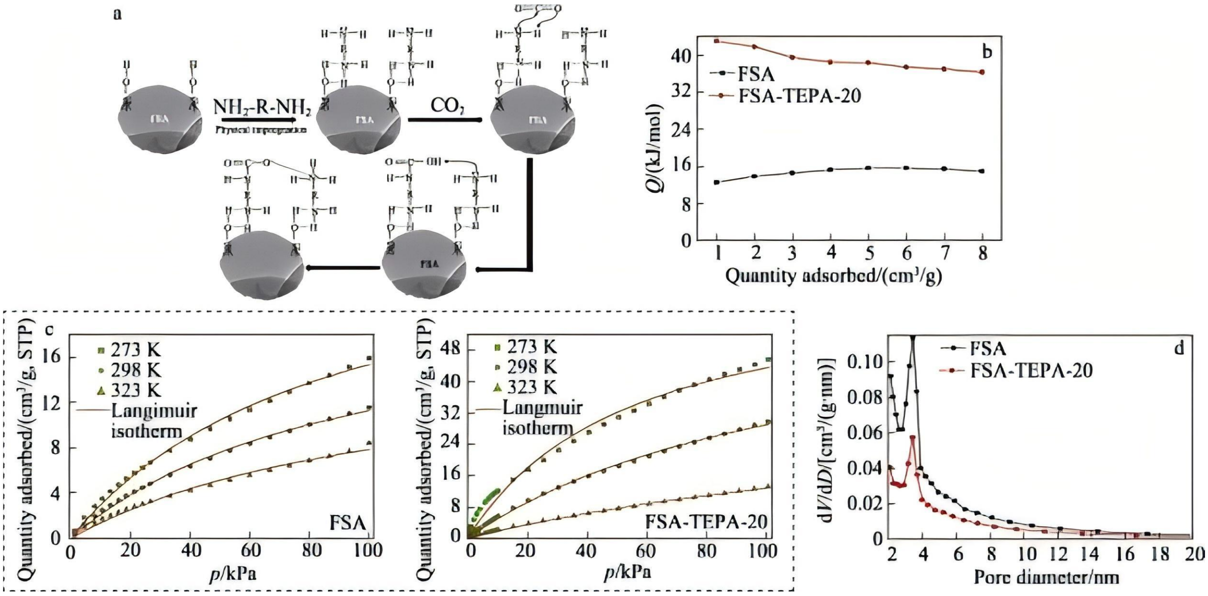

Figure 4 Schematic diagram of preparation mechanism of amino-modified FSA adsorbent(a); Isosteric heats of CO_2 adsorption of FSA-TEPA-20(b); CO_2 adsorption isotherms(c) and pore size distribution curves(d) of FSA and FSA-TEPA-20[26]

The findings demonstrated that escalating organic amine molecular weight correlated with increased amino group loading density, expanded chemisorption site availability, and enhanced CO_2 capture capacity. Nevertheless, excessive amine incorporation engendered pore blockage within the FSA framework, impeding intraporous CO_2 diffusion and consequently diminishing sorption performance. Therefore, identifying an optimal amine loading to harmonize pore structural attributes with surface basicity represents a critical determinant for maximizing CO_2 capture efficiency. At 20% TEPA mass fraction loading, FSA-TEPA-20 achieved superior performance, exhibiting a specific surface area of 185 m^2/g and pore volume of 0.543 cm^3/g. Under conditions of 298 K and 5% CO_2 volumetric concentration, the CO_2 sorption capacity reached 1.32 mmol/g, corresponding to a 156.39% enhancement relative to pristine FSA. Following ten adsorption-desorption cycles, CO_2 capacity declined by 10.61%, attributable to amine volatilization and degradation during thermal regeneration. Adsorption kinetic analysis and isosteric heat calculations revealed that CO_2 uptake on the modified material transitioned from purely physisorption to a hybrid physisorption-chemisorption mechanism, with an increasingly dominant chemisorption contribution. Although the physical impregnation method is simple to operate and allows high amine loading, the organic amines are mainly loaded onto the carrier via van der Waals forces and electrostatic interactions, resulting in poor thermal stability and susceptibility to agglomeration that blocks pores. SUN Jiajun et al.[27] adopted a chemical grafting method to graft 3-aminopropyltriethoxysilane (APTES) onto acid-leached slag (AFS) prepared from hydrochloric acid-treated coal gasification slag, producing an amino-functionalized adsorbent (AFS-A-*x*, where *x*is the addition amount of APTES in mL) with excellent CO_2 capture capacity under low CO_2 pressure. Acidic leaching not only dissolved the majority of metal oxide constituents, thereby enriching the porous architecture of the material, but also induced scission of Si–O–Al linkages within the gasification slag matrix during the process, generating nascent

Si–OH functionalities favorable for subsequent amino group grafting. At 60 °C and 0.1 MPa, the CO_2 adsorption capacity of AFS-A-3 reached 0.61 mmol/g, a 19.6% increase compared to AFS, and after 10 adsorption/desorption cycles, the product's adsorption capacity decreased by only 5%, demonstrating good adsorption cyclic stability. Although organic amine modification can effectively improve the CO_2 capture capacity of silicon-based carbon capture materials, problems such as easy blockage of carrier pores, severe amine loss, and low adsorption capacity remain. It is necessary to improve the spatial structure of silicon-based CO_2 capture materials, study methods for stably loading organic amines on the surface of silicon-based CO_2 capture materials, and enhance the CO_2 capture capacity of silicon-based CO_2 capture materials derived from gasification slag.

2.2 Carbon-Based CO_2 Capture Materials

Activated carbon, as one of the most commonly used CO_2 capture materials, offers advantages such as wide raw material availability, low cost, well-developed pore structure, and wide application range, with easily modifiable surface groups, and is widely used in industrial adsorption separation processes[28]. Following coal gasification, the residual carbon fraction within gasification slag contains minimal uncombusted organic matter and volatile components, while exhibiting substantial specific surface area and microporous volume. In contrast to conventional activated carbon feedstocks such as coal, biomass, and synthetic polymers, activated carbon derived from gasification slag residual carbon obviates the carbonization step, thereby streamlining the overall process. Nevertheless, ash particulates in gasification slag frequently coat the residual carbon surface or become entrapped within its pore network, causing pore occlusion. Consequently, preliminary separation and enrichment of residual carbon through screening, gravity concentration, froth flotation, or acid leaching is imperative [29]. In addition, the high temperature of the coal gasification process causes carbon structure polycondensation, crystallite growth, and aliphatic side chain scission, resulting in a high graphitization degree of the residual carbon, low surface functional group content, and limited CO_2 adsorption sites[30]. Hence, subsequent physical and/or chemical activation treatments are necessary to modulate the specific surface area, pore architecture, and surface chemical characteristics of the enriched residual carbon fraction, thereby fabricating activated carbon materials with enhanced CO_2 capture performance.

2.2.1 Physical Activation

Physical activation refers to the use of oxidative gases such as water vapor, CO_2, air, or their mixtures as activating agents. At temperatures of 300–800 °C, redox reactions occur between the activating agents and carbon atoms in the residual carbon lattice of gasification slag, causing carbon atoms to escape in gaseous form. This creates "cavities" at the original active sites, forming a large number of pores, thereby achieving pore creation and expansion of the raw material. Simultaneously, physical activation can also remove residual inorganic minerals and tar produced during the gasification process, and introduce active oxygen-containing functional groups by oxidizing the carbon surface via the oxidizing agent, thereby improving the structural characteristics and surface properties of the residual carbon to enhance the CO_2 capture capacity of carbon-based CO_2 capture materials. During physical activation, gaseous activating agents such as water vapor and carbon dioxide diffuse toward and adsorb onto surface active sites of the residual carbon fraction at relatively moderate temperatures. With progressive elevation of activation temperature, carbon atom reactivity intensifies, promoting reaction with adsorbed water vapor or CO_2 to yield transient oxygenated intermediates of limited stability. These intermediates further decompose to produce CO, or react with CO to generate CO_2, which then desorbs and diffuses into the gas stream, forming a large number of new micropores within the residual carbon and creating more active sites for continued reaction. The specific reaction mechanisms are shown in Eqs. (10)–(15)[31].

C∗+H2 O→C∗(H2 O)C∗+CO2 →C∗(CO2)C∗(H2 O)→C∗(O)+H2 C∗(CO2)→C∗(O)+COC∗(O)→COCO +C∗(O)→C∗(CO2) (10)(11)(12)(13)(14)(15)

Where: C∗represents the active site on the residual carbon lattice of gasification slag; C∗(H2 O)and C∗(CO2)represent H2 Oand CO2 attached to the active sites of gasification slag residual carbon, respectively; C∗(O)represents the unstable oxygen-containing intermediate.

The effectiveness of physical activation is usually influenced by factors such as the type of activating agent, activation temperature, reaction time, and activating agent flow rate.

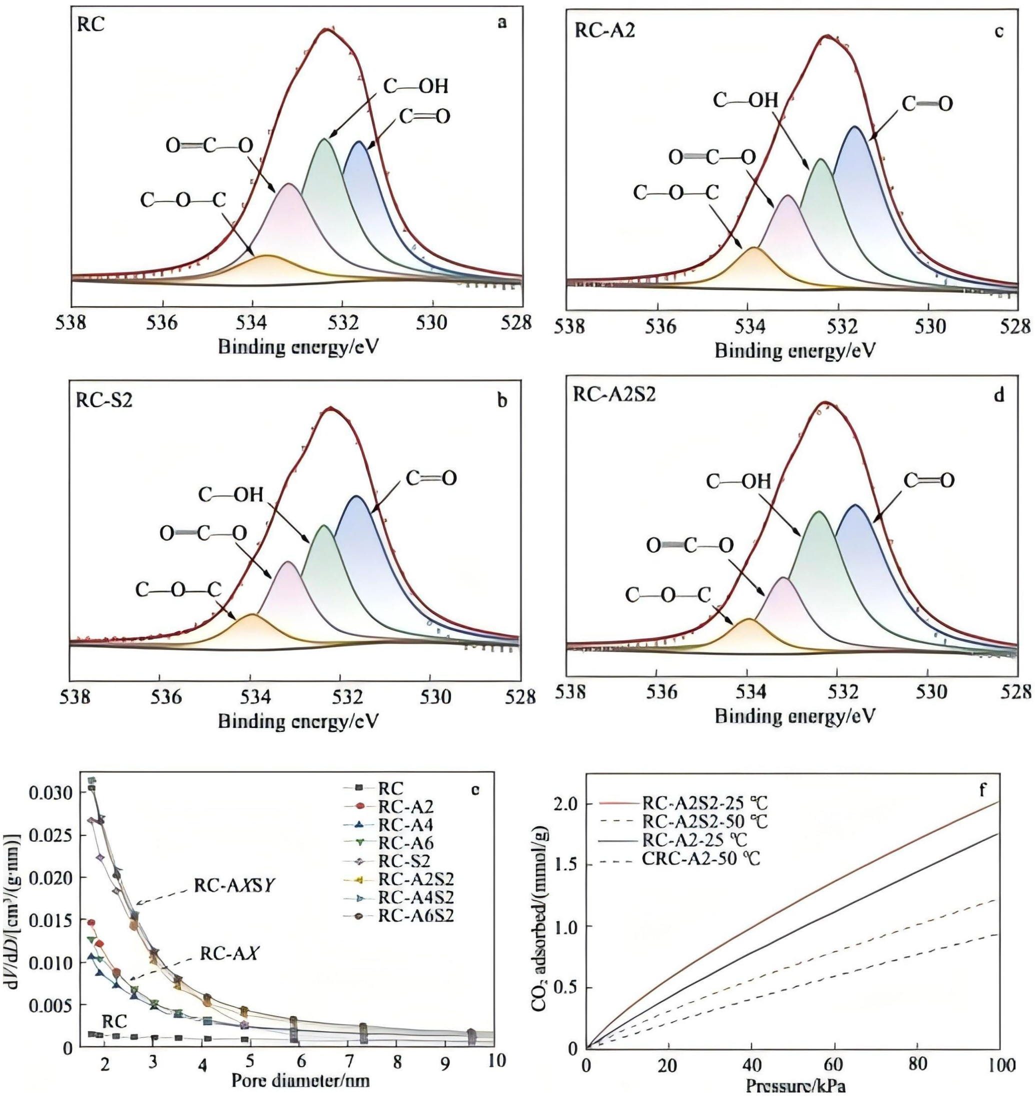

Figure 5 Effects of RC, RC-A2, RC-S2, RC-A2S2 on surface functional groups(a~d), pore volume(e) and CO_2 adsorption capacity(f) of residue carbon from coal gasification slag[32]

REN et al.[32] used residual carbon (RC, ignition loss 91.29%) separated and enriched from gasification fine slag via ultrasound-assisted flotation as a raw material. They activated the residual carbon using air (300 °C), water vapor (600 °C), and air-water vapor mixtures, respectively, to prepare a series of gasification slag-based activated carbon CO_2 capture materials, and investigated the effects of different process parameters on the CO_2 capture capacity of the products (Figure 5). The results showed that compared with air activation, water vapor has smaller molecular dimensions, faster diffusion rates in residual carbon pores, lower reaction activation energy with carbon, and stronger reactivity. Therefore, more intense oxidation reactions occurred in RC under water vapor activation, leading to more significant improvements in specific surface area and total pore volume. Compared with unactivated RC, after 2 h of activation with air, water vapor, and air-water vapor mixtures, the specific surface areas of the residual carbon (denoted as RC-A2, RC-S2, and RC-A2S2, respectively) increased from 12.00 m^2/g to 108.00, 289.24, and 327.03 m^2/g, respectively, and the total pore volumes increased from 0.04 cm^3/g to 0.12, 0.20, and 0.24 cm^3/g, respectively. At 25 °C and 0.1 MPa, RC-A2S2 exhibited the maximum CO_2 adsorption capacity, reaching 2.00 mmol/g. GAO et al.[33] used dried gasification fine slag (CGFS) as a raw material and prepared activated carbon CO_2 capture materials via a one-step low-temperature air activation method. During the low-temperature air activation at 485 °C, slight oxidation of the carbon matrix, combustion of ash and tar blocking the pores, and decomposition of some inorganic mineral carbonates opened up blocked pore channels. Compared with CGFS, after 20 min of low-temperature air activation, the specific surface area and pore volume of the sample (CGFS-20) increased from 247.53 m^2/g and 0.2895 cm^3/g to 300.84 m^2/g and 0.3093 cm^3/g, representing improvements of 21.5% and 6.8%, respectively. At 25 °C, the maximum theoretical CO_2 adsorption capacity of CGFS-20 reached 0.94 mmol/g.The physical activation method features a simple process flow, low cost, minimal environmental pollution, no equipment corrosion, and the produced activated carbon can be used directly without washing, facilitating large-scale promotion and application. However, gaseous activating agents such as water vapor and CO_2 have relatively weak reactivity; the activation process usually takes a long time, consumes high energy, and cannot form a rich pore structure. Therefore, the specific surface area of the products is often lower than that from chemical activation methods, resulting in relatively lower CO_2 capture capacity.

2.2.2 Chemical Activation

Chemical activation entails blending or impregnating gasification slag residual carbon with a chemical activating agent at a predetermined proportion, enabling the activator to permeate the internal structure of the carbonaceous material. Subsequent high-temperature activation under inert atmosphere is followed by exhaustive washing to eliminate residual activator and contaminants, yielding the final activated carbon product. Chemical activation not only facilitates the development of the residual carbon pore structure but also introduces basic groups, increasing the surface basicity of the carbon and enhancing the material's CO_2 capture capacity. Commonly used chemical activating agents mainly include strong alkalis (KOH, NaOH), strong acids (HCl, HNO_3, H_2SO_4, H_3PO_4), and salts ($ZnCl_2$, K_2CO_3, $CaCl_2$), among which KOH is the most frequently used[34]. Because of the small radius and low electronegativity of K, the specific surface area of activated carbon after KOH activation increases by approximately 4 times compared to other activation methods[35]. In the KOH activation protocol, the residual carbon fraction is initially immersed in potassium hydroxide solution for a defined duration to ensure complete diffusion of the activator onto the carbon surface and throughout its porous network. Then, under molten conditions induced by heating, a series of redox reactions between KOH and C consume carbon atoms, continuously etching the carbon material and forming new microporous structures. The specific activation mechanisms are shown in Eqs. (16)–(20)[36]. During the activation process, elemental K generated can intercalate into the carbon lattice in vapor form, widening the interlayer spacing of carbon and forming pore structures[37-38]. Additionally, H_2O and CO_2 evolved from the KOH-carbon reaction can further activate the carbon framework through physical activation pathways as described in Eqs. (10)–(15), generating a synergistic enhancement effect. Miao Zekai et al. [39] employed residual carbon from gasification fine slag (ash content <1.5%) obtained through froth flotation and acid washing for deashing as the precursor material, utilizing KOH as the chemical activator to fabricate a series of activated carbon CO_2 capture sorbents via high-temperature chemical activation. They systematically examined the influence of activation temperature, activator-to-carbon ratio, and activation duration on the porous architecture and CO_2 capture performance of the resulting activated carbons. The findings demonstrated that under optimal conditions of 800 °C, KOH-to-residual carbon mass ratio of 2:1, and 90 min activation time, the synthesized activated carbon exhibited abundant macroporous surface features with micropores and mesopores distributed along macropore walls, collectively constituting an interconnected hierarchical pore network spanning macro-, meso-, and microporous regimes. The specific surface area and total pore volume attained 1596 m^2/g and 1.297 cm^3/g, respectively. The optimized product demonstrated exceptionally rapid adsorption kinetics, approaching saturation within approximately 1.5 min. At 0, 25, and 50 °C, the CO_2 sorption capacities reached 4.90, 2.75, and 0.86 mmol/g, respectively. Following ten consecutive adsorption-desorption cycles, no appreciable capacity degradation was observed. Furthermore, the CO_2 capture performance across these three temperatures exhibited strong correlation with narrow micropore (<1.5 nm) volume. The aperture dimensions of these ultrafine micropores approximate the kinetic diameter of CO_2 molecules (0.33 nm), which amplifies van der Waals interactions and electrostatic forces between pore walls and CO_2 molecules, thereby governing the adsorption capacity of the activated carbon sorbent.

$6KOH+2C\rightarrow 2K+3H_2+2K_2CO_3\quad K_2CO_3\rightarrow K_2O+CO_2\quad K_2CO_3+C\rightarrow K_2O+2CO K_2O+C\rightarrow 2K+CO_2K+CO_2\rightarrow K_2O+CO$ (16)(17)(18)(19)(20)

Pre-oxidation treatment of carbonaceous precursors represents an effective strategy for generating abundant porous architectures and enhancing CO_2 capture performance in activated carbons. Through the introduction of oxygenated surface functionalities onto carbon materials, these groups subsequently react with KOH to generate novel active centers (C – O – K). C–O–K reacts with KOH to generate K_2CO_3 [Eqs. (21)–(22)], promoting the penetration of KOH into deeper layers of the carbon structure[40-41]. Based on this, MIAO et al.[42] used HNO_3, NaClO, H_2O_2, and air as pre-oxidizing agents to pre-oxidize gasification slag residual carbon, and investigated the effects of different types of pre-oxidation treatments on the pore structure characteristics and CO_2 capture capacity of activated carbon. In comparison with unmodified residual carbon, the surface abundance of C=O and C(=O)–OH moieties on pre-oxidized residual carbon increased markedly, whereas C–OH, C – O – C, and O – C=O functionalities diminished. Correlation analysis between C=O and O – C=O surface concentrations across diverse carbon precursors and the resultant activated carbon specific surface area (Figure 6) demonstrated that O – C=O content exhibited positive association with specific surface area development, while C=O presence constrained pore structural evolution. This may be because O–C=O is acidic and can better react with KOH to form C–O–K active sites, strengthening the chemical activation process via Eqs. (21)–(22); conversely, basic C=O limits the KOH activation process. Compared with samples without pre-oxidation treatment, the activated carbon pre-oxidized with HNO_3 and with an oxygen mass fraction of 15% (15 NARC) had the largest specific surface area and total pore volume, increasing from 1246.00 m²/g and 0.88 cm³/g for the untreated sample (RC) to 1812.00 m²/g and 1.37 cm³/g, respectively. At 25 °C and 0.1 MPa, its CO_2 adsorption capacity was maximized, reaching 3.36 mmol/g, and it exhibited a high adsorption rate, achieving 86% adsorption efficiency within 1 min. Although pre-oxidation treatment can effectively improve the pore structure and CO_2 capture capacity of activated carbon, it easily causes carbon loss, leading to a low activated carbon yield of only 42%–56%.

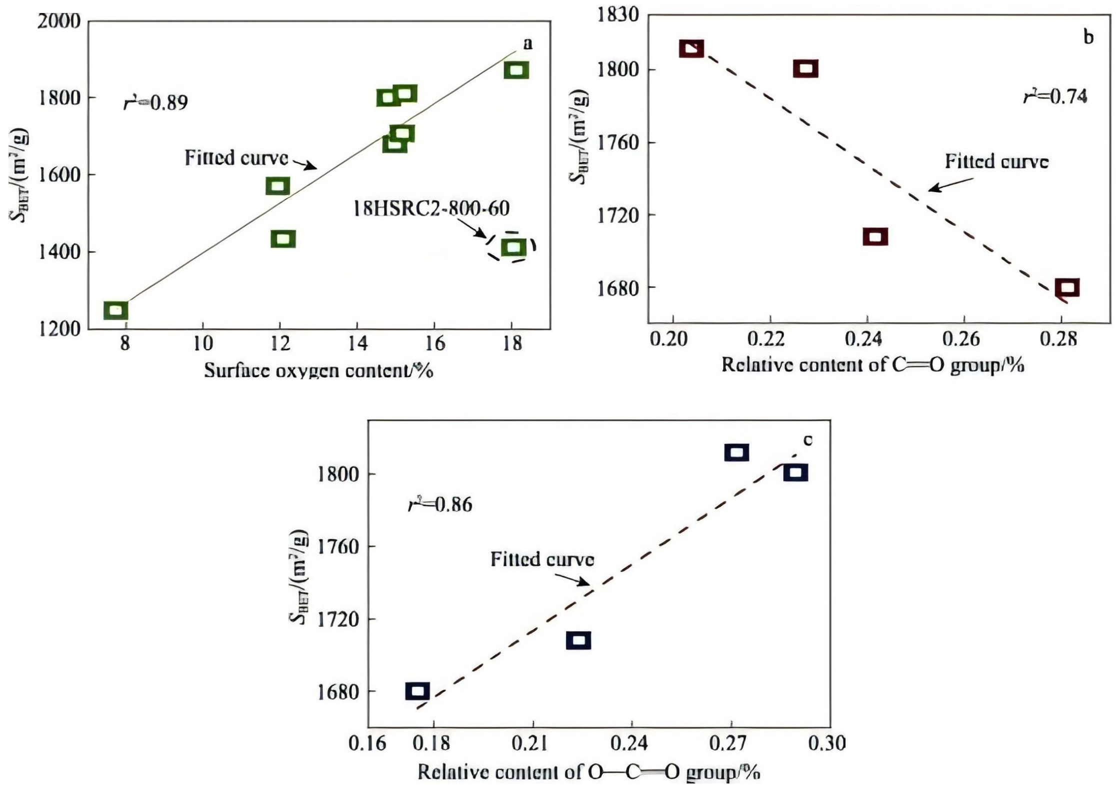

Figure 6 Relationship between surface oxygen content(a), C=O group content(b) and O–C=O group content(c) and surface area of activated carbon after different pre-oxidation treatment[42]

$\text{C–O–K+KOH+H}_2\ \text{O} \rightarrow \text{K}_2\ \text{CO}_3\ +23\ \ \text{H}_2\ \ \text{O=C–O–K+KOH} \rightarrow \text{K}_2\ \text{CO}_3\ +21\ \ \text{H}_2$ (21)(22)

The formation of the pore structure of gasification slag-based CO_2 capture materials not only stems from the activation process but also from the acid washing process after activation. Acid washing can further improve the pore structure of the product by removing potassium-containing compounds formed during activation and dissolving inorganic mineral particles. MIAO et al.[43] investigated the effects of different acid washing conditions (acid type, acid washing temperature, acid washing time, acid concentration) on the pore structure of porous carbon materials after alkali melting treatment via orthogonal experiments. The results showed that acid treatment to remove inorganic minerals in the micropores of residual carbon is a diffusion-controlled process. Low-temperature, low-concentration acid treatment removes most of the inorganic minerals in the mesopores. With escalating treatment temperature and acid concentration, the acidic medium progressively permeates into microporous channels to dissolve entrapped mineral constituents, thereby exposing previously occluded pores. Post-activation, the carbon capture materials exhibited near-complete elimination of inorganic mineral particulates from both surface and intraporous regions, developing a more refined microporous architecture while preserving the porous carbon framework established during activation. Under optimal conditions of 15% H_2SO_4 at 25 °C for 4 h, the product attained a maximum specific surface area of 1295 m^2/g. At 25 and 50 °C, the material achieved CO_2 sorption capacities of 2.64 and 1.02 mmol/g within 2 min, respectively. The adsorption selectivity for N_2/CO_2 -dominated flue gas reached 10.8, indicating preferential CO_2 affinity. Following ten consecutive adsorption-desorption cycles, the sorption capacity remained at 97% of its initial value, demonstrating excellent regenerative stability.

Relative to physical activation methodologies, chemical activation presents superior reaction kinetics, more extensively developed porous architectures in the resulting activated carbon, greater specific surface areas, and enhanced suitability for CO_2 capture applications. However, existing research mainly uses KOH as the activating agent, and the cleaning process consumes large amounts of acid, which is difficult to recover, easily causes equipment corrosion and secondary pollution, and increases production costs. Low-cost, non-corrosive, and environmentally friendly chemical reagents should be further developed to improve the economic and environmental benefits of the chemical activation method for preparing activated carbon.

2.3 Carbon-Ash Composite CO_2 Capture Materials

Gasification slag contains a large amount of ash, which typically exists in forms such as complete separation, carbon-ash melting, attachment to the residual carbon surface, or embedding within its pores. Using gasification slag to prepare silicon-based or carbon-based CO_2 capture materials usually requires consuming large amounts of flotation reagents and acids for carbon-ash separation and impurity element removal, resulting in high processing costs and low economic benefits. Simultaneously, large amounts of difficult-to-treat wastewater are generated, easily causing secondary pollution, and leading to the waste of abundant resources such as Al, Ca, and Mg, failing to realize the full utilization of valuable resources in gasification slag. Consequently, investigations into the development of composite CO_2 capture materials leveraging the inherent carbon-ash coexistence within gasification slag have garnered escalating research interest, aiming to achieve concurrent valorization of both mineral and carbonaceous fractions. A systematic series of studies by Miao et al. [36,44-46] on mineral-mediated pore generation mechanisms during gasification slag chemical activation revealed that the ash component in gasification fine slag functions as a structural scaffold preventing pore collapse while concurrently facilitating the chemical activation process during fabrication of carbon-ash composite CO_2 sorbents. This mineral fraction thus constitutes a critical determinant governing porous material architecture and ultimate CO_2 capture performance. During the preparation of carbon-ash composite CO_2 capture materials from gasification fine slag via the KOH chemical activation method, KOH diffuses into the pores of residual carbon via impregnation, dissolving part of the Fe, Ca, Mg, Na, K, and other metal elements in the ash, allowing them to disperse evenly on the carbon surface. During the heating process, part of the leached metal elements can bind to the carbon matrix via oxygen atoms to form C–O–M bonds (M = metal element), and convert into low eutectic mixtures such as $KFeO2$ and $Mg3Ca(CO3)4$ during the pyrolysis process. These low eutectic mixtures exhibit good fluidity at high temperatures, helping to improve the fluidity of potassium-containing compounds generated from the reaction between KOH and C, allowing them to disperse better on the residual carbon surface and inside pores, promoting the activation reaction and the development of pore structure. Meanwhile, the metal elements in the low eutectic mixtures can catalyze the physical activation process of water vapor and CO_2 generated during the chemical activation process, further enhancing the synergistic effect of physical-chemical activation[48]. MIAO et al.[36] used gasification fine slag (FS) and foam-floated, acid-leached, enriched residual carbon (RC) as raw materials, respectively, to prepare a series of CO_2 capture materials with interconnected macroporous-meso/microporous structures via the KOH activation method. The findings demonstrated that ash incorporation effectively facilitated pore structural development in gasification slag-derived CO_2 capture materials. Under comparable ash content, with an FS-to-KOH mass ratio of 2:1, activation temperature of 800 °C, and activation duration of 60 min, the synthesized carbon capture material (FS2-800-60) attained a specific surface area of 1187 m^2/g, exceeding the 1114 m^2/g achieved using residual carbon alone, while reducing activation time by approximately 30 min. Nevertheless, product yield remained comparatively low at 36%–42%. Furthermore, the alkali and alkaline earth metal content within FS furnished supplementary active sites for CO_2 adsorption. At 0 and 25 °C, the FS-based activated carbon achieved CO_2 capture capacities of 4.01 and 2.53 mmol/g within 2 min, respectively. Following five adsorption-desorption cycles, no appreciable capacity degradation was observed, attesting to favorable regenerative stability. The underlying reaction mechanisms and their influence on material architecture and CO_2 capture performance are illustrated in Figure 7.

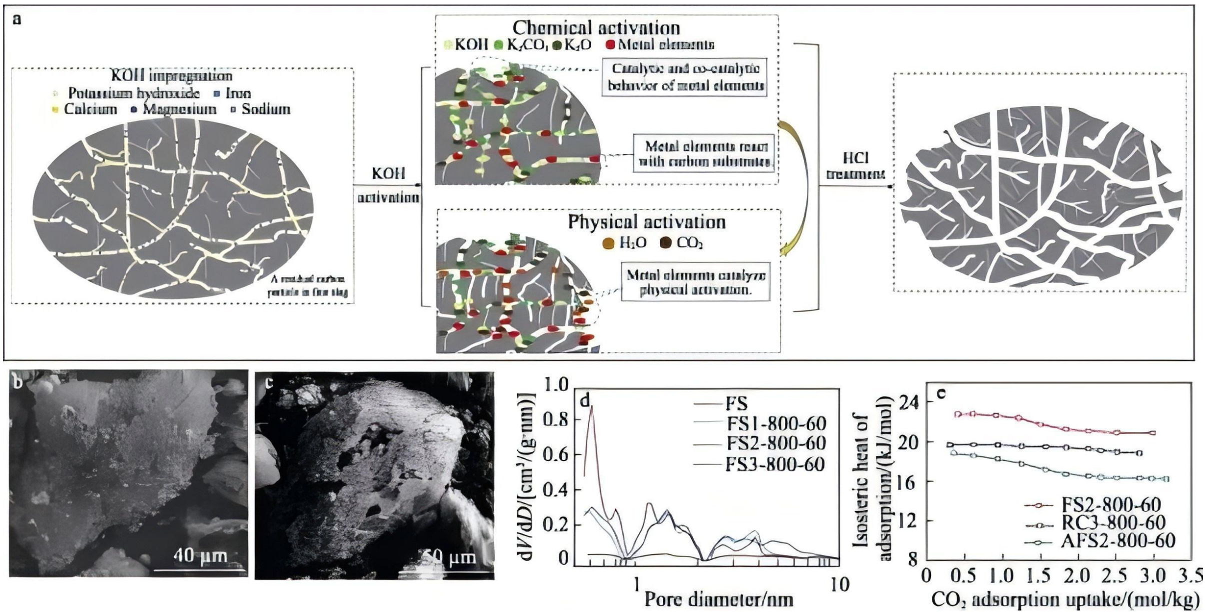

Figure 7 Schematic diagram of preparation of carbon-ash composite carbon capture materials based on coal gasification slag(a); SEM images of FS(b) and FS2-800-60(c); Pore size distribution curves(d) and isosteric heats of CO_2 adsorption(e) of diverse adsorbents[36]

Mineral particles in gasification slag not only help promote the chemical activation process during the preparation of carbon-ash composite CO_2 capture materials, but the contained SiO_2 and Al_2O_3 can also serve as raw materials for preparing zeolites, synergistically synthesizing porous carbon-zeolite composite adsorbents with residual carbon[49-50]. MIAO et al.[45] mixed KOH-activated samples (FSAC) with NaOH solution, aged for a period, and then subjected them to hydrothermal crystallization. Through 9 sets of orthogonal experiments, they developed a method for preparing gasification slag-based porous carbon-zeolite composite CO_2 capture materials [(x-FSAC-HPC, where x is the orthogonal experiment number)] via chemical activation-hydrothermal treatment (Figure 8). After KOH activation and acid washing, the mineral particles transformed from smooth spherical particles into a layered porous structure with a loose texture. During the NaOH solution aging process, OH^- ions could enter the interior of mineral particles via pores and react with amorphous aluminosilicates, causing the cleavage of Si–O–Al and Si–O–Si bonds to form new Si–O, Si–OH, Al–O, or Al–OH bonds. These then re-formed silicates or aluminosilicates via interactions of these chemical bonds [Eq. (23)]. Subsequently, the silicates or aluminosilicates continuously grew using nucleation points provided by the porous carbon surface, forming silicate or aluminosilicate films on the surface of the porous carbon substrate. This transformation converted mesoporous and macroporous channels within the porous carbon into microporous and mesoporous regimes, substantially amplifying the specific surface area and pore volume of the resulting materials while furnishing additional active sorption sites for CO_2 molecules. Relative to the FSHPC precursor, the optimized FSHPC-NM specimen exhibited a specific surface area of 2194 m^2/g and total pore volume of 2.095 cm^3/g. At 25 °C and 101.325 kPa, the CO_2 adsorption capacity of FSHPC-NM reached a maximum of 3.72 mmol/g, an increase of more than 40% compared to before hydrothermal treatment, and exhibited a high adsorption rate and adsorption selectivity, with a CO_2/N_2 adsorption selectivity of 9.5–10.8[44-46]. Adsorption equilibrium could be reached within 3 min, and after 10 adsorption-desorption cycles, 98% of the adsorption capacity was retained. In the process of preparing porous carbon capture materials from gasification slag, large amounts of KOH are often consumed, which is not only costly but also easily causes secondary pollution. To solve this problem, ZHU et al.[51] used deionized water leachate from two types of biomass power plant fly ash (wheat straw and rice husk incineration fly ash) to replace KOH as the alkali and potassium source (potassium carbonate, potassium sulfate, and potassium chloride). They prepared a series of gasification slag-based carbon-ash composite CO_2 capture materials via chemical activation and hydrothermal methods. The results showed that wheat straw incineration fly ash had the highest alkali metal leaching amount and pH. Immersing 10 g of wheat straw power generation fly ash in 50 mL of water yielded a leachate; the introduced alkali and potassium sources along with other metal ions facilitated micropore formation within the material and opened some previously occluded pore channels, generating a well-developed, loofah-like porous architecture that enhanced the material's specific surface area. Relative to the product (CAC) obtained through KOH activation alone, the specific surface area of the fly ash-activated product (CAC-10) increased from 1270 m^2/g to 1406 m^2/g. At 25 °C and 101.325 kPa, CAC-10 achieved CO_2 adsorption equilibrium within 3 min, with a maximum sorption capacity of 2.00 mmol/g.

$NaOH+NaAl(OH)_4(aq)+Na_2SiO_3(aq)\rightarrow Na(AlO_2)(SiO_2)\cdot 3NaOH\cdot H_2O$(23)

Compared with silicon-based and carbon-based CO_2 capture materials, the preparation of carbon-ash composite CO_2 capture materials can achieve full utilization of gasification slag and reduce by-product generation. However, existing methods still face challenges such as complex process flows, high energy consumption, and difficulty in large-scale utilization.

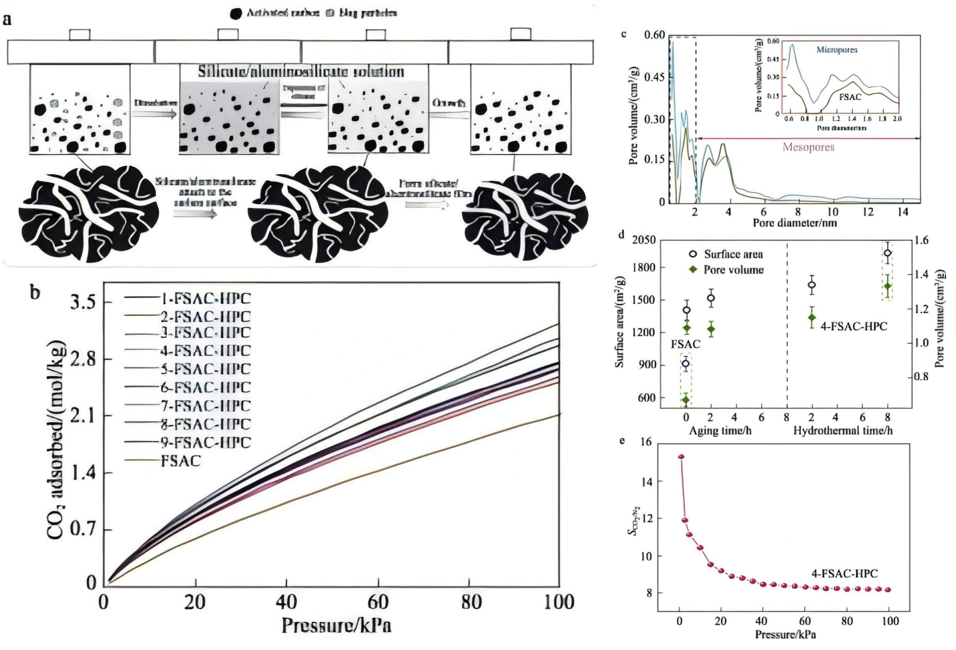

Figure 8 Schematic diagram of preparation carbon-ash composite CO_2 capture materials treated by hydrothermal method(a); CO_2 adsorption isotherms(b) and pore distribution curves(c) of diverse samples; Change of specific surface area and pore volume of sample before and after hydrothermal treatment of samples(d); and CO_2/N_2 selectivity(SCO2/N2) of 4-FSAC-HPC(e)[45]

2.4 Analysis of CO_2 Capture Capacity of Different Carbon Capture Materials

Based on the interaction mechanisms between CO_2 molecules and carbonaceous sorbents, CO_2 capture can be categorized into physisorption and chemisorption pathways. Physisorption predominantly proceeds through van der Waals interactions, electrostatic forces, and pore volume filling between CO_2 molecules and the internal pore surfaces of carbon capture materials. The sorption capacity is primarily governed by the structural attributes of the sorbent, including pore dimensions, pore volume, and specific surface area [52]. The physisorption process is exothermic in nature; with increasing adsorption temperature, the kinetic energy of CO_2 molecules intensifies, attenuating the intermolecular forces between CO_2 and the carbonaceous substrate, thereby promoting desorption and diminishing physical CO_2 uptake at elevated temperatures [53]. Chemisorption exploits Lewis acid-base interactions and hydrogen bonding between acidic CO_2 molecules and basic surface functionalities on the carbon capture material, undergoing an irreversible exothermic chemical transformation for CO_2 sequestration. The carbon capture performance is mainly affected by the composition of surface functional groups and surface basicity[54]. The CO_2 capture capacity of carbon capture materials is mainly evaluated through indicators such as adsorption capacity, adsorption rate, adsorption cyclic stability, and adsorption selectivity[55]. Table 1 lists the structural characteristics and CO_2 capture performance indicators of different gasification slag-based CO_2 capture materials. As can be seen from Table 1, existing research generally focuses on the adsorption capacity, cyclic stability, and adsorption rate of gasification slag-based CO_2 capture materials, lacking research on their adsorption selectivity. Under certain adsorption conditions, the CO_2 adsorption capacity of gasification slag-based carbon capture materials can reach 0.61–3.72 mmol/g, and adsorption saturation can be achieved within 1.5–10.0 min. After 5–20 adsorption-desorption cycles, they can still maintain a high adsorption capacity. MIAO et al.[56], through correlation analysis between the pore characteristics of gasification slag-based CO_2 capture materials and their carbon capture capacity, found that at 101.325 kPa, the CO_2 adsorption capacity of carbon capture materials had a significant correlation with the pore volume of narrow micropores (<1.5 nm), but had little correlation with total pore volume and specific surface area. Compared with silicon-based CO_2 capture materials, carbon-based and carbon-ash composite CO_2 capture materials have relatively higher adsorption capacities. This may be because carbon-based and carbon-ash composite CO_2 capture materials have relatively higher micropore volumes, and the micropore size better matches the kinetic diameter (0.33 nm) of CO_2 molecules, favoring CO_2 capture. Currently, there are large differences in the test conditions for CO_2 capture performance in the literature, and a unified standard has not yet been formed. Adsorption results cannot be mutually converted, making it impossible to accurately evaluate the CO_2 capture potential of gasification slag. In addition, the CO_2 capture of existing gasification slag-based carbon capture materials is mainly controlled by the physical adsorption mechanism. By selecting appropriate preparation methods and adjusting reaction parameters to regulate the structural characteristics of the materials, their CO_2 capture performance can be improved. As can also be seen from Table 1, under the same adsorption conditions, carbon capture materials after chemical activation have relatively higher specific surface areas, micropore volumes, and CO_2 capture capacities. Among them, the porous carbon-zeolite composite CO_2 capture material (FS-25-HA-HT) prepared from gasification slag via KOH activation and hydrothermal treatment exhibited the maximum CO_2 capture capacity, reaching 3.72 mmol/g. However, owing to variability in feedstock coal properties, gasification reactor configurations, operational parameters, and slag discharge methodologies, the compositional and physicochemical attributes of coal gasification slag exhibit substantial heterogeneity, consequently engendering pronounced disparities in CO_2 capture performance even under identical fabrication conditions. Targeted research needs to be conducted based on different characteristics of gasification slag to determine the corresponding optimal preparation methods for CO_2 capture materials.

3 CO_2 Mineralization Utilization Technologies Based on Gasification Slag

Captured and separated CO_2 needs to be transferred to suitable storage or utilization sites for safe storage via geological sequestration or deep-sea sequestration technologies, or converted into high-value-added chemicals via chemical or biological technologies for utilization. CO_2 mineralization utilization technology refers to the process of reacting captured CO_2 with ores rich in alkaline oxides and hydroxides such as CaO and MgO in nature, or alkaline solid wastes, to convert it into carbonates, facilitating CO_2 sequestration and utilization. Compared with other sequestration technologies, the products of CO_2 mineralization utilization have stable chemical properties, are environmentally friendly, and can achieve permanent storage of CO_2, effectively avoiding risks associated with traditional geological and ocean sequestration such as CO_2 leakage, groundwater contamination, and ecological damage[57-58]. Meanwhile, purified carbonates obtained from mineralization can be directly sold or converted into high-value-added products, offering higher utilization value. Gasification slag contains 5%–32% by mass of CaO and MgO with certain reactivity, making it an ideal raw material for CO_2 mineralization utilization. At present, CO_2 mineralization utilization technologies employing gasification slag as feedstock are generally classified into direct mineralization and indirect mineralization pathways based on process routing distinctions.

3.1 Direct Mineralization of CO_2 by Gasification Slag

Direct mineralization methods include dry and wet processes. Dry (gas-solid) direct mineralization refers to the direct reaction of CO_2 gas with mineralization raw materials to generate carbonates, requiring no additional chemical reagents. The relative humidity during the gas-solid carbonation process is usually <20%, with low reaction rates and conversion rates. Pretreatment such as grinding and thermal activation of raw materials, or increasing temperature and pressure, is required to accelerate the reaction rate[59]. Since Ca and Mg in gasification slag usually exist in an embedded or encapsulated form with aluminosilicates[60], their reactivity for dry direct mineralization with CO_2 is low, resulting in low carbon conversion rates and CO_2 sequestration capacity. Aqueous-phase direct mineralization can enhance carbonation kinetics and elevate mineralization conversion efficiency through a gas-solid-liquid three-phase reaction framework, constituting a more promising approach among direct mineralization strategies. The wet direct mineralization process occurs in an aqueous environment, where CO_2 first dissolves in water to generate H_2CO_3/HCO_3^-, which then reacts with alkali metals dissociated from the mineralization raw materials in water to form carbonates[61]. ZHANG Yi[62] used ground, dried, and 80-mesh sieved gasification slag (GS) and modified gasification slag (nGS) after ethanol wet ball milling as raw materials to evaluate the wet direct mineralization capacity of gasification slag before and after modification based on the wet direct carbonation reaction. The results showed that after ball milling modification, the particle size of gasification slag decreased, the specific surface area increased, and the original surface structure was destroyed, exposing more calcium-based active sites and increasing the probability of the mineralization reaction between nGS and CO_2. Compared with GS, the CO_2 mineralization and sequestration capacity of nGS increased from 70.44 g/kg (calculated based on the mass of gasification slag, the same below) to 112.27 g/kg. HUO et al.[63] used Gibbs free energy minimization software to evaluate the CO_2 mineralization capacity of gasification slag slurry with a water-to-cementitious material mass ratio of 0.8 prepared via NaOH activation when used as goaf backfill material. Under alkali excitation, Si–O and Al–O bonds in the gasification slag broke, forming a series of low-polymeric silicon (aluminum) tetrahedron units. These oligomers further dehydrated and condensed, undergoing hydration reactions with $Ca^{2+}$and $Mg^{2+}$to form C–S–H and M–S–H gels, which could further react with CO_2 to generate $CaCO_3$ and $MgCO_3$ [Eqs. (24)–(25)]. Under the premise of ensuring the strength of the gasification slag slurry used as goaf backfill paste, when the CO_2 volume fraction was 20%, the theoretical CO_2 storage capacity of coal gasification slag could reach 215.77 g/kg.

$$(CaO)_a(SiO_2)_b(H_2O)_c+aCO_2\rightarrow aCaCO_3+bSiO_2+cH_2O \quad (MgO)_d(SiO_2)_e(H_2O)_f+dCO_2\rightarrow dMgCO_3+eSiO_2+fH_2O \quad (24)(25)$$

In addition, the National Energy Group Guoyuan Electric Power Co., Ltd.[64] is conducting an industrial demonstration project for a 10,000-ton-level CO_2 mineralization absorption coupled with mine fire prevention (extinguishing) materials. Based on coal mine backfill mining technology, coal-based solid wastes (fly ash, coal gangue, bottom slag, desulfurization gypsum, gasification slag, etc.) are used to react with CO_2 for mineralization to excite the activity of the materials and prepare carbon-sequestering backfill cementitious materials. It is expected to sequester 10,000 tons of CO_2 annually.

Furthermore, gasification slag is rich in amorphous SiO_2, Al_2O_3, CaO, and Fe_2O_3, resembling the composition of Portland cement, and has good hydration activity and pozzolanic activity. Under certain conditions, its latent cementing ability can be excited, allowing it to be used as an admixture or aggregate. Via a CO_2 mineralization curing process, it can be used to prepare cement-based materials or geopolymers, realizing CO_2 mineralization sequestration. The calcium carbonate crystals precipitated during mineralization can adhere to or become embedded within the calcium-silicate-hydrate gel hydration products, occupying voids and micro-fissures in the interfacial transition zone. This enhances aggregate-matrix interfacial adhesion, mitigates transition zone imperfections, establishes robust bonding, and consequently improves mechanical performance and long-term durability of the composite materials [65]. Wang et al. [66] employed gasification slag and magnesium slag as feedstocks to fabricate a low-carbon composite concrete through CO_2 mineralization curing. Their investigation revealed that silicate mineralization and hydration processes in magnesium slag created favorable conditions for aluminosilicate depolymerization within gasification slag. The aluminosilicate constituents in gasification slag facilitated composite matrix reconstruction and carbonation reactions through generation of C–A–S–H and C–(A–F)–S–H gels, thereby enhancing the mechanical properties of the composite material. At an optimal magnesium slag-to-gasification slag mass ratio of 0.4, the composite concrete achieved maximum compressive and flexural strengths of 38.9 MPa and 9.1 MPa, respectively, following 28 days of CO_2 mineralization curing, with a $CaCO_3$ yield of approximately 9.21%. Utilizing gasification slag via CO_2 mineralization curing concrete technology for CO_2 capture and utilization is an effective pathway to achieve gasification slag resource utilization and carbon emission reduction. During the CO_2 carbonation process of gasification slag, heavy metals can be co-precipitated and physically adsorbed, thereby preventing heavy metal leaching. However, relevant research remains limited. Future studies should further fully investigate the feasibility and mechanism of gasification slag CO_2 mineralization curing concrete technology, and deeply discuss the effects of mineralization temperature, pressure, alkali concentration, liquid-solid ratio, and other factors on the CO_2 mineralization efficiency of gasification slag.

3.2 Indirect Mineralization of CO_2 by Gasification Slag

Indirect CO_2 mineralization technology mainly includes two steps: first, using leaching agents such as HCl, H_2SO_4, NaOH, and ammonium salts to extract active components such as $Ca^{2+}$and $Mg^{2+}$from the mineralization raw materials; second, under alkaline conditions, introducing CO_2 into the solution rich in $Ca^{2+}$and $Mg^{2+}$to undergo a carbonation reaction to generate carbonates, realizing CO_2 mineralization utilization[67]. Compared with direct mineralization technology, the indirect mineralization process can remove impurity elements from gasification slag, obtain high-purity, high-value-added carbonate products, and operate under mild reaction conditions. However, using HCl, H_2SO_4, NaOH, etc., as leaching agents results in high leaching efficiency but suffers from high acid and alkali consumption, difficulty in extracting agent recovery, and high regeneration energy consumption.

To solve the problem of extracting agent regeneration, the indirect mineralization process based on NH_4Clcycling has attracted widespread attention in recent years because it requires no acid/base consumption and allows chemical reagent recycling[68-69]. During the NH_4Clcyclic indirect mineralization process, HCl and NH_3 generated from the thermal decomposition of ammonium chloride can be recycled for leaching Ca^{2+}, Mg^{2+}, etc., from gasification slag and adjusting the pH of the leachate before the carbonation reaction, respectively [Eqs. (26)–(31)]. LI Xiangyu et al.[70] conducted in-depth research on the process of preparing $CaCO_3$ via a three-step decarbonized gasification slag indirect mineralization cycle comprising Ca^{2+}leaching–CO_2 carbonation–NH_4Clrecycling. They systematically examined the influence of leaching agent identity, concentration, liquid-to-solid ratio, contact duration, and temperature on calcium extraction efficiency from decarbonized gasification slag, alongside the effects of CO_2 flow rate, reaction temperature, and carbonation duration on both carbonation conversion efficiency and calcium carbonate crystallographic characteristics. Under optimized conditions of 2 mol/L HCl, 20 mL/g liquid-solid ratio, 50 °C reaction temperature, and 30 min contact time, the calcium ion leaching efficiency from decarbonized ash slag attained 96.18%. When CO_2 flow rate was 300 mL/min, reaction temperature 60 °C, and carbonation duration 120 min, the carbonation conversion reached 99.59%. By adjusting the CO_2 flow rate, carbonation reaction temperature, and reaction time, the mutual transformation between different $CaCO_3$ crystal forms such as vaterite, calcite, and aragonite could be effectively regulated to obtain $CaCO_3$ products with different crystal structure compositions. However, the aforementioned method still requires the consumption of certain amounts of acid and alkali in the early stage, and does not utilize the large amounts of leached aluminum and iron ions, resulting in resource waste. YU et al.[71] proposed a new process for CO_2 mineralization utilization by reacting NH_4HSO_4 with $NH_4Cl$to generate HCl and NH_3 under atmospheric pressure and without acid/base consumption, which are used for Ca^{2+}leaching from gasification slag and the carbonation reaction [Figure 9, Eqs. (32)–(33)]. A pilot-scale experiment with a capacity of 1 kg/h (calculated based on CO_2 mass) was conducted using an airlift loop reactor. In this process, based on the difference in solubility product constants (K_{sp}) of $Al(OH)_3$ and $Fe(OH)_3$, selective precipitation of Al, Fe, and Ca was achieved by adjusting the pH of the acid leachate to 4.5–5.0 and 10.6–11.0, realizing the synchronous recovery of multiple value-added products including $Al(OH)_3$, $Fe(OH)_3$, and $CaCO_3$. When the CO_2 flow velocity was 1.4

cm/s, pH = 10.6–11.0, and the CO_2 volume fraction was 85%, the carbonation rate reached 91.5%, and the calcium utilization rate reached 75%. Under pilot experimental conditions, per kilogram of gasification slag, this process could generate 344.5 g of crude carbonate ($CaCO_3$ mass fraction 72.6%) and 328.2 g of aluminum-rich precipitate (Al_2O_3 mass fraction 47.8%), with a CO_2 mineralization capacity (same basis as above) reaching 121 g/kg. This method requires no acid or alkali throughout the process and realizes the full utilization of the main components of coal gasification slag, greatly improving the economic viability of CO_2 mineralization utilization and possessing great potential for industrial application. In addition, gasification slag is rich in amorphous SiO_2, Al_2O_3, CaO, and Fe_2O_3, resembling the composition of Portland cement, and has good hydration activity and pozzolanic activity. Under certain conditions, its latent cementing ability can be excited, allowing it to be used as an admixture or aggregate. Via a CO_2 mineralization curing process, it can be used to prepare cement-based materials or geopolymers, realizing CO_2 mineralization.

$$NH_4Cl \rightarrow NH_3\uparrow + HCl\uparrow CaX_nO_m\ (MgX_nO_m) + 2HCl \rightarrow CaCl_2\ (MgCl_2) + X_nO_{m-1} + H_2O Al_2O_3 + 6HCl \rightarrow 2AlCl_3 + 3H_2O FeO + 2HCl \rightarrow FeCl_2 + H_2O AlCl_3\ [FeCl_3] + 3NH_3 + 3H_2O \rightarrow Al(OH)_3\ [Fe(OH)_3]\downarrow + 3NH_4Cl CaCl_2\ (MgCl_2) + CO_2 + 2NH_3 + H_2O \rightarrow CaCO_3\ (MgCO_3)\downarrow + 2NH_4Cl NH_4Cl + NH_4HSO_4 \rightarrow HCl + (NH_4)_2SO_4\ (NH_4)_2SO_4 \rightarrow NH_4HSO_4 + NH_3 \quad (26)(27)(28)(29)(30)(31)(32)(33)$$

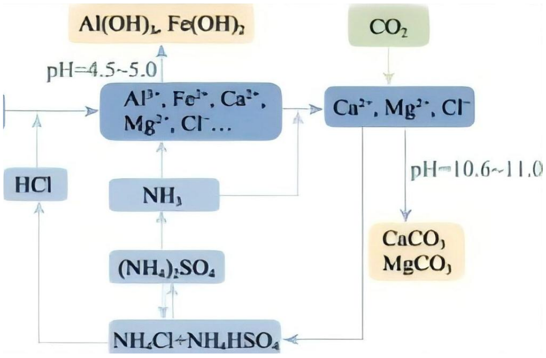

Figure 9 Process flow diagram for indirect mineral carbonation of coal gasification slag based on chemical looping[71]

Although the gasification slag ammonium salt cyclic indirect mineralization process can effectively realize CO_2 mineralization utilization, research on indirect CO_2 mineralization using gasification slag remains scarce. Ammonia escape is inevitable during the ammonium salt cycling process, necessitating further research on the evaluation of mineralization capacity after multiple ammonium salt cycles, mineralization utilization kinetics, and the CO_2 mineralization capacity of different gasification slags. In addition, the overall energy consumption of this process is high, and production costs are elevated, requiring further research on renewable leaching agents and optimization of the process flow to reduce process energy consumption and costs.

4 Conclusions and Prospects

The extensive disposal and valorization of gasification slag, coupled with carbon dioxide emission mitigation, constitute critical challenges confronting the sustainable advancement of the coal chemical sector. The abundant Si and C resources in coal gasification slag serve as cost-effective precursors for CO_2 capture materials. After impurity removal, silicon-based, carbon-based, and carbon-ash composite CO_2 capture materials with large specific surface areas, pore volumes, and excellent CO_2 capture capacities can be prepared via hydrothermal templating, physical activation, chemical activation, and organic amine modification. Currently, the CO_2 capture capacity of gasification slag-based carbon capture materials can reach 0.61–3.72 mmol/g (Table 1), and adsorption saturation can be achieved within 1.5–10 min. After 5–20 adsorption-desorption cycles, they still retain a high adsorption capacity. Compared with silicon-based gasification slag CO_2 capture materials, carbon-based and carbon-ash composite CO_2 capture materials exhibit relatively higher CO_2 capture capacities. Meanwhile, CaO, MgO, and other alkaline earth metal elements in gasification slag serve as important raw materials for CO_2 mineralization utilization, enabling CO_2 utilization and sequestration via wet direct and indirect carbonation technologies. Currently, the CO_2 mineralization capacity can reach 112.27–215.77 g/kg[62-63]. Notably, the acid leachate generated during the preparation of gasification slag-based CO_2 capture materials is rich in Ca, Mg, and other elements, which can be further used as active components for indirect CO_2 mineralization after pH adjustment and recovery of Al, Fe, and other elements. This not only realizes the synchronous recovery and utilization of Si, Ca, C, Mg, Al, Fe, and other resources in gasification slag, but also effectively reduces acid usage and waste liquid generation during the CO_2 capture and mineralization processes, delivering significant economic, environmental, and social benefits. However, research on the coupling technology of gasification slag-based CO_2 capture and mineralization utilization is currently lacking. Although gasification slag shows great potential in the fields of CO_2 capture and utilization, relevant research is still in its infancy, and some shortcomings remain in existing research and large-scale promotion and utilization. In future research on using gasification slag for CO_2 capture and mineralization utilization, efforts should focus on the following aspects:

(1) **Slag-specific strategies for developing gasification slag-based CO_2 capture material preparation and mineralization utilization.** Although different gasification slags all contain elements such as Si, Ca, Mg, and C, influenced by factors such as the type and origin of raw coal, furnace type, gasification process, and slagging method, the composition of different gasification slags varies greatly. Appropriate CO_2 capture material preparation methods should be explored based on the differences in physicochemical characteristics of different gasification slags. The correlations between the physicochemical characteristics of gasification slag and its CO_2 capture and mineralization utilization capacities should be established to quantitatively evaluate its CO_2 capture and mineralization potentials, fully exploiting the CO_2 capture and mineralization utilization potential of gasification slag.

(2) **Developing new strategies for preparing gasification slag-based CO_2 capture materials with excellent yield, adsorption capacity, selectivity, and impurity gas tolerance.** Existing preparation methods for gasification slag-based CO_2 capture materials usually consume large amounts of strong acids and strong alkalis, and generally suffer from problems such as complex processes, high energy consumption, low product yield, susceptibility to equipment corrosion, and secondary pollution. Moreover, there is a lack of evaluation on the CO_2 capture capacity and selectivity from flue gas containing impurities such as water vapor, dust, and sulfides. Based on a deep understanding of the mechanisms of gasification slag for CO_2 capture material preparation and carbonation, feasibility studies should be conducted on using weakly acidic and saline substances with low regeneration energy consumption and environmental friendliness to replace strong acids and strong alkalis for gasification slag-based CO_2 capture and mineralization utilization. Combined with CO_2 adsorption kinetics research, the structure and preparation methods of CO_2 capture materials should be designed and regulated.

(3) **Acid leaching treatment serves as both the impurity removal process in the preparation of silicon-based and carbon-based CO_2 capture materials from gasification slag and the first step of indirect CO_2 mineralization.** The acid leachate generated during the preparation of gasification slag-based CO_2 capture materials can be used for CO_2 carbonation after pH adjustment and recovery of Al, Fe, and other elements. This not only realizes the synchronous recovery of Si, Ca, C, Mg, Al, Fe, and other resources in gasification slag, but also effectively reduces acid usage and waste liquid generation during the CO_2 capture and mineralization processes. Further research is needed on the feasibility of coupling gasification slag CO_2 capture and mineralization utilization technologies, and optimization of related technical processes.

(4) **Most existing studies are still limited to the laboratory research stage, and lack quantitative economic feasibility assessments for their application in the CCUS field.** Efforts should be continuously made to translate related technologies from laboratory research to industrial applications, and conduct economic feasibility studies for large-scale application of related technologies, thereby promoting the large-scale promotion and application of gasification slag in the CCUS field.

References

[1] ABUELNOOR N, ALHAJAJ A, KHALEEL M, et al. Activated carbons from biomass-based sources for CO_2 capture applications[J]. Chemosphere, 2021, 282: 131111.

[2] CHANG L N. Study on the preparation of activated carbon/nano-carbon hybrid material by chemical activation[D]. Beijing: Beijing University of Chemical Technology, 2012.

[3] CHANG R Q, ZHANG J B, LI H Q, et al. Research progress and application of cementing materials prepared from coal-based solid waste[J]. Clean Coal Technology, 2024, 30(2): 316-330.

[4] CHENG H G, SONG H P, TOAN S P, et al. Experimental investigation of CO_2 adsorption and desorption on multi-type amines loaded HZSM-5 zeolites[J]. Chemical Engineering Journal, 2021, 406: 122882.

[5] FU W Y, SUN W Q, WANG L Y. Advances in resource utilization technology of coal gasification slag[J]. Environmental Engineering, 2023, 41(12): 319-328.

[6] GAO M Q, YANG Z R, WANG Y L, et al. Impact of calcium on the synergistic effect for the reactivity of coal char gasification in H_2O/CO_2 mixtures[J]. Fuel, 2017, 189: 312-321.

[7] GAO Y, ZHANG J F, TU Y N, et al. Synthesis of hierarchical porous silica aerogel for CO_2 adsorption using decarbonized coal gasification fine slag[J]. Microporous and Mesoporous Materials, 2025, 382: 113399.

[8] GAO Y, TU Y N, WANG W D, et al. Research progress on CO_2 mineralization of coal-based solid waste containing calcium and magnesium and its product performance[J]. Coal Science and Technology, 2024, 52(5): 301-315.

[9] GU Y Y, QIAO X C. A carbon silica composite prepared from water slurry coal gasification slag[J]. Microporous and Mesoporous Materials, 2019, 276: 303-307.

[10] GUO F H, ZHAO X, GUO Y, et al. Fractal analysis and pore structure of gasification fine slag and its flotation residual carbon[J]. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2020, 585: 124148.

[11] HASZELDINE R S. Carbon capture and storage: How green can black be?[J]. Science, 2009, 325(5948): 6.

[12] HE X F, FAN H, SHEN Z X, et al. Development progress of chemical absorbents for carbon dioxide chemical absorption from flue gas of coal-fired power plants[J]. Clean Coal Technology, 2024, 30(11): 82-96.

[13] HU J, LIU L J, CUI M Q, et al. Calcium-promoted catalytic activity of potassium carbonate for gasification of coal char: The synergistic effect unrelated to mineral matter in coal[J]. Fuel, 2013, 111: 628-635.

[14] HU J P, LIU W Z, WANG L, et al. Indirect mineral carbonation of blast furnace slag with $(NH_4)_2SO_4$ as a recyclable extractant[J]. Journal of Energy Chemistry, 2017, 26(5): 927-935.

[15] HUAN Q, WIBOWO H, YAN M, et al. A review of CO_2 mineral storage: Current processes, typical applications, and life cycle assessment[J]. Journal of Environmental Chemical Engineering, 2024, 12(6): 114785.

[16] HUO B B, ZHANG J X, LI M, et al. Effect of CO_2 mineralization on the composition of alkali-activated backfill material with different coal-based solid wastes[J]. Sustainability, 2023, 15: 4933.

[17] IGALAVITHANA A D, CHOI S W, DISSANAYAKE P D, et al. Gasification biochar from biowaste (food waste and wood waste) for effective CO_2 adsorption[J]. Journal of Hazardous Materials, 2020, 391: 101147.

[18] International Energy Agency. CO_2 Emissions in 2023[R]. Paris, 2024.

[19] International Energy Agency. Energy Technology Perspectives 2020: Special Report Carbon Capture Utilization and Storage[R]. Paris, 2023.

[20] IZUMI Y, IIZUKA A, HO H J. Calculation of greenhouse gas emissions for a carbon recycling system using mineral carbon capture and utilization technology in the cement industry[J]. Journal of Cleaner Production, 2021, 312: 127618.

[21] LI L R, AI S, YANG X Z, et al. Performance optimization strategy and analysis of carbon capture solid amine adsorbent carrier[J]. Fine Chemicals, 2024, 41(7): 1414-1423.

[22] LI X Y, LI X, FAN P, et al. Study on the impact of using decarbonized gasification slag for CO_2 mineralization and storage to prepare calcium carbonate[J]. Journal of Fuel Chemistry and Technology, 2024, 52(8): 1193-1202.

[23] LI Y, WANG J M, ZHANG X, et al. Research progress on the development of high-value-added materials by using coal gasification slag[J]. Materials Reports, 2023, 37(23): 12.

[24] LIU X D, JIN Z W, JING Y H, et al. Review of the characteristics and graded utilisation of coal gasification slag[J]. Chinese Journal of Chemical Engineering, 2021, 35(7): 92-106.

[25] LIU X X, LIU X M, ZHANG Z Q. Application of red mud in carbon capture, utilization and storage (CCUS) technology[J]. Renewable and Sustainable Energy Reviews, 2024, 202: 114683.

[26] LU C L, XU S P, WANG M, et al. Effect of pre-oxidation on the development of porosity in activated carbons from petroleum coke[J]. Carbon, 2007, 45(1): 206-209.

[27] MACDOWELL N, FENNELL P S, SHAH N, et al. The role of CO_2 capture and utilization in mitigating climate change[J]. Nature Climate Change, 2017, 7(4): 243-249.

[28] MIAO Z K. Synthesis of hierarchical porous carbon from coal gasification fine slag carbon residue and its

application in CO_2 capture[J]. Coal Conversion, 2024, 47(2): 44-56.

[29] MIAO Z K, GE H, WU R, et al. Insight into the synergism of residual carbon and slag particles in coal gasification fine slag on porous composites preparation for CO_2 capture[J]. Separation and Purification Technology, 2024, 339: 126540.

[30] MIAO Z K, GUO Z K, QIU G F, et al. Influence of pre-oxidization on the characterizations of coal gasification fine slag-derived activated carbons for CO_2 capture[J]. Journal of CO_2 Utilization, 2021, 54: 101754.

[31] MIAO Z K, GUO Z K, QIU G F, et al. Insight into the role of slag particles in coal gasification fine slag on hierarchical porous composites preparation and CO_2 capture[J]. Fuel, 2022, 310: 122475.

[32] MIAO Z K, GUO Z K, QIU G F, et al. Synthesis of activated carbon from high-ash coal gasification fine slag and their application to CO_2 capture[J]. Journal of CO_2 Utilization, 2021, 50: 101585.

[33] MIAO Z K, HAN X R, GE H, et al. Insight into the synergism of residual carbon and slag particles in coal gasification fine slag on porous composites preparation for CO_2 capture[J]. Separation and Purification Technology, 2024, 339: 126540.

[34] MIAO Z K, WU J J, NIU Y J, et al. Development of a novel type hierarchical porous composite from coal gasification fine slag for CO_2 capture[J]. Chemical Engineering Journal, 2022, 435: 134909.

[35] MIAO Z K, WU J J, QIU G F, et al. Solving two industrial waste issues simultaneously: Coal gasification fine slag-based hierarchical porous composite with enhanced CO_2 adsorption performance[J]. Science of the Total Environment, 2022, 821: 153347.

[36] MOHD AZMI N Z, BUTHIYAPPAN A, ABDUL RAMAN A A, et al. Recent advances in biomass based activated carbon for carbon dioxide capture-A review[J]. Journal of Industrial and Engineering Chemistry, 2022, 116: 1-20.

[37] MU J Q, FANG Z H, ZHU H B, et al. Research progress on solid adsorption materials for CO_2 capture in flue gas[J]. Fine Chemicals, 2023, 40(9): 1857-1866.

[38] PANG W, QIN S J, HAO L L, et al. Research progress in preparation of fly ash based aluminosilicate materials and their CO_2 capture[J]. Low-Carbon Chemistry and Chemical Engineering, 2024, 49(7): 42-54.

[39] PATEL H, MOHANTY A, MISRA M. Post-combustion CO_2 capture using biomass based activated porous carbon: Latest advances in synthesis protocol and economics[J]. Renewable and Sustainable Energy Reviews, 2024, 199: 114484.

[40] PHAM L H H P, RUSLI R, KEONG L K. Consequence study of CO_2 leakage from ocean storage[J]. Procedia Engineering, 2016, 148: 1081-1088.

[41] QU J S, ZHANG J B, LI H Q, et al. Coal gasification slag-derived highly reactive silica for high modulus sodium silicate synthesis: Process and mechanism[J]. Chemical Engineering Journal, 2024, 479: 147771.

[42] RASHIDI N A, YUSUP S. An overview of activated carbons utilization for the post-combustion carbon dioxide capture[J]. Journal of CO_2 Utilization, 2016, 13: 1-16.

[43] REN L, GONG Y, WANG J X, et al. Study on recovery of residual carbon from coal gasification fine slag and the influence of oxidation on its characteristics[J]. Energy, 2023, 279: 128099.

[44] RODRIGUEZ-REINOSO F, GONZALEZ M T, MOLINA-SABIO M. The use of steam and CO_2 as activating agents in the preparation of activated carbons[J]. Carbon, 1995, 33(1): 115-123.

[45] SHI X Z, XU L H, TIAN J, et al. In situ preparation of carbon/zeolite composite materials derived from coal gasification fine slag for removing malachite green: Performance evaluation and mechanism insight[J]. Journal of Water Process Engineering, 2025, 69: 106670.

[46] SU S F, TAHIR M H, CHENG X X, et al. Modification and resource utilization of coal gasification slag-based material: A review[J]. Journal of Environmental Chemical Engineering, 2024, 12(2): 112112.

[47] SUN J J, GUO J Y, ZHANG L, et al. CO_2 adsorption performance of coal gasification fine slag-based adsorbent[J]. Coal Conversion, 2024, 47(5): 75-84.

[48] TANG B, SUN Z J, MEN X Y, et al. Synthesis of porous carbon/zeolite composites by low-temperature acid-alkaline leaching from coal gasification fine slag for adsorption of dye wastewater[J]. Journal of Environmental Chemical Engineering, 2024, 12(3): 112819.

[49] WANG D Z, JIN K R, ZHAO Y, et al. Production of low-carbon composite materials using magnesium slag and coal gasification slag via CO_2 curing[J]. Construction and Building Materials, 2025, 463: 140003.

[50] WANG F C. Coal gasification technologies in China: Review and prospect[J]. Clean Coal Technology, 2021, 27(1): 1-33.

[51] WANG J C, KASKEL S. KOH activation of carbon-based materials for energy storage[J]. Journal of Materials Chemistry, 2012, 22(45): 23710-23725.

[52] WEI L J, WEI W, XUE N, et al. One-step synthesis of solid-liquid composite microsphere for CO_2 capture[J].

ACS Applied Materials & Interfaces, 2021, 13(4): 5814-5822.

[53] WEI X F, LIU J, YAN H Y, et al. Synthesis of large mesoporous silica for efficient CO_2 adsorption using coal gasification fine slag[J]. Separation and Purification Technology, 2025, 353: 128348.

[54] WEN H, HAN W, CHE C X, et al. Progress of post-combustion carbon dioxide capture technology development and applications[J]. Fine Chemicals, 2022, 39(8): 1584-1595, 1632.

[55] XU R, ZHU F X, ZOU L, et al. CO_2 mineralization by typical industrial solid wastes for preparing ultrafine $CaCO_3$: A review[J]. Green Energy & Environment, 2024, 9(11): 1679-1697.

[56] YANG H Q, SUN Z G, QU J S, et al. Analysis and research on basic physical properties of gasification slag in representative areas of Sinopec[J]. Clean Coal Technology, 2021, 27(3): 101-108.

[57] YANG P J, PENG S, WANG J, et al. Carbon capture, utilization and storage (CCUS) technology development status and application prospects[J]. China Environmental Science, 2024, 44(1): 404-416.

[58] YAN S Y, XUAN W W, CAO C Y, et al. A review of sustainable utilization and prospect of coal gasification slag[J]. Environmental Research, 2023, 238: 117186.

[59] YU C J, CAI L H, JIANG G Q, et al. Mineral carbonation of CO_2 with utilization of coal gasification slags based on chemical looping[J]. Asia-Pacific Journal of Chemical Engineering, 2021, 16(4): 1-11.

[60] ZHANG J P, ZUO J, AI W D, et al. Preparation of mesoporous coal-gasification fine slag adsorbent via amine modification and applications in CO_2 capture[J]. Applied Surface Science, 2021, 537: 147938.

[61] ZHANG J T, ZHANG L. Preliminary discussion on development of carbon capture, utilization and storage for carbon neutralization[J]. Thermal Power Generation, 2021, 50(1): 1-6.

[62] ZHANG Y. Study on the mechanism of heavy metal adsorption and mineralization carbon dioxide by solid waste modified materials[D]. Xi'an: Shaanxi University of Science & Technology, 2023.

[63] ZHANG Y Z. Preparation of granular activated carbon by CO_2-chemical activation and its application in pressure swing adsorption separation for CH_4/N_2[D]. Chongqing: Chongqing University, 2017.

[64] ZHAO K P, LI X Y, LI R H, et al. Research progress on preparation and capture performance of CaO-based CO_2 capture materials from solid wastes[J]. Bulletin of the Chinese Ceramic Society, 2023, 42(2): 520-530.

[65] ZHENG X F, HUANG Y, XU D, et al. Alkaline solid waste CO_2 mineralization utilization technology engineering application progress[J/OL]. Clean Coal Technology, 1-14[2025-02-24]. http://kns.cnki.net/kcms/detail/11.3676.td.20240730.1432.011.html.

[66] ZHU L, GU W Z, SONG T Q, et al. Research progress of CO_2 storage technology by mineralization of coal-based solid waste[J]. Coal Science and Technology, 2024, 52(2): 309-328.

[67] ZHU Y K, WU J J, ZHANG Y X, et al. Preparation of hierarchically porous carbon ash composite material from fine slag of coal gasification and ash slag of biomass combustion for CO_2 capture[J]. Separation and Purification Technology, 2024, 330: 125452.

[68] ZOU Y J, SONG Q, ZHANG P, et al. Research status of building materials utilization and CO_2 curing technology on typical coal-based solid waste: A critical review[J]. Journal of CO_2 Utilization, 2024, 84: 102860.

[69] ZHAO X L, ZENG C, MAO Y Y, et al. The surface characteristics and reactivity of residual carbon in coal gasification slag[J]. Energy & Fuels, 2010, 24(1): 91-94.

[70] LIU Y F, WANG Z Q, ZHAO W H, et al. Hierarchical porous nanosilica derived from coal gasification fly ash with excellent CO_2 adsorption performance[J]. Chemical Engineering Journal, 2023, 455: 140622.