Granular Bamboo-Derived Activated Carbon for High CO₂ Adsorption: The Dominant Role of Narrow Micropores


Cost-effective biomass-derived activated carbons with a high CO₂ adsorption capacity are attractive for carbon capture. Bamboo was found to be a suitable precursor for activated carbon preparation through KOH activation. The bamboo size in the range of 10–200 mesh had little effect on CO₂ adsorption, whereas the KOH/C mass ratio and activation temperature had a significant impact on CO₂ adsorption. The bamboo-derived activated carbon had a high adsorption capacity and excellent selectivity for CO₂, and also the adsorption process was highly reversible. The adsorbed amount of CO₂ on the granular activated carbon was up to 7.0 mmol g⁻¹ at 273 K and 1 bar, which was higher than almost all carbon materials. The pore characteristics of activated carbons responsible for high CO₂ adsorption were fully investigated. Based on the analysis of narrow micropore size distribution of several activated carbons prepared under different conditions, a more accurate micropore range contributing to CO₂ adsorption was proposed. The volume of micropores in the range of 0.33–0.82 nm had a good linear relationship with CO₂ adsorption at 273 K and 1 bar, and the narrow micropores of about 0.55 nm produced the major contribution, which could be used to evaluate CO₂ adsorption on activated carbons.

Introduction

As a typical greenhouse gas, CO₂ has drawn considerable attention in recent years because of its rapidly increasing concentration in the atmosphere and the concern about the global warming effect.[1–6] Currently, fossil-fuel power plants are still the main source of CO₂ emissions, and postcombustion capture is considered as an effective way to reduce the amount of CO₂ emitted into the atmosphere.[2,6]

Adsorption has been viewed as an effective technology for CO₂ capture and many solid adsorbents, such as activated carbon, zeolites, metal–organic frameworks, and zeolitic imidazolate frameworks, have been reported.[6–13] Among these adsorbents, activated carbon is one of the most attractive adsorbents for CO₂ adsorption.[13] Commercial activated carbons are cost-effective, but they normally have an adsorption capacity of less than 3.0 mmol g⁻¹ for CO₂ at 273 K and 1 bar.[13] Recently, many researchers have focused their efforts on enhancing CO₂ adsorption capacity and selectivity on porous carbon materials. Incorporation of nitrogen atoms into the carbon skeleton of activated carbons can increase CO₂ adsorption. Xie et al. prepared nitrogen-doped carbon materials by a chemical vapor deposition (CVD) method.[14] Hao et al. synthesized nitrogen-doped porous carbon monoliths by pyrolysis of the copolymer of resorcinol, formaldehyde, and lysine (or different amines).[15,16] Wang et al. prepared nitrogen-doped carbon by a CVD process of acetonitrile on the zeolite template.[17] These carbon materials showed CO₂ adsorption in the range of 3.1–4.4 mmol g⁻¹ at 298 K and 1 bar.[14–17] Although these new porous carbons described above have higher CO₂ uptakes than commercial activated carbons,[18] carbon sourcing is expensive and synthetic processes are complicated.

Activated carbons prepared by KOH activation also have high CO₂ adsorption and the precursors including petroleum pitch, carpet, polypryrole, polyfurfuryl alcohol, and sawdust have been used.[19–25] High-performance activated carbons could be prepared by KOH activation when appropriate carbon sources and activation conditions are selected. Biomass as a carbon source is more competitive because it is sustainable and cost-effective. So far, only few biomass-derived activated carbons have been prepared by KOH activation for CO₂ adsorption,[25] and it may be possible to find other widely available kinds of biomass for the preparation of activated carbons with higher adsorption capacities for CO₂.

It has been found that CO₂ adsorption on porous carbons is mostly attributed to narrow micropores,[25,26,27] micropores below 1, 0.8, and 0.7 nm in diameter are mainly responsible for CO₂ uptake at 1 bar.[20,25,28] The accurate relationship between micropore-size range and CO₂ adsorption should be further investigated. Most researchers used N₂ as a probe molecule to characterize the pore-size distribution of activated carbons,[20] but micropores below 1 nm cannot be accurately determined.

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due to the difficult diffusion of N$_2$ molecules at 77 K. In contrast, CO$_2$ adsorption at 273 K is more effective than N$_2$ adsorption at 77 K for the detection of narrow micropores.$^{[29–32]}$ The application of nonlocal density functional theory (NLDFT) models on CO$_2$ adsorption isotherms at 273 K can provide an accurate narrow micropore distribution ($<1$ nm) of porous carbon materials.$^{[33,34]}$

In this study, cost-effective bamboo was selected to prepare activated carbons using KOH activation. The bamboo-derived activated carbon had high CO$_2$ uptake, which has not been previously reported. The granular bamboo-derived activated carbons were optimized under different activation conditions, and the optimal activated carbon was used to adsorb CO$_2$ for the evaluation of adsorption capacity, selectivity, and reusability. The activated carbon was characterized by SEM analysis and a gas adsorption instrument. The relationship between narrow micropores and CO$_2$ adsorption was elucidated, and a more accurate micropore-size range responsible for CO$_2$ adsorption was proposed.

Results and Discussion

Influence of activation parameters on CO$_2$ adsorption

For CO$_2$ adsorption on fixed beds, granular activated carbon has an advantage over powdered activated carbon. In this study, the bamboo-derived activated carbon had the same particle size as its precursor. The activated carbons ranging from 10 to 200 mesh (2.0–0.075 mm) almost had the same adsorbed amounts of CO$_2$ (see the Supporting Information, Figure S1), indicating that the bamboo particle size had little effect on the microporous structure of activated carbons. Bamboo particles in the range of 20–30 mesh (0.85–0.60 mm) were selected to prepare the activated carbons in the following experiments.

Among a variety of preparation conditions, the KOH/C mass ratio, activation temperature, and activation time have a significant effect on activated carbons for CO$_2$ adsorption.$^{[20]}$ To find the optimum conditions for the preparation of bamboo-derived activated carbons, the three parameters were optimized. The optimum activation time for the preparation of activated carbons depended on KOH/C mass ratio and activation temperature. The optimum activation time was 1.5 h for Bamboo-3-973 to achieve the highest CO$_2$ adsorption (see the Supporting Information, Figure S2). The activation time of 1.5 h was used in the following experiments.

When the activation temperature and time were fixed at 973 K and 1.5 h, respectively, the amount of CO$_2$ adsorbed on activated carbon first increased and then decreased with the increase of the KOH/C mass ratio (Figure 1 a), and the maximum value was achieved at a KOH/C mass ratio of 3. Sevilla and Fuertes found that activated carbon prepared at a KOH/C mass ratio of 4.5 showed higher CO$_2$ uptake than that prepared at a KOH/C mass ratio of 4.$^{[24]}$ Hu et al. prepared a series of activated carbons at KOH/C mass ratios of 3–6, and pointed out that severe activation conditions (KOH/C mass ratio of 5 or 6) were not favorable for CO$_2$ adsorption at ambient pressure.$^{[178]}$ Evidently, only the appropriate alkaline content may etch the bamboo char to create the desired pore structure for CO$_2$ adsorption.

Similarly, CO$_2$ adsorption first increased sharply and then reached a plateau in the activation temperature range of 873–973 K, and finally decreased quickly with an increase of temperature from 973 to 1123 K (Figure 1 b). The optimal temperature was 873 K. To verify that CO$_2$ adsorption was maximized on this activated carbon with an activation time of 1.5 h, the effect of activation time on CO$_2$ adsorption on the activated carbon prepared at a KOH/C mass ratio of 3 and 873 K (denoted as Bamboo-3-873) was studied. CO$_2$ adsorption reached maximum values for activation times between 1.5–2.5 h, and then decreased significantly with an increase in activation time (see the Supporting Information, Figure S3 a). When activated carbon was prepared at the activation temperature of 873 K, with an activation time of 1.5 h, and KOH/C mass ratios ranging from 1 to 5, the highest CO$_2$ adsorption was still obtained at a KOH/C ratio of 3 (see the Supporting Information, Figure S3 b). Therefore, Bamboo-3-873 had the highest CO$_2$ adsorption capacity (up to 7.0 mmol g$^{-1}$) after optimization of the three activation parameters. Among the three activation parameters, the KOH/C ratio and activation temperature had more pronounced effects on CO$_2$ adsorption than the activation time.

Adsorption capacity, selectivity, and reusability

Both Bamboo-3-873 and Bamboo-1-973 suffered a clear loss in adsorbed CO$_2$ with the increase in temperature from 273 to 298 K (Figure 2). The adsorbed amounts of CO$_2$ at 273 K and 1 bar on Bamboo-3-873 and Bamboo-1-973 were 7.0 and
5.3 mmol g\(^{-1}\), respectively, but decreased to 4.5 and 4.0 mmol g\(^{-1}\), respectively, at 298 K and 1 bar. The adsorption isotherms of \(\text{CO}_2\) on Bamboo-1-973 were more nonlinear than those on Bamboo-3-873, suggesting the presence of smaller micropores in Bamboo-1-973. Although Bamboo-3-873 adsorbed higher amounts of \(\text{CO}_2\) at 1 bar than Bamboo-1-973, the amount of \(\text{CO}_2\) adsorbed on Bamboo-1-973 was higher than that on Bamboo-3-873 at pressures below 0.15 bar, implying that Bamboo-1-973 was more effective for \(\text{CO}_2\) capture than flue gas at low \(\text{CO}_2\) partial pressures. Relative to Bamboo-3-873, Bamboo-1-973 (prepared at a lower KOH/C ratio and higher temperatures) may have considerably smaller micropores. In addition, desorption isotherms of \(\text{CO}_2\) on the two activated carbons at 273 and 298 K almost completely overlapped with corresponding adsorption isotherms (Figure 2), suggesting the highly reversible nature of the \(\text{CO}_2\) adsorption–desorption process.

Many researchers have reported the adsorption of \(\text{CO}_2\) on different activated carbons (Table 1). Activated carbons prepared using KOH as an activating agent had higher \(\text{CO}_2\) adsorption capacities, and the carbon precursors also significantly affected the adsorption capacity. The bamboo-derived activated carbon in our study had a higher \(\text{CO}_2\) adsorption capacity at 273 and 298 K than other activated carbons except for those derived from petroleum pitch at 273 K and sawdust at 298 K. Relative to the bamboo-derived activated carbon, the petroleum-pitch-derived activated carbon monolith had a higher \(\text{CO}_2\) adsorption at 273 K, but lower at 298 K. In particular, petroleum mesophase pitch is not a renewable material because it is obtained from vacuum residue by pyrolysis. Notably, only monoliths prepared by pressing the activated carbon powder at 400 MPa had a high \(\text{CO}_2\) adsorption, whereas the materials in powder form had a significantly lower adsorption capacity.\(^{[16]}\) Sawdust-derived activated carbon had a lower \(\text{CO}_2\) adsorption (6.1 mmol g\(^{-1}\)) at 273 K than bamboo-derived activated carbon. Because bamboo is a cheap, abundant, and renewable material, bamboo-derived activated carbon is promising for applications relevant to \(\text{CO}_2\) capture.

Because flue gas from fossil-fuel-fired power plants is mainly a mixture of \(\text{CO}_2\) and \(\text{N}_2\), selective adsorption of \(\text{CO}_2\) is important for activated carbons. Bamboo-3-873 showed a \(\text{CO}_2/\text{N}_2\) selectivity \([\text{S}(\text{CO}_2/\text{N}_2)]\) of 8.6 at 298 K and 10.2 at 273 K and at a pressure of 1 bar (Figure 3). It has been reported that activated carbons usually show low selectivities due to their weak physical interaction with \(\text{CO}_2\).\(^{[2]}\) Activated carbons and carbon molecular sieves reported recently still fail to overcome this drawback (Table 1).\(^{[19–20, 25]}\) For example, petroleum-coke-derived activated carbon exhibited a \(\text{CO}_2/\text{N}_2\) selectivity of only 5.1 at 298 K;\(^{[20]}\) carbon molecular sieves had a poor selectivity of 2.8 at 298 K;\(^{[19]}\) sawdust-derived activated carbon showed a selectivity of 5.4 at 298 K.\(^{[25]}\) Although incorporating N-containing groups into the carbon framework can enhance the selectivity,\(^{[38–40]}\) it may increase the preparation cost and regeneration difficulty.

The regeneration property of spent adsorbents is also an important factor in practical applications for \(\text{CO}_2\) adsorption. Figure 4 illustrates the amount of \(\text{CO}_2\) adsorbed on the Bamboo-3-873 at 273 and 298 K in four reuse cycles, and no

<table>
<thead>
<tr>
<th>Precursors</th>
<th>Activating agents</th>
<th>Adsorption temperature(^{[K]})</th>
<th>(\text{CO}_2) uptake ([\text{mmol g}^{-1}])</th>
<th>([\text{S}(\text{CO}_2/\text{N}_2)])</th>
<th>Ref.</th>
</tr>
</thead>
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<tr>
<td>olive stone</td>
<td>(\text{CO}_2)</td>
<td>273</td>
<td>4.5</td>
<td>NA</td>
<td>([12])</td>
</tr>
<tr>
<td>almond shell</td>
<td>(\text{CO}_2)</td>
<td>298</td>
<td>2.7</td>
<td>NA</td>
<td>([35])</td>
</tr>
<tr>
<td>anthracite</td>
<td>steam</td>
<td>303</td>
<td>1.5</td>
<td>NA</td>
<td>([36])</td>
</tr>
<tr>
<td>N-containing resin</td>
<td>(\text{K}_2\text{CO}_3)</td>
<td>298</td>
<td>1.9</td>
<td>NA</td>
<td>([37])</td>
</tr>
<tr>
<td>petroleum coke</td>
<td>KOH</td>
<td>298</td>
<td>3.5</td>
<td>5.1</td>
<td>([20])</td>
</tr>
<tr>
<td>petroleum pitch</td>
<td>KOH</td>
<td>273/298</td>
<td>8.6/4.2</td>
<td>2.8</td>
<td>([19])</td>
</tr>
<tr>
<td>carpet</td>
<td>KOH</td>
<td>298</td>
<td>1.9</td>
<td>NA</td>
<td>([21])</td>
</tr>
<tr>
<td>sawdust</td>
<td>KOH</td>
<td>273/298</td>
<td>6.1/4.8</td>
<td>5.4</td>
<td>([25])</td>
</tr>
<tr>
<td>polypyrrole</td>
<td>KOH</td>
<td>273</td>
<td>6.2</td>
<td>5.3</td>
<td>([22])</td>
</tr>
<tr>
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<td>KOH</td>
<td>298</td>
<td>4.3</td>
<td>15.9</td>
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<tr>
<td>polyfurfuryl</td>
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<td>Bamboo-3-873</td>
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<td>7.0/4.5</td>
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<td>this study</td>
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<td>273/298</td>
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<td>this study</td>
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</table>

\(^{[a]}\) Pressure: 1 bar. \(^{[b]}\) Data was measured at 298 K and 1 bar; NA = not available.
adsorption loss was observed after vacuum regeneration, indicating highly reversible CO$_2$ adsorption. Overall, the bamboo-derived activated carbon has a high adsorption and excellent selectivity for CO$_2$ and can be regenerated under vacuum, making it a good adsorbent for CO$_2$ capture.

Influence of textural properties of activated carbons on CO$_2$ adsorption

Pristine bamboo exhibited a unidirectional fibrous structure and no obvious pores were observed (Figure 5a). After carbonization at 773 K, irregular pores were formed on carbonized bamboo (see the Supporting Information, Figure S4a). Carbonized bamboo was activated at a KOH/C mass ratio of 3 at 873 K to yield Bamboo-3-873, which had a cellular texture and a highly porous structure (Figure 5b). The ordered micron-sized pores were formed in the cross section of activated carbon and were parallel to the cellulose fibers, and the outer surface was etched severely due to the high concentration of deposited KOH. The pores were closely related to the natural properties of bamboo, and the soft components in the fiber pipes were easily etched by KOH. A large number of nanosized pores were also formed on the walls of the ordered micron-sized pores (see the Supporting Information, Figure S4b). Not all pores apparent in the SEM images were responsible for CO$_2$ adsorption, but made mass transfer of CO$_2$ easier; micropores on the walls of the ordered micron-sized pores mainly contributed to CO$_2$ adsorption at low pressures. Bamboo-3-873 showed high CO$_2$ adsorption capacity because bamboo is a good precursor for activated carbon preparation and its texture is suitable for developing a large number of narrow micropores by KOH activation.

CO$_2$ adsorption depends on the textural properties of activated carbon, such as specific surface area (SSA), total pore volume, and pore size (see the Supporting Information, Table S1). With the increase of KOH/C mass ratios, both SSA and total pore volume increased, but their yields decreased.

The amount of CO$_2$ adsorbed on these activated carbons at 273 K and 1 bar was measured, and its relationship with SSA is shown in Figure 6a. CO$_2$ adsorption on the activated carbons prepared at a fixed activation temperature first increased and then decreased with increasing SSA, and the maximum amount of CO$_2$ adsorbed was achieved at a moderate SSA of about 2000 m$^2$ g$^{-1}$. Bamboo-derived activated carbons prepared under severe activation conditions were not favorable for CO$_2$ adsorption, although they had higher SSAs. Similarly,
the total pore volume was also not proportional to CO₂ amounts adsorbed (Figure 6b). These results indicated that large pores produced under severe activation conditions caused the increase of SSA and pore volume, but they contributed little to CO₂ adsorption at 1 bar because no pore filling occurred. However, the amount of CO₂ adsorbed at higher pressures may be positively correlated with their SSA and pore volume. Evidently, both SSA and total pore volume cannot be used to evaluate CO₂ adsorption at atmospheric pressure on bamboo-derived activated carbons.

It has been reported that micropores play an important role in CO₂ adsorption,[20,25–28] but the correlation between pore size and CO₂ adsorption (important in the evaluation of carbonaceous adsorbents) has rarely been investigated. Presser et al. found the perfect linear correlation between pore (with diameters of <0.8 nm) volume and CO₂ uptake at 1 bar for carbide-derived carbons (CDCs).[28] We also used CO₂ adsorption isotherms at 273 K to accurately determine the narrow micropore size distribution (NMPSD) of bamboo-derived activated carbons (<1 nm). The NMPSD curves (Figure 7) showed three peaks at about 0.36, 0.55, and 0.82 nm, which represent the volume of different pores (denoted as \( V_{0.36} \), \( V_{0.55} \), and \( V_{0.82} \), respectively), and of which \( V_{0.55} \) was the dominant one. For activated carbons prepared at 873 K, \( V_{0.36} \) decreased, whereas \( V_{0.82} \) increased with the increase of KOH/C ratios from 1 to 5 (Figure 7a), indicating that pores were enlarged with the increase in KOH/C ratios; \( V_{0.55} \) first increased and then decreased, consistent with the trend of CO₂ adsorption (Figure 6a). Bamboo-3-873 had the highest \( V_{0.55} \) and the highest CO₂ adsorption. Therefore, micropores of about 0.55 nm in diameter were mainly responsible for CO₂ adsorption. A similar trend was also observed for activated carbons prepared at 973 and 1073 K (see the Supporting Information, Figure S5). Figure 7b displays NMPSDs in activated carbons prepared at 773, 873, and 1123 K, and it can be seen that the activation temperature had an effect similar to the KOH/C mass ratio on the NMPSD. Bamboo-3-873 had a higher \( V_{0.55} \) than the other two activated carbons and it also showed a higher CO₂ adsorption (Figure 1b). Micropores of about 0.36 nm in diameter were produced at low KOH/C mass ratios and at a low temperature and were subsequently enlarged to about 0.55 and 0.82 nm with the increase in KOH/C ratios and activation temperatures. We correlated CO₂ uptake at 1 bar with their \( V_{0.55} \) (see the Supporting Information, Figure S6d), and an approximately linear correlation was observed (\( R^2 = 0.96 \)), indicating that the dominant \( V_{0.55} \) played an important role in the adsorption of CO₂. Therefore, the KOH/C ratio and activation temperature should be carefully selected to produce a high \( V_{0.55} \). In the preparation of activated carbons for high CO₂ adsorption using KOH activation at 1 bar. In addition, \( V_{0.55}/V_{0.82} \) ratios were found to be 3.6, 2.0, 1.2, and 0.9 for Bamboo-1-973, Bamboo-3-873, Bamboo-5-973, and Bamboo-5-1073, respectively, and their \( (S(CO_2/N_2)) \) values at 298 K and 1 bar were calculated to be 11.1, 8.6, 7.9, and 6.6, respectively. \( (S(CO_2/N_2)) \) values decreased with the decrease of \( V_{0.55}/V_{0.82} \) ratios, indicating that pores of about 0.55 nm in diameter were effective for CO₂ adsorption, whereas pores of about 0.82 nm in diameter also allowed nitrogen adsorption.

To further build an accurate relationship between micropore volume and CO₂ adsorption, fifteen bamboo-derived activated carbons prepared at various KOH/C ratios and activation temperatures were analyzed (Figure 6). When the upper limit of pore size for calculating pore volume decreased from 1.02 to 0.60, the relationship between different micropore volumes and adsorbed amounts of CO₂ was established (Figure 8, and also see the Supporting Information, Figure S6). Linear correlation coefficients (\( R^2 \)) first increased and then decreased with the decrease in the upper limit of the pore size, and the best linear relationship (\( R^2 = 0.98 \)) was achieved at pore sizes of <0.82 nm (Figure 8b). This was consistent with results reported by Presser et al., indicating that this correlation might be applicable to all porous carbons, not just CDCs or activated carbons. It was thus deduced that possibly there is no influence of carbon precursors and preparation method on the linear relationship between the volume of pores in the range 0.33–0.82 nm and amount of CO₂ adsorbed at 273 K and 1 bar. For Bamboo-5-1073, pore volume was 0.34 cm³ g⁻¹ (diameter of <1 nm), but the adsorbed amount of CO₂ was only 4.6 mmol g⁻¹, which was far below the linear fitting value (see the Supporting Information, Figure S6a). This can be attributed to the fact that Bamboo-5-1073 had more pores with a diameter of >0.82 nm, which were not effective for CO₂ adsorption because these micropores were too large to achieve dense packing of CO₂ molecules at 1 bar.[29] In Figure 8d there were some data points deviating from the linear regression such as for Bamboo-1-873 with a pore volume of 0.2 cm³ g⁻¹ (diameter of <0.72 nm) and an amount of adsorbed CO₂ of 4.3 mmol g⁻¹.
The reason was that Bamboo-1-873 had a large $V_{0.36}$ (Figure 7 a) and these micropore sizes were close to the kinetic diameter of $CO_2$ (0.33 nm), making $CO_2$ adsorption less effective.\textsuperscript{29} Micropores of about 0.55 nm in diameter could provide more space for $CO_2$ to adjust its orientation to the pore wall.\textsuperscript{33, 41} These results revealed that micropores of about 0.55 nm in diameter were highly efficient for $CO_2$ adsorption at 1 bar and the volume of micropores with diameters of $<0.82$ nm had a linear relationship with the amounts of $CO_2$ adsorbed on the activated carbons, indicating that this micropore range can be regarded as a standard to evaluate $CO_2$ adsorption capacity on activated carbons. KOH activation is widely used to prepare highly activated carbons, but the preparation process requires higher chemical consumption, increases cost, and raises environmental issues. Because our bamboo-derived activated carbon shows a high adsorption capacity for $CO_2$ and can be used repeatedly, it is competitive for $CO_2$ capture in practical applications.

Conclusions

Bamboo has been used as a cost-effective precursor to prepare high-performance activated carbons for $CO_2$ capture. The high adsorption capacity, high regeneration stability, and good selectivity for $CO_2$ indicate that bamboo-derived carbon prepared by KOH activation is one of the most promising adsorbents for $CO_2$ capture. Bamboo is an ideal precursor for activated carbon preparation because of its low price, great availability, and high biomass yield. In particular, the unique textural structure of bamboo favors the formation of some narrow micropores using KOH activation. The micropore-size distribution of activated carbon can be regulated by changing the activation conditions to meet the requirements for $CO_2$ adsorption at different pressures. Because a positive correlation exists between $V_{0.55}$ and $CO_2$ adsorption, narrow micropores of about 0.55 nm dominated the adsorption of $CO_2$ on activated carbons at 1 bar. The volume of narrow micropores with diameters of $<0.82$ nm have a linear correlation with the amounts of adsorbed $CO_2$, indicating that this micropore range can be regarded as a standard to evaluate $CO_2$ adsorption capacity on activated carbons.

Experimental Section

Materials

The bamboo used in this study was purchased from a local market in Beijing and it was crushed and sieved into different particle sizes in the range of 10–20 (2.0–0.85 mm), 20–30 (0.85–0.60 mm), 40–65 (0.42–0.23 mm), and 150–200 mesh (0.105–0.075 mm). KOH was purchased from Beijing Modern Eastern Fine Chemical Co., Ltd.

Bamboo-derived activated carbon preparation

The bamboo was first added into a tubular furnace (KSY-6-16A, Tianjin Zhonghuan Co. Ltd, China) and heated to 773 K at an increasing rate of 5 K min$^{-1}$; then the temperature was kept for 1.5 h. In the activation process, the carbonized materials were impregnated by the KOH solution at the predetermined KOH/C mass ratios, and the mixture was dried at 378 K for 12 h. The resulting dry material was placed in a tubular furnace, followed by heating to the predetermined activation temperature at a ramp of 10 K min$^{-1}$, which was held for 1.5 h. The heating process was conducted under $N_2$ flow protection. Finally, the activated carbon particles were washed by using aq. HCl (1 mol L$^{-1}$), followed by washing with deionized water until the pH value of the wash water was less than 8.0. The bamboo-derived activated carbon is denoted as Bamboo-$X$-$Y$, where $X$ represents the KOH/C mass ratio, and $Y$ denotes the activation temperature in K.

Characterization

The surface morphology of the bamboo and bamboo-derived activated carbon was characterized by means of SEM (LEO-1530, LEO, Germany). The textural properties of activated carbons were characterized by $N_2$ adsorption at 77 K and $CO_2$ adsorption at 273 K in a gas adsorption instrument (Autosorb iQ, Quantachrome Corp., US). Prior to each measurement, the sample was outgassed at 300 °C for 6 h in vacuum to clean its surface. SSA$s$ were calculated with the Brunauer–Emmett–Teller (BET) equation from $N_2$ adsorption data in the relative pressure ($P/P_0$) range of 0.01–0.1 for most activated carbon samples, whereas the appropriate $P/P_0$ range was 0.05–0.15 for microporous materials.

Figure 8. Relationship between $CO_2$ adsorption and the volume of micropores in the range of (a) 0.33–0.90 nm, (b) 0.33–0.82 nm, (c) 0.33–0.75 nm, and (d) 0.33–0.72 nm.
from 0.05 to 0.25 for Bamboo-5-1073 containing a considerable amount of mesopores. The multipoint BET fitting had a high R² (>,0.9999) and a positive line intersect. Total pore volume was calculated from the amount of nitrogen adsorbed at P/P₀ = 0.99. Narrow micropore size (< 1 nm) distribution and volume were calculated by applying the NLDFT model for CO₂ adsorption at 273 K.

**CO₂ adsorption–desorption experiments**

CO₂ adsorption–desorption data in the pressure range of 0.01–1 bar were obtained using a static gas adsorption instrument (Autosorb iQ, Quantachrome) at 273 K and 298 K. The adsorption selectivity of the activated carbon was evaluated by the molar ratio of the equilibrium amounts of CO₂ and N₂ adsorbed at 1 bar, which was denoted as S(CO₂/N₂). The regeneration of the activated carbon was performed at 298 K under vacuum (< 0.1 bar). After regeneration, the cycle was repeated at the same temperature (273 K and 298 K) and pressure (1 bar). Four cycles were repeated for CO₂ adsorption on the same activated carbon.

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**Keywords:** adsorption · biomass · electron microscopy · green chemistry · microporous materials

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