

Preparation and characterization of templated porous carbons from sucrose by one-pot method and application as a CO₂ adsorbent

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Abstract: The templated porous carbons were prepared from sucrose by one-pot method. In this method in which the pre-synthesis of the hard template is eliminated, the porous carbons were produced by organic-inorganic self-assembly of sucrose, tetraethyl ortosilicate (TEOS), Pluronic P123 and n-butanol in an acidic medium, and subsequent carbonization. The synthesis parameters such as sucrose amount, TEOS molar ratio and carbonization temperature were evaluated for describing their effects on the pore structures of the synthesized carbons. The prepared porous carbons were characterized by N₂ adsorption, thermogravimetric analysis (TGA), Raman spectroscopy, X-ray diffraction (XRD), field emission scanning electron microscopy (FESEM), and transmission electron microscopy (TEM) techniques. The carbon dioxide adsorption uptakes of the obtained porous carbons were determined at 1 bar and 273 K. The templated carbon obtained with the lowest TEOS molar ratio exhibited the highest BET surface area of 1289 m²/g and micropore volume of 0.467 cm³/g, and showed the highest CO₂ uptake of 2.28 mmol/g.

Key words: Porous carbon, templated synthesis, one-pot method, CO₂ adsorption

1. Introduction

Nowadays, climate change due to the increase in greenhouse gas emissions accumulated in the atmosphere is a major threat to the world. Carbon dioxide (CO₂) is one of the gases that has a major share in global warming. The share of CO₂ in the greenhouse effect factors is about 55% [1–2]. CO₂ emissions, as a result of from industry, power plants and combustion of fossil fuels, which are worldwide problems [3]. Therefore, reducing the CO₂ concentration in the atmosphere has recently been an important issue. For that reason, the development of CO₂ capture and storage techniques is extremely important [4–5].

Recently, solid adsorption, liquid absorption and membrane separation can be mentioned as the main methods for CO₂ capture [2,6]. Among these methods, CO₂ adsorption is a prominent method due to its advantages such as low energy requirement, low cost, ease of application, and regeneration of the adsorbent [7–10]. In order for CO₂ adsorption to be efficient, it is important to develop an adsorbent with a high adsorption capacity, selectivity, kinetics and stability [7,11]. Commonly used solid adsorbents for CO₂ capture are zeolites [12–13], silica [14], clay minerals [15], metal-organic frameworks [16–19], porous polymer materials [20–22], and carbon materials [23–29].

Because the carbon materials have properties such as large surface areas and pore volumes, hydrophobicity of the surface, relatively easy regeneration, good thermal and mechanical stability, and inexpensive preparation costs, they stand out for CO₂ adsorption among other adsorbents [1–5,30]. Activated carbons are the most widely used carbon materials in this area [30–35]. However, since activated carbons are produced from various raw materials and by various methods, they offer an uncontrollable pore structure and surface properties. The carbon adsorbents with controlled porous structure were prepared by using different synthesis ways like template method. The hard or soft template carbonization methods have attracted much attention to prepare porous carbon materials with desirable properties [4,36]. In particular, the ordered porous carbons which have quite narrow and uniform pore size distribution can be prepared with this method and they are considered to be very suitable CO₂ adsorbents [37].

The template synthesis of ordered mesoporous carbons was first reported by Ryoo and coworkers [38,39] using mesoporous silica materials such as MCM-48 and SBA-15 as hard templates and sucrose as the carbon source. Although the ordered mesoporous carbons obtained by this method have large surface areas, large pore volumes, and narrow pore

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size distributions, the process of preparing these carbons by the hard template method is time-consuming and includes multiple steps such as the need to prepare the hard template first and then impregnation. Later, a one-pot method that eliminates the pre-synthesis step of silica and allows the simultaneous formation of carbon and silica was presented. Ting and co-workers [40] reported a simple one-pot method for preparing of hexagonally ordered mesoporous carbon. In their method, a composite was formed in a one-pot using sucrose, tetraethyl orthosilicate (TEOS), and Pluronic P123 via organic-inorganic self-assembly under acidic conditions, and then mesoporous carbons were obtained by removing silica following carbonization. They showed that the structural properties of ordered mesoporous carbons can be adjusted simply by changing the reaction parameters and compositions [40]. Prabhu et al. [41] presented a work that involves the simultaneous production of KIT-6 silica and carbon by one-pot method. In this method, P123/n-butanol/sucrose/silica composite directly catalyzed by H_2SO_4 in the synthesis mixture was generated, and the mesoporous carbon was prepared after carbonization followed by silica removal. Thus, the mesoporous carbon with three-dimensional cubic symmetry was obtained [41]. In their report, the synthesis of this carbon was carried out under a specific condition only; some important points such as the effects of the synthesis parameters and of the amounts of components in the synthesis mixture on the structure of the resulting carbons were not addressed. In addition, it was emphasized that the synthesis conditions and compositions still need to be optimized. However, to the best of our knowledge, no reports have been found in the published literature regarding the effects of synthesis conditions of mesoporous carbon with three-dimensional cubic symmetry produced by the one-pot method. To overcome this gap, the synthesis parameters and compositions were investigated in this study by employing one-pot technique for these carbons development. To ensure the widespread use of porous carbons, it is important to develop simple synthesis methods that directly lead to their formation and to optimize these synthesis methods.

In particular, the studies based on high performance adsorbents for carbon dioxide retention have attracted great attention. Currently, the researches focus on using low-cost resources to develop efficient and economical synthesis pathways for ideal performance sorbents. The present study is thought to be the first attempt to introduce CO_2 adsorption potentials of the templated porous carbons which produced using one-pot method a simplified technique, from sucrose as an economical and abundant source.

In this study, templated carbons were prepared using sucrose as a carbon precursor and tetraethyl orthosilicate (TEOS) as silica precursor by one-pot method. In this method, the organic-inorganic self-assembly of sucrose, TEOS, Pluronic P123, and n-butanol in acidic medium was performed, thus the pre-synthesis of hard template was eliminated. In addition, the porous carbons produced from sucrose can be advantageous since sucrose is a low-cost, environmentally friendly, and abundantly available chemical. The CO_2 adsorption potentials of the templated porous carbons were determined. The effects of synthesis parameters such as carbonization temperature, molar ratio of TEOS and amount of sucrose on the properties of carbons were also investigated. This examination was supported by different characterization tests including field emission scanning electron microscopic (FESEM) imaging, transmission electron microscopic (TEM) imaging, thermogravimetric analysis (TGA), Raman spectroscopy, X-ray diffraction (XRD), surface area, and porosity analysis.

2. Materials and methods

2.1. Chemicals

In the synthesis of carbons, sucrose (Carlo Erba), tetraethyl orthosilicate (TEOS) (Acros Organics), triblock copolymer (Pluronic P123 MW = 5800, Sigma Aldrich), n-butanol (VWR Chemicals), and sulfuric acid (H_2SO_4) (Fluka) were used as the carbon source, silica source, structure directing agent, cosolvent, and catalyst, respectively. Hydrochloric acid (HCl) (Merck) was used to provide the acidic medium and hydrofluoric acid (HF) (Fisher Chemical) was used to remove silica. All of the chemicals used in the study were analytical grade and they were used as received.

2.2. Synthesis of templated porous carbons

The templated porous carbons were synthesized via the one-pot method with some modifications according to the method found in the related literature [41]. In a typical synthesis, 4 g of P123 was added to the acidic solution containing 7.9 g of HCl and 144 g of water and the mixture was stirred at room temperature for 3 h. Then, 4 g of n-butanol was added to the same solution and stirred for a further 2 h. To the resulting homogeneous solution was added 1 g of H_2SO_4 and a certain amount of sucrose (0.6, 0.73, and 0.85 g) and again stirred for 2 h. A certain molar ratio (0.52, 1.70, and 2.88) of TEOS was added to this solution and the mixture was allowed to stand at 35 °C for 24 h under vigorous stirring. This solution was aged hydrothermally at 100 °C for 24 h in polypropylene bottles. Subsequently, it was kept in the oven at 100 °C for 6 h and then at 160 °C for 6 h. The resulting composite powder was subjected to carbonization under nitrogen flow at various temperatures (766, 850, and 934 °C) for 3 h. A 10% HF solution was used to remove the silica from the resulting solid and the carbonized solid was allowed to stand in this solution for 24 h. It was then filtered, washed with ethanol, and dried at

100 °C. Since it was aimed to investigate the effects of sucrose content, TEOS molar ratio and carbonization temperature on the properties of the formed carbons, these conditions were changed at the values indicated in brackets and synthesis was applied. The porous carbons are named as S-x/T-y/C-z, where x is the amount of sucrose and y is the molar ratio of TEOS and z is the carbonization temperature. All notations of the prepared carbon adsorbents along with their synthesis conditions are given in Table 1.

2.3. Characterization

The pore volumes and specific surface areas of the porous carbons were determined by analyzing the nitrogen adsorption-desorption isotherms which found at 77 K using an Autosorb 1-C (Quantachrome, USA) analyzer. Before the analysis, the carbon samples were degassed at 300 °C for 3 h under vacuum. The Brunauer–Emmett–Teller (BET) method was used to determine the specific surface areas of carbons and Barret-Joyner-Halenda (BJH) method was applied to adsorption isotherm to determine the pore size distributions of carbons. The total pore volume (V_{total}) was obtained from the adsorbed volume of N_2 at relative pressure of 0.99. The micropore volumes (V_{micro}) were determined by using the Dubinin–Radushkevich (DR) method. The X-ray diffraction (XRD) patterns were collected by Panalytical Empyrean at a scanning speed of 5 °/min and a scanning angle of 10–70 ° for analyzing the structures of carbons. In addition, Raman spectroscopy (Renishaw inVia) was also used with a laser wavelength of 532 nm and in a scanning range of 100–4000 cm^{-1} . Field emission scanning electron microscopy (FESEM) (Hitachi Regulus 8230) and transmission electron microscopy (TEM) (Hitachi HT7800) were used to characterize the surface morphology and microstructure of carbons. Elemental composition was demonstrated by energy dispersive X-ray spectroscopy (EDS). Thermal behavior of carbon was performed on a thermal analyzer (Perkin Elmer STA 8000) at 10 °C/min. The CO_2 adsorption isotherms of the porous carbons were determined at a temperature of 273 K and in a pressure range of 0–1 bar by using a volumetric adsorption apparatus (Quantachrome Autosorb 1-C).

3. Results and discussion

The characterization results obtained for carbons produced under the conditions specified in Table 1 and the results for CO_2 adsorption are presented in the following sections.

3.1. Characterization of porous carbons

The molecular morphology characterization of carbon materials was performed by Raman spectroscopy. The Raman spectra for all carbon samples are given in Figure 1. The Raman analysis of the carbon samples showed two main peaks at around 1335 and 1590 cm^{-1} . The G band at 1590 cm^{-1} indicates that the carbon samples contain sp^2 bonded carbon in planar sheets. This represents the presence of ordered carbon structure. The broad band at 1335 cm^{-1} is known as the D band and this is due to a hybridized vibrational mode associated with graphene edges in disordered carbon with structural defects and disorders [8,26,42–43]. The intensity ratio of D to G band, I_D/I_G , is usually used to characterize the graphitization degree of carbon materials. The I_D/I_G ratios for the carbon samples are given in Table 2. A higher I_D/I_G ratio indicates a lower degree of graphitization. The results show that the S-0.73/T-1.70/C-850 carbon has the highest and S-0.73/T-1.70/C-934 carbon has the lowest graphitic degree. For all porous carbon samples, the I_D/I_G ratios are close to 1 and found to be well compatible with similar mesoporous carbon materials [44–46].

The XRD patterns of templated porous carbons are presented in Figure 2. Two broad peaks at around 25 ° and around 44 ° shown in the XRD patterns can be attributed to (0 0 2) and (1 0 0) plane for all porous carbons [8,42–43]. These peaks

Table 1. Carbon samples and their synthesis conditions.

Carbon	Sucrose amount (g)	TEOS molar ratio	Carbonization temperature (°C)
S-0.60/T-1.70/C-850	0.60	1.70	850
S-0.73/T-1.70/C-850	0.73	1.70	850
S-0.85/T-1.70/C-850	0.85	1.70	850
S-0.73/T-0.52/C-850	0.73	0.52	850
S-0.73/T-2.88/C-850	0.73	2.88	850
S-0.73/T-1.70/C-766	0.73	1.70	766
S-0.73/T-1.70/C-934	0.73	1.70	934

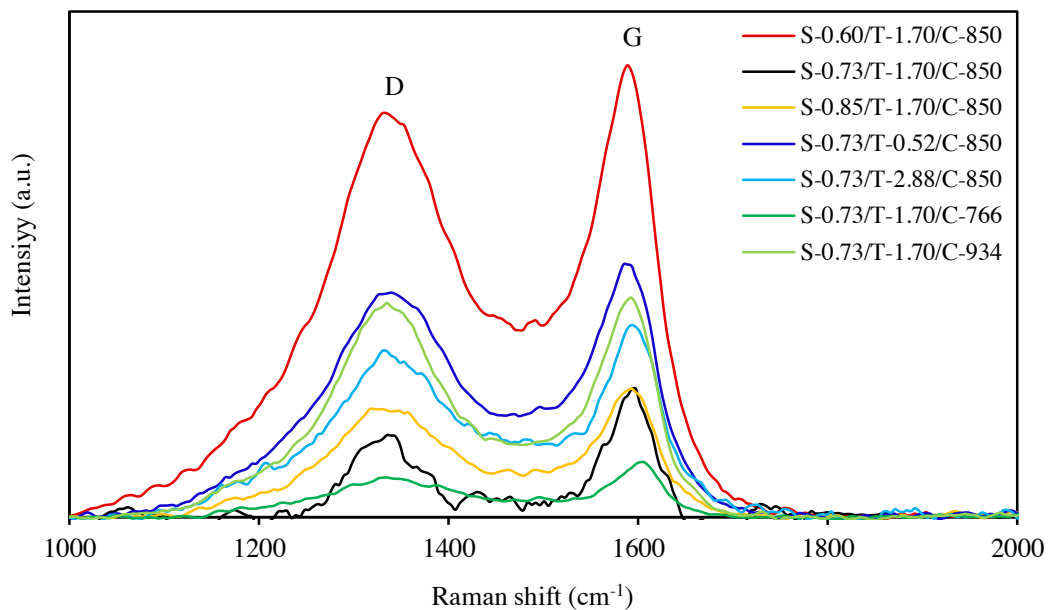


Figure 1. Raman spectra for porous carbons.

Table 2. Structural parameters of porous carbons.

Carbon	I_D/I_G	d_{002} (nm)
S-0.60/T-1.70/C-850	0.89	0.3543
S-0.73/T-1.70/C-850	0.64	0.3600
S-0.85/T-1.70/C-850	0.83	0.3687
S-0.73/T-0.52/C-850	0.88	0.3628
S-0.73/T-2.88/C-850	0.87	0.3737
S-0.73/T-1.70/C-766	0.72	0.3535
S-0.73/T-1.70/C-934	0.98	0.3657

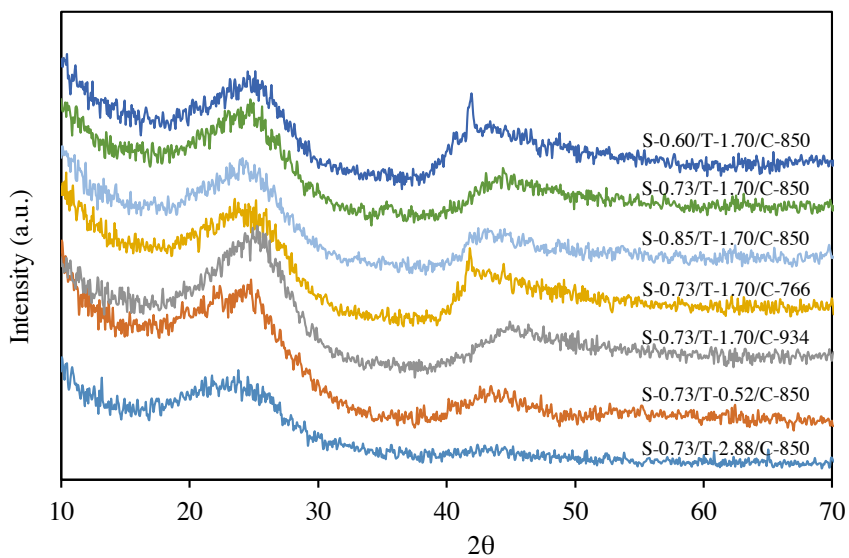


Figure 2. XRD patterns of porous carbons.

are typical for amorphous carbons [23]. The (0 0 2) peak for carbons indicates inter-planar stacking structures of graphitic carbon [42]. The (1 0 0) diffraction peak is caused by the disordered structure of carbons [1]. The values of d-spacing (d_{002}) from XRD measurement are given in Table 2. The d_{002} of porous carbons increased from 0.3535 nm to 0.3657 nm as the carbonization temperature increases. A similar situation is observed with an increase in the amount of sucrose. Again, the increase of the TEOS molar ratio to 2.88 also caused an increase in the d-spacing.

Figure 3 shows the FESEM images of the carbon samples prepared at different TEOS molar ratio. The pores and folds are observed on the carbon surfaces. The FESEM image of S-0.73/T-2.88/C-850 carbon prepared with the highest TEOS molar ratio shows a smoother surface with less porous structure. The surface appears to become rougher as the TEOS molar ratio decreases. The porous characteristics of the carbons can be viewed directly in the TEM images in Figure 4. In this figure, the mesopores of 2–4 nm in diameter can be distinguished on the carbon surfaces. The TEM image of the S-0.73/T-1.70/C-850 carbon sample also shows cubic arrays of structure. There are relatively regular distributed pores which is a typical characteristic of ordered porous carbons. Some disordered pores are also shown at edge positions. S-0.73/T-0.52/C-850 carbon exhibits a structure with more uniform pore size compared to other samples. This result is in good agreement with pore size distribution described later in this article (Figures 5a-d). The EDS analysis determined with FESEM indicated that the carbon content of the samples is at about 94 wt%, O content is at about 5 wt% and Si content is at about 0.23 wt%. This result proves that the silica is almost completely removed from the structure.

The nitrogen adsorption-desorption isotherms of porous carbons and pore size distributions are shown in Figure 5. The specific surface areas and pore properties of the porous carbons are given in Table 3. The adsorption-desorption isotherms of all carbons can be ascribed to type IV according to the IUPAC classification. This type of the isotherm is typical for materials containing mesopores, besides micropores. This is also seen in pore size distributions. All porous carbons show

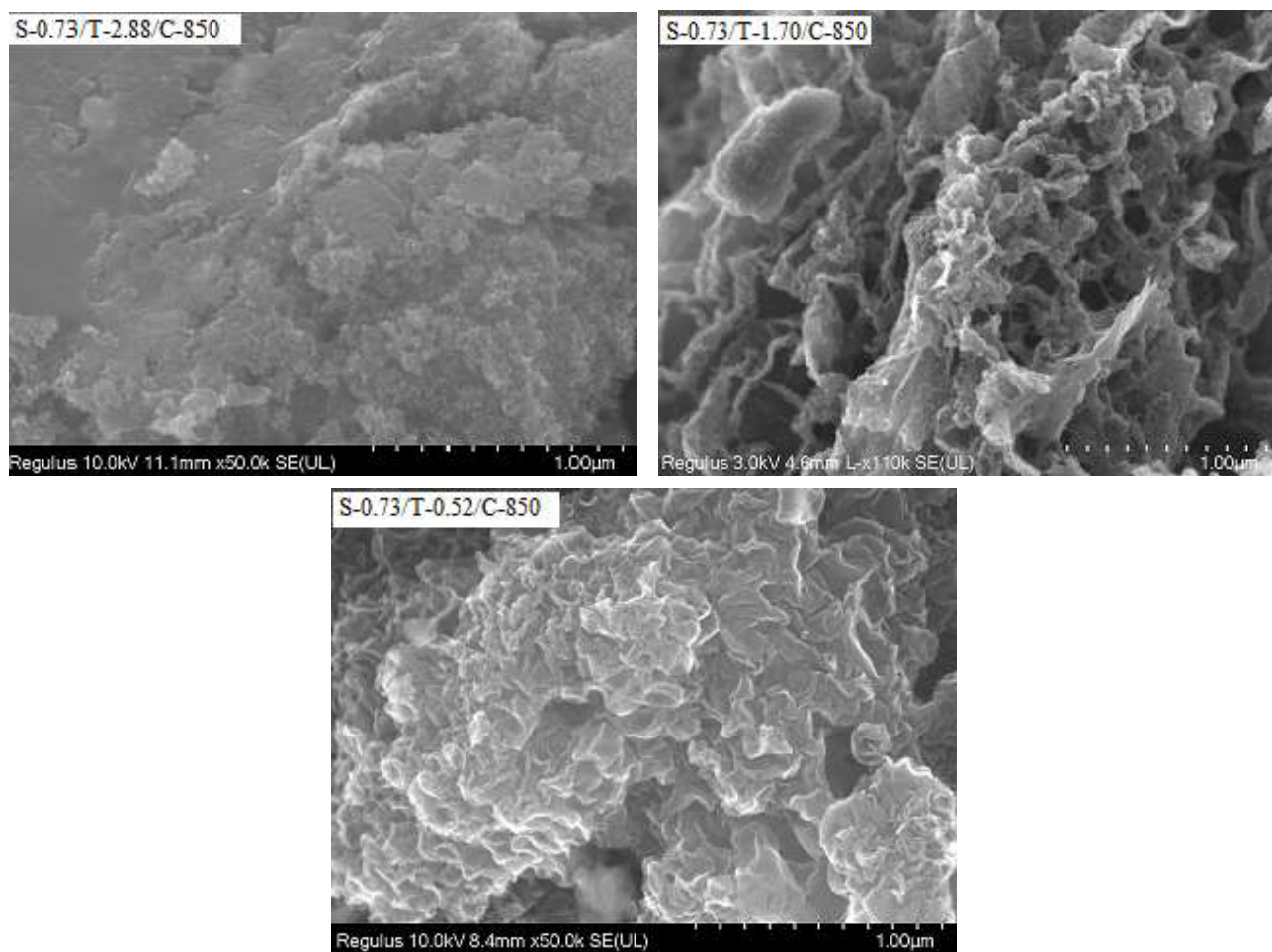


Figure 3. FESEM images of the porous carbons.

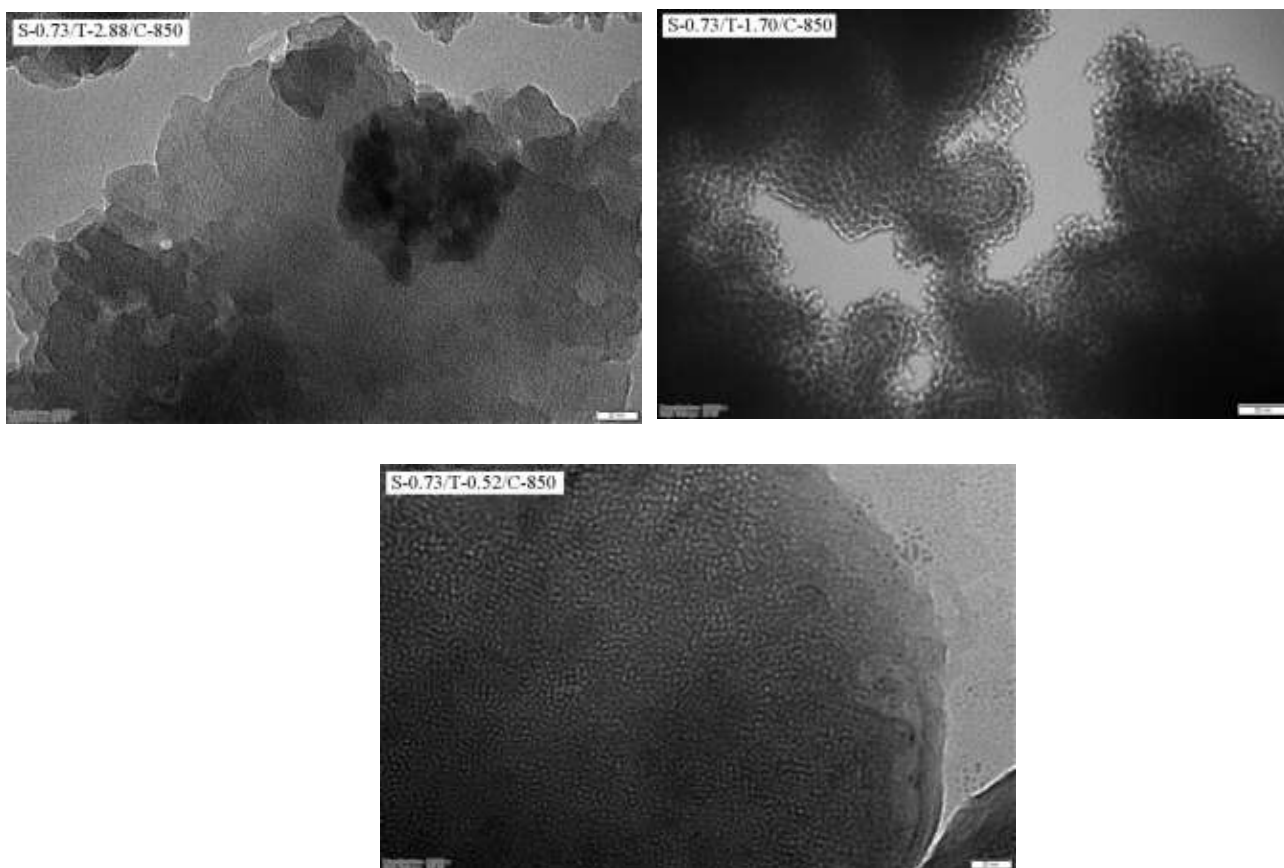


Figure 4. TEM images of the porous carbons.

well developed pore size distribution below 10 nm, indicating the presence of both micropores and mesopores. Almost all isotherms show type H2 hysteresis loops. Such loops are characterized by a long and nearly flat adsorption branch and a steep desorption branch. It is said that the pore structures of materials showing such isotherms are complex and interconnected. As the molar ratio of TEOS increased, the amount of nitrogen adsorbed decreased and the shape of the hysteresis loop was similar to the H4 type (Figure 5c). It can be concluded that the molar ratio of TEOS changes the pore properties of the formed carbons. This result can be seen from Table 3. When the TEOS molar ratio increased from 0.52 to 2.88, the specific surface areas and pore volumes sharply decreased from 1289 to 495 m²/g and from 1.196 to 0.557 cm³/g, respectively. The effects of sucrose amount and carbonization temperature on the pore properties of carbons were not as significant as the molar ratio of TEOS.

The thermal stability of the obtained porous carbons was examined by TGA analysis. Thermal behaviors of the S-0.73/T-1.70/C-850 carbon under N₂ and air atmosphere are shown in Figure 6. The curve obtained under N₂ flow exhibits three weight loss steps. The initial step weight loss is about 1.8% at below 100 °C, which is mainly attributed to the loss of moisture outside the surface and adsorbed water in the structure. The second step shows the weight loss of 3.7% at about 500 °C. The largest weight loss of 10.45% is in the third stage from 500 to 800 °C. As compared with that in N₂ atmosphere, the template porous carbon under air flow shows a significant weight loss which represents the oxidation of carbon in the temperature range of 500–700 °C. The mass content in TGA curve of carbon under air atmosphere is close to zero at temperature above 700 °C. The weight of residue was only 4.5% indicating that most components were burnt in air. In addition, little residue showed that the dissolution of silica was nearly complete. The results confirmed that the template porous carbon materials have high thermal stability in N₂ and air.

3.2. CO₂ adsorption

Figure 7 shows CO₂ adsorption isotherms of porous carbons at 273 K. The corresponding uptakes at 1 bar are presented in Table 3. The effects of sucrose amount on the CO₂ adsorption is shown in Figure 7a. The CO₂ adsorption isotherms for carbons prepared at different amount of sucrose are very close to each other. The effects of TEOS molar ratio are displayed

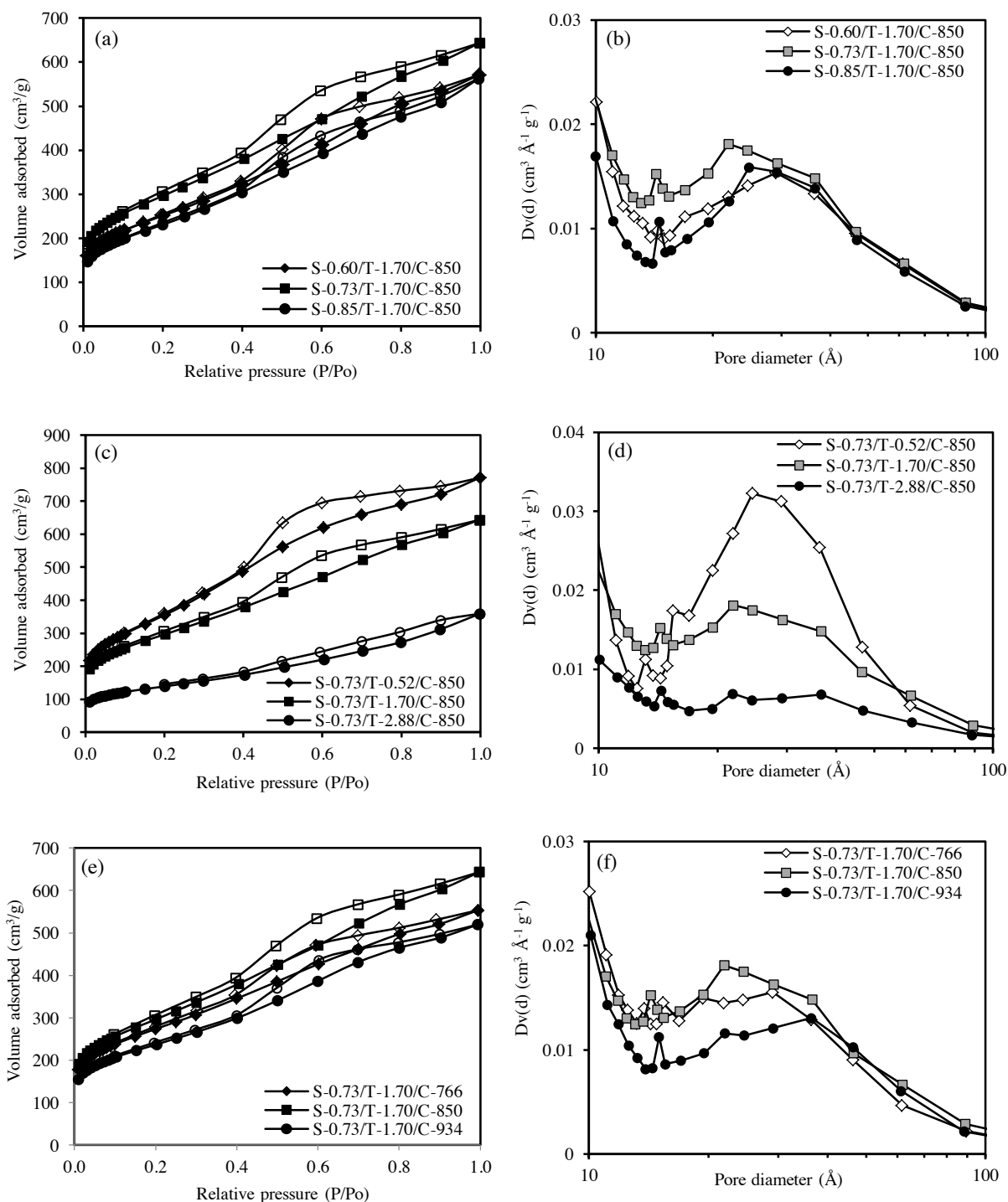


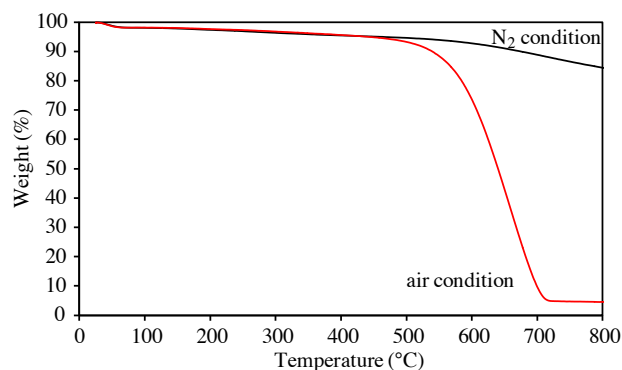
Figure 5. The adsorption-desorption isotherms (a, c, e) and pore size distributions (b, d, f) of porous carbons.

in Figure 7b. Increasing of the TEOS molar ratio from 0.52 to 2.88 gives rise to negative impacts on CO₂ uptake. In Figure 7c, carbon samples carbonized at 766 and 850 °C have very close CO₂ adsorption capacities, however CO₂ adsorption amount decreases when the carbonization temperature reaches to 934 °C.

Figure 8 shows the relationship of the adsorbed amount of CO₂ at 1 bar with the pore properties of the templated porous carbons. As can be seen in Figure 8, there is a nearly linear relationship between the CO₂ uptakes and pore properties. A very similar trend is observed for the adsorbed CO₂ amount in relation to the specific surface area and the micropore

Table 3. Specific surface areas and pore properties of porous carbons and CO₂ uptakes.

Carbon	S _{BET} (m ² /g)	V _{total} (cm ³ /g)	V _{micro} (cm ³ /g)	V _{meso} (cm ³ /g)	D _p (nm)	CO ₂ uptake at 273 K, 1 bar (mmol/g)
S-0.60/T-1.70/C-850	900	0.886	0.340	0.546	3.98	1.85
S-0.73/T-1.70/C-850	1052	0.998	0.398	0.600	3.80	1.87
S-0.85/T-1.70/C-850	827	0.873	0.310	0.563	4.24	1.77
S-0.73/T-0.52/C-850	1289	1.196	0.467	0.729	3.71	2.28
S-0.73/T-2.88/C-850	495	0.557	0.191	0.366	4.57	1.27
S-0.73/T-1.70/C-766	977	0.858	0.372	0.486	3.56	1.95
S-0.73/T-1.70/C-934	845	0.806	0.324	0.482	3.87	1.63

**Figure 6.** Thermogravimetric analysis for the S-0.73/T-1.70/C-850 carbon sample.

volume (Figures 8a and b). These pore properties have more linear relationship with CO₂ uptake as compared with total pore volume (Figure 8c). As the micropore volume and surface area presented by porous carbons increased, the CO₂ adsorption amount increased.

The effect of the synthesis parameters on the CO₂ adsorption capacities of the templated carbons is presented in Figure 9. The results show that the TEOS molar ratio has more influence on the CO₂ adsorption amount. While the S-0.73/T-0.52/C-850 carbon prepared with the lowest TEOS molar ratio exhibits the highest capacity of 2.28 mmol/g, the S-0.73/T-2.88/C-850 carbon synthesized with the highest TEOS molar ratio has the lowest CO₂ uptake of 1.27 mmol/g. The higher CO₂ adsorption capacity of S-0.73/T-0.52/C-850 carbon can be attributed to the higher surface area and micropore volume of this carbon compared to other samples. As mentioned earlier, the CO₂ capacity is directly related to the micropore volumes and surface areas of the carbons. Since TEOS is used as a source of silica in the synthesis of these carbons, it is thought that increasing the amount of TEOS leads to an increase in the pore wall thickness of the silica formed simultaneously with the carbon structure. It was concluded that when the TEOS molar ratio is high, the porous carbon formed after the silica was removed from the structure had larger pores and therefore the surface area of carbon decreased. When the TEOS molar ratio was 2.88, the average pore size of the formed carbon S-0.73/T-2.88/C-850 had the largest value of 4.57 nm among the synthesized carbons and the surface area had the lowest value of 495 m²/g. Increasing the amount of sucrose did not have a significant effect on the CO₂ adsorption capacities of the carbons while increasing the carbonization temperature led to a slight decrease in the amount of CO₂ adsorption. The high carbonization temperature caused much more micropores to collapse and form larger micropores and mesopores. In addition, average pore size enlarged from 3.56 nm to 3.87 nm when temperature was increased from 766 °C to 934 °C. It can be said that the most effective parameter on the surface areas and micropore volumes of the carbons synthesized in this study is the TEOS molar ratio. Therefore, the TEOS molar ratio was the most effective parameter, on the CO₂ adsorption capacity of carbons, among the synthesis parameters examined.

The measured CO₂ uptake values for the templated carbons synthesized in this study are close to the results presented in some previous studies in the literature while they are lower than others. Kim et al. synthesized three-dimensional

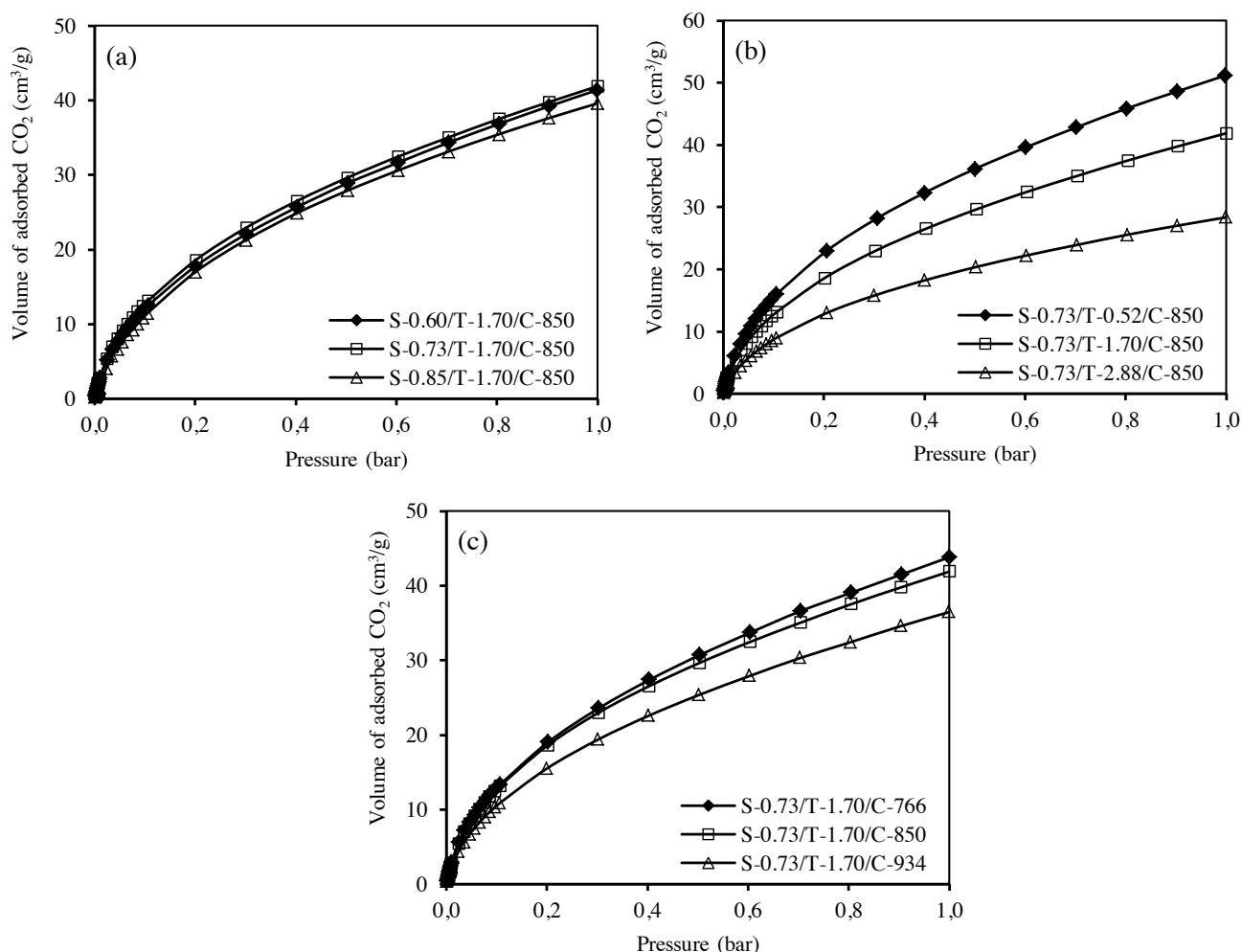


Figure 7. The CO₂ adsorption isotherms of templated porous carbons at 273 K.

hierarchical porous carbon materials by using furfuryl alcohol (PCM-F) or phloroglucinol (PCM-P) as carbon precursor and acid-labile mesoporous ZnO/Zn(OH)₂ spheres as hard template. The CO₂ uptakes of PCM-F and PCM-P are 1.83 and 2.55 mmol/g at 273 K, respectively [47]. Saha and Deng synthesized ordered mesoporous carbon from phloroglucinol by soft-template approach and measured adsorption properties of CO₂, methane, nitrous oxide, and ammonia. The adsorption equilibrium capacity of the ordered mesoporous carbon synthesized of the CO₂ is 1.49 mmol/g at 800 Torr and 298 K [48]. Tiwari et al. synthesized oxygen-enriched nanostructured carbon derived from resorcinol-formaldehyde by using mesoporous silica as template and reported the CO₂ uptake of 1.5 mmol/g at 30 °C [27]. Shi et al. prepared hierarchically porous carbon frameworks with the combination of hard template and NaOH activation. For this carbon, the CO₂ uptake at 273 K and 1 bar was reported as 3.80 mmol/g [49]. The nitrogen and sulfur dual-doped ordered mesoporous carbon spheres were prepared by Konnola and Anirudhan [50] and the capacity of 4.25 mmol/g at 273 and 1 bar was reported for CO₂ uptake. In another research, the hierarchical porous carbons from sugar as the carbon precursor and nano-CaCO₃ as the hard template were prepared and the results showed that the CO₂ uptake reaches 2.84 mmol/g at 25 °C and 1 bar and 3.66 mmol/g at 0 °C and 1 bar [51]. According to these results, higher capacities were generally obtained for the activated or nitrogen, sulfur doped carbons. Besides the pore structure of carbons, surface chemistry is known to be an effective factor on the CO₂ adsorption.

The cyclic stability of the adsorbent was tested by repeated consecutive adsorption and desorption steps. The adsorption/desorption cycle of CO₂ for S-0.73/T-0.52/C-850 carbon shows almost identical isotherm curves after four cycles (Figure 10). The average adsorption capacity was not changed during these cycles. These results indicate that the templated porous carbon is reversible and exhibits good adsorption stability.

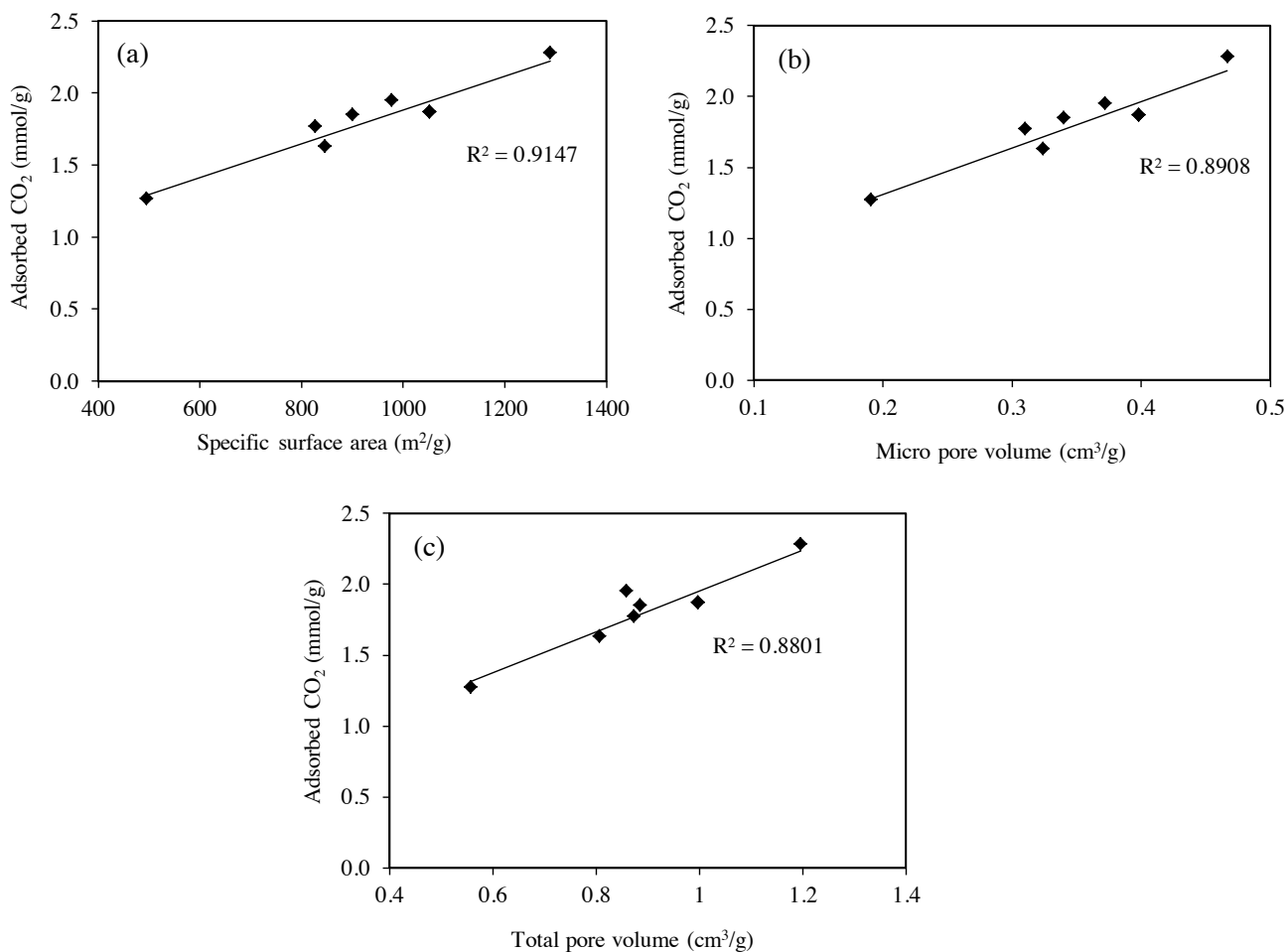


Figure 8. The relationship of adsorbed amount of CO₂ with (a) specific surface area, (b) micropore volume and (c) total pore volume of the templated carbons.

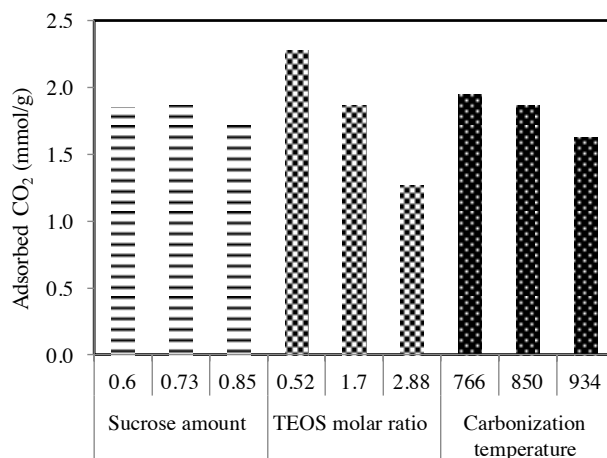


Figure 9. The change of CO₂ uptake with synthesis parameters.

The organic-inorganic self-assembly can be achieved in the one-pot method. Thus, the silica template is formed simultaneously with the carbon. Since this process does not require silica hard template preparation prior to the carbon synthesis, it significantly simplifies the process compared to the traditional hard template process and saves time, labour

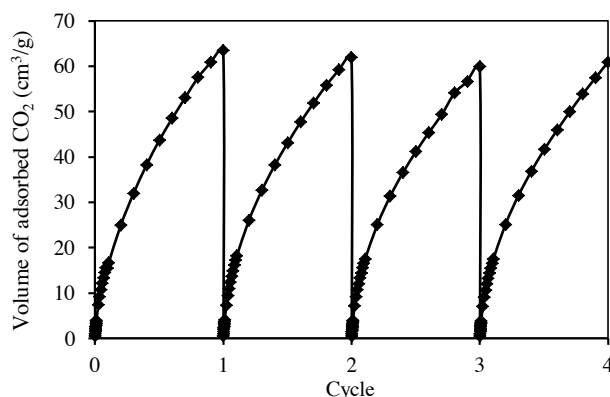


Figure 10. CO₂ adsorption cycles obtained for the S-0.73/T-0.52/C-850 carbon.

and energy. At the same time, using a low-cost carbon precursor such as sucrose can make the process more economical. As a result, the carbons obtained in this study may be of interest as potential adsorbents in CO₂ adsorption.

4. Conclusion

The templated porous carbons from sucrose were synthesized using one-pot method and characterized with various techniques such as Raman spectroscopy, FESEM, TEM, TGA, XRD, and N₂ adsorption. The sucrose amount, TEOS molar ratio and carbonization temperature were changed during the synthesis of carbons and the influences of these parameters on the pore properties and CO₂ adsorption of carbon materials were investigated. Results showed that the TEOS molar ratio is the most effective parameter on the pore properties of the synthesized carbons. The highest surface area of 1289 m²/g and the highest micropore volume of 0.467 cm³/g were measured for the carbon prepared with the lowest TEOS molar ratio. For this templated carbon, the highest CO₂ uptake of 2.28 mmol/g was also measured. Hence, the templated porous carbons can be used as CO₂ adsorbent. It is hoped that these results for CO₂ uptake with the templated carbons provides the benefits for further researches on the related porous carbons for CO₂ capture.

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Conflicts of interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

References

1. Kaur B, Gupta RK, Bhunia H. Chemically activated nanoporous carbon adsorbents from waste plastic for CO₂ capture: breakthrough adsorption study. *Microporous and Mesoporous Materials* 2019; 282: 146-158. doi: 10.1016/j.micromeso.2019.03.025
2. Yang G, Song S, Li J, Tang Z, Ye J et al. Preparation and CO₂ adsorption properties of porous carbon by hydrothermal carbonization of tree leaves. *Journal of Materials Science & Technology* 2019; 35: 875-884. doi: 10.1016/j.jmst.2018.11.019
3. Abd AA, Naji SZ, Hashim AS, Othman MR. Carbon dioxide removal through physical adsorption using carbonaceous and non-carbonaceous adsorbents: a review. *Journal of Environmental Chemical Engineering* 2020; 8: 104142. doi: 10.1016/j.jece.2020.104142
4. Zhang X, Li W, Lu A. Designed porous carbon materials for efficient CO₂ adsorption and separation. *New Carbon Materials* 2015; 30 (6): 481-501. doi: 10.1016/S1872-5805(15)60203-7
5. Wu X, Zhang C, Tian Z, Cai J. Large-surface-area carbons derived from lotus stem waste for efficient CO₂ capture. *New Carbon Materials* 2018; 33 (3): 252-261. doi: 10.1016/S1872-5805(18)60338-5
6. Zhang W, Bao Y, Bao A. Preparation of nitrogen-doped hierarchical porous carbon materials by a template-free method and application to CO₂ capture. *Journal of Environmental Chemical Engineering* 2020; 8: 103732. doi: 10.1016/j.jece.2020.103732
7. Acar B, Başar MS, Eropak BM, Caglayan BS, Aksoylu AE. CO₂ adsorption over modified AC samples: a new methodology for determining selectivity. *Catalysis Today* 2018; 301: 112-124. doi: 10.1016/j.cattod.2017.10.011

8. Huang G, Liu Y, Wu X, Cai J. Activated carbons prepared by the KOH activation of a hydrochar from garlic peel and their CO₂ adsorption performance. *New Carbon Materials* 2019; 34 (3): 247-257. doi: 10.1016/S1872-5805(19)60014-4
9. Gouveia LGT, Agustini CB, Perez-Lopez OW, Gutierrez M. CO₂ adsorption using solids with different surface and acid-base properties. *Journal of Environmental Chemical Engineering* 2020; 8: 103823. doi: 10.1016/j.jece.2020.103823
10. Sibera D, Narkiewicz U, Kapica J, Serafin J, Michalkiewicz B et al. Preparation and characterisation of carbon spheres for carbon dioxide capture. *Journal of Porous Materials* 2019; 26: 19-27. doi: 10.1007/s10934-018-0601-8
11. Sun Y, Li K, Zhao J, Wang J, Tang N et al. Nitrogen and sulfur co-doped microporous activated carbon macro-spheres for CO₂ capture. *Journal of Colloid and Interface Science* 2018; 526: 174-183. doi: 10.1016/j.jcis.2018.04.101
12. Thakkar H, Eastman S, Hajari A, Rownaghi AA, Knox JO et al. 3D-printed zeolite monoliths for CO₂ removal from enclosed environments. *ACS Applied Materials & Interfaces* 2016; 8: 27753-27761. doi: 10.1021/acsami.6b09647
13. Pham TD, Hudson MR, Brown CM, Lobo RF. Molecular basis for the high CO₂ adsorption capacity of chabazite zeolites. *ChemSusChem* 2014; 7: 3031-3038. doi: 10.1002/cssc.201402555
14. Alkhabbaz MA, Bollini P, Foo GS, Sievers C, Jones CW. Important roles of enthalpic and entropic contributions to CO₂ capture from simulated flue gas and ambient air using mesoporous silica grafted amines. *Journal of the American Chemical Society* 2014; 136: 13170-13173. doi: 10.1021/ja507655x
15. Cecilia JA, Vilarrasa-García E, Cavalcante Jr. CL, Azevedo DCS, Franco F et al. Evaluation of two fibrous clay minerals (sepiolite and palygorskite) for CO₂ capture. *Journal of Environmental Chemical Engineering* 2018; 6: 4573-4587. doi: 10.1016/j.jece.2018.07.001
16. Yoon M, Moon D. New Zr (IV) based metal-organic framework comprising a sulfur-containing ligand: Enhancement of CO₂ and H₂ storage capacity. *Microporous and Mesoporous Materials* 2015; 215: 116-122. doi: 10.1016/j.micromeso.2015.05.030
17. Yu J, Wu Y, Balbuena PB. Response of metal sites toward water effects on postcombustion CO₂ capture in metal-organic frameworks. *ACS Sustainable Chemistry & Engineering* 2016; 4: 2387-2394. doi: 10.1021/acssuschemeng.6b00080
18. Belmabkhout Y, Guillerm V, Eddaoudi M. Low concentration CO₂ capture using physical adsorbents: are metal-organic frameworks becoming the new benchmark materials? 2016; *Chemical Engineering Journal* 296: 386-397. doi: 10.1016/j.cej.2016.03.124
19. Siegelman RL, McDonald TM, Gonzalez MI, Martell JD, Milner PJ et al. Controlling cooperative CO₂ adsorption in diamine-appended Mg₂(dobpdc) metal-organic frameworks. *Journal of the American Chemical Society* 2017; 139: 10526-10538. doi: 10.1021/jacs.7b05858
20. Patel HA, Karadas F, Byun J, Park J, Deniz E et al. Highly stable nanoporous sulfur-bridged covalent organic polymers for carbon dioxide removal. *Advanced Functional Materials* 2013; 23: 2270-2276. doi: 10.1002/adfm.201202442
21. Mane S, Gao ZY, Li YX, Xue DM, Liu XQ et al. Fabrication of microporous polymers for selective CO₂ capture: the significant role of crosslinking and crosslinker length. *Journal of Materials Chemistry A* 2017; 5: 23310-23318. doi: 10.1039/C7TA07188D
22. Patel HA, Karadas F, Canlier A, Park J, Deniz E et al. High capacity carbon dioxide adsorption by inexpensive covalent organic polymers. *Journal of Materials Chemistry A* 2012; 22: 8431-8437. doi: 10.1039/C2JM30761H
23. Han J, Zhang L, Zhao B, Qin L, Wang Y et al. The N-doped activated carbon derived from sugarcane bagasse for CO₂ adsorption. *Industrial Crops & Products* 2019; 128: 290-297. doi: 10.1016/j.indcrop.2018.11.028
24. Shi J, Yan N, Cui H, Liu Y, Weng Y. Sulfur doped microporous carbons for CO₂ adsorption. *Journal of Environmental Chemical Engineering* 2017; 5: 4605-4611. doi: 10.1016/j.jece.2017.09.002
25. Jribi S, Miyazaki T, Saha BB, Pal A, Younes MM et al. Equilibrium and kinetics of CO₂ adsorption onto activated carbon. *International Journal of Heat and Mass Transfer* 2017; 108: 1941-1946. doi: 10.1016/j.ijheatmasstransfer.2016.12.114
26. Li D, Zhou J, Wang Y, Tian Y, Wei L et al. Effects of activation temperature on densities and volumetric CO₂ adsorption performance of alkali-activated carbons. *Fuel* 2019; 238: 232-239. doi: 10.1016/j.fuel.2018.10.122
27. Tiwari D, Kaur S, Bhunia H, Bajpai PK. CO₂ adsorption on oxygen enriched nanostructured carbons derived from silica templated resorcinol-formaldehyde. *Journal of Industrial and Engineering Chemistry* 2018; 65: 146-155. doi: 10.1016/j.jiec.2018.04.023
28. Jang E, Choi SW, Lee KB. Effect of carbonization temperature on the physical properties and CO₂ adsorption behavior of petroleum coke-derived porous carbon. *Fuel* 2019; 248: 85-92. doi: 10.1016/j.fuel.2019.03.051
29. Jin Z, Wang J, Zhao R, Guan T, Zhang D et al. Synthesis of S, N co-doped porous carbons from polybenzoxazine for CO₂ capture. *New Carbon Materials* 2018; 33 (5): 392-401. doi: 10.1016/S1872-5805(18)60347-6
30. Ogungbenro AE, Quang DV, Al-Ali KA, Vega LF, Abu-Zahra MRM. Physical synthesis and characterization of activated carbon from date seeds for CO₂ capture. *Journal of Environmental Chemical Engineering* 2018; 6: 4245-4252. doi: 10.1016/j.jece.2018.06.030
31. Fiuza-Jr RA, Andrade RC, Andrade HMC. CO₂ capture on KOH-activated carbons derived from yellow mombin fruit stones. *Journal of Environmental Chemical Engineering* 2016; 4: 4220-4236. doi: 10.1016/j.jece.2016.09.025

32. Boujibar O, Souikny A, Ghamouss F, Achak O, Dahbi M et al. CO₂ capture using N-containing nanoporous activated carbon obtained from argan fruit shells. *Journal of Environmental Chemical Engineering* 2018; 6: 1995-2002. doi: 10.1016/j.jece.2018.03.005
33. Kongnoo A, Intharapat P, Worathanakul P, Phalakornkule C. Diethanolamine impregnated palm shell activated carbon for CO₂ adsorption at elevated temperatures. *Journal of Environmental Chemical Engineering* 2016; 4: 73-81. doi: 10.1016/j.jece.2015.11.015
34. Ogungbenro AE, Quang DV, Al-Ali KA, Vega LF, Abu-Zahra MRM. Synthesis and characterization of activated carbon from biomass date seeds for carbon dioxide adsorption. *Journal of Environmental Chemical Engineering* 2020; 8: 104257. doi: 10.1016/j.jece.2020.104257
35. Zhang C, Wang R, Wang Y, Ren G, Zhang X et al. Synthesis of millimeter-sized porous carbon spheres derived from different precursors for CO₂ capture. *Journal of Porous Materials* 2020; doi: 10.1007/s10934-020-00967-0
36. Barczak M, Michalak-Zwierz K, Gdula K, Tyszczyk-Rotko K, Dobrowolski R et al. Ordered mesoporous carbons as effective sorbents for removal of heavy metal ions. *Microporous and Mesoporous Materials* 2015; 211: 162-173. doi: 10.1016/j.micromeso.2015.03.010
37. Lee SY, Park SJ. A review on solid adsorbents for carbon dioxide capture. *Journal of Industrial and Engineering Chemistry* 2015; 23: 1-11, doi: 10.1016/j.jiec.2014.09.001
38. Ryoo R, Joo SH, Jun S. Synthesis of highly ordered carbon molecular sieves via template-mediated structural transformation. *The Journal of Physical Chemistry B* 1999; 103 (37): 7743-7746. doi: 10.1021/jp991673a.
39. Jun S, Joo SH, Ryoo R, Kruk M, Jaroniec M et al. Synthesis of new, nanoporous carbon with hexagonally ordered mesostructure. *Journal of the American Chemical Society* 2000; 122: 10712-10713. doi:10.1021/ja002261e
40. Ting C, Wu H, Vetrivel S, Saikia D, Pan Y et al. A one-pot route to synthesize highly ordered mesoporous carbons and silicas through organic-inorganic self-assembly of triblock copolymer, sucrose and silica. *Microporous and Mesoporous Materials* 2010; 128: 1-11. doi: 10.1016/j.micromeso.2009.07.018
41. Prabhu A, Al Shoaibi A, Srinivasakannan C. Synthesis and characterization of mesoporous carbon by simple one pot method. *Materials Letters* 2014; 136: 81-84. doi: 10.1016/j.matlet.2014.08.012
42. Rehman A, Park SJ. Tunable nitrogen-doped microporous carbons: Delineating the role of optimum pore size for enhanced CO₂ adsorption. *Chemical Engineering Journal* 2019; 362: 731-742. doi: 10.1016/j.cej.2019.01.063
43. Liu L, Lu J, Zhang Y, Liu M, Yu Y et al. Synthesis of nitrogen-doped graphitic carbon nanocapsules from a poly(ionic liquid) for CO₂ capture. *New Carbon Materials* 2017; 32 (4): 380-384. doi: 10.1016/S1872-5805(17)60129-X
44. Tyagi D, Scholz K, Varma S, Bhattacharya K, Mali S et al. Development of Pt-carbon catalysts using MCM-41 template for HI decomposition reaction in S-I thermochemical cycle. *International Journal of Hydrogen Energy*; 2012; 37: 3062-3611. doi: 10.1016/j.ijhydene.2011.04.206
45. Vinu A, Srinivasu P, Takahashi M, Mori T, Balasubramanian VV et al. Controlling the textural parameters of mesoporous carbon materials. *Microporous and Mesoporous Materials* 2007; 100: 20-26. doi: 10.1016/j.micromeso.2006.10.008
46. Ignat M, Van Qers CJ, Vernimmen J, Mertens M, Potgieter-Vermaak S et al. Textural property tuning of ordered mesoporous carbon obtained by glycerol conversion using SBA-15 silica as template. *Carbon* 2010; 48: 1609-1618, doi: 10.1016/j.carbon.2009.12.062
47. Kim HC, Hwang YK, Seo SJ, Huh S. Gas sorption and supercapacitive properties of hierarchical porous graphitic carbons prepared from the hard-templating of mesoporous ZnO/Zn(OH)₂ composite spheres. *Journal of Colloid and Interface Science* 2020; 564: 193-203. doi: 10.1016/j.jcis.2019.12.117
48. Saha D, Deng S. Adsorption equilibrium and kinetics of CO₂, CH₄, N₂O, and NH₃ on ordered mesoporous carbon. *Journal of Colloid and Interface Science* 2010; 345: 402-409. doi: 10.1016/j.jcis.2010.01.076
49. Shi J, Cui H, Xu J, Yan N, Liu Y. Design and fabrication of hierarchically porous carbon frameworks with Fe₂O₃ cubes as hard template for CO₂ adsorption. *Chemical Engineering Journal* 2020; 389: 124459. doi: 10.1016/j.cej.2020.124459
50. Konnola R, Anirudhan TS. Efficient carbon dioxide capture by nitrogen and sulfur dual-doped mesoporous carbon spheres from polybenzoxazines synthesized by a simple strategy. *Journal of Environmental Chemical Engineering* 2020; 8: 103314. doi: 10.1016/j.jece.2019.103614
51. Zhang H, Wang Z, Luo X, Lu J, Peng S et al. Constructing hierarchical porous carbons with interconnected micro-mesopores for enhanced CO₂ adsorption. *Frontiers in Chemistry* 2020; 7: 919. doi: 10.3389/fchem.2019.00919