

# Characterization of the PSD of activated carbons from peach stones for separation of combustion gas mixtures

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**Abstract** Controlled series of microporous carbons were prepared through chemical activation with phosphoric acid from peach stones as the precursor material, corresponding to different preparation conditions. Adsorption isotherms of N<sub>2</sub> at 77 K and of CO<sub>2</sub> at 273 K were measured to be used in the characterization of the samples. The recently proposed mixed-geometry model (MGM), which assumes that the activated carbon is better represented by a mixture of slit and triangular geometry pores, is used to obtain the PSDs of the samples, on the basis of Grand Canonical Monte Carlo (GCMC) simulated ideal isotherms, both for N<sub>2</sub> at 77 K and of CO<sub>2</sub> at 273 K. Our results emerging from the analysis of two families of activated carbons reveal a consistent picture supporting the thesis that the PSDs of the same sample obtained through N<sub>2</sub> and CO<sub>2</sub> adsorption are different, a still controversial issue in the literature. Comparison of predictions from the MGM with those of the pure slit geometry model (PSGM) shows that the former gives a more consistent picture and more similar PSDs for the two adsorbates used.

**Keywords** Activated carbon · Pore size distribution · Slit geometry · Triangular geometry

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## 1 Introduction

The removal of carbon dioxide from combustion gas mixtures is becoming increasingly necessary in order to reduce its effects on climatic changes. Carbon dioxide can be captured selectively by suitable microporous adsorbents. Activated carbons (AC) are among the most convenient of these materials, due to their effectiveness and low cost. For the physical characterization of these materials, N<sub>2</sub> adsorption at 77 K is the most widely used method and is applied as a routine technique to obtain relevant information such as the specific surface, the micropore volume and the pore size distribution (PSD). Several problems have been identified in the characterization by N<sub>2</sub> adsorption, as pointed out by Lozano-Castelló et al. (2004): diffusion problems of the molecules of nitrogen inside the ultra-narrow pores (<0.7 nm), density changes of the adsorptive, lack of applicability of the DR equation in the low relative pressure range and different adsorption mechanisms according to the nature of the adsorbent/adsorptive. To overcome these problems, the alternative use of carbon dioxide at 273 K as adsorbate has been proposed in order to provide complementary information of the micropore volume and the heterogeneity of the pore sizes (Rodríguez-Reinoso and Molina-Sabio 1998). CO<sub>2</sub> adsorption at 273 K presents clear advantages including (i) a temperature high enough to avoid activated diffusion effects and (ii) the ability to measure adsorption at low relative pressures (where much important information is to be found) without the use of complex equipment (Marsh and Rodríguez-Reinoso 2006). Therefore, according to Marsh and Rodríguez-Reinoso (2006), the adsorption of carbon dioxide at 273 K should always be carried out for the characterization of any porous carbon as well as the adsorption of nitrogen. In other words, the charac-

terization of a porous carbon should always consist of determination of both isotherms, not just one. However, the use of two different adsorbates to characterize an AC brings about a number of questions, which have not yet received definitive answer, such as: In which way the two characterizations are complementary? Should the specific surface, the micropore volume and, very specially, the PSD corresponding to the two adsorbates be the same for a given sample? To what extent the PSD obtained with  $N_2$  will predict accurately an adsorption isotherm for  $CO_2$ ? These questions will be addressed in the present study by examining the structural characterization of two series of activated carbons prepared from peach stones by chemical activation.

The effectiveness of the microporous activated carbon for a given process, in this case the selective adsorption of  $CO_2$  from combustion gas mixtures, depends strongly on PSD, which also determines other properties like the specific surface and the micropore volume. The PSD of the material depend on the procedure followed in the preparation of the activated carbon and on the precursor material, but its determination through adsorption experiments depend on the geometrical model used to represent the microporous structure. High resolution STM images of AC treated with digital techniques (Huang et al. 2002) show clearly that AC have generally a quite disordered porous structure and that there are a relevant quantity of sites where an adsorbate molecule will be interacting simultaneously with three graphitic walls. These facts lead to the proposal of the Mixed Geometry Model (MGM), which assumes that the porous space is better represented by a collection of a mixture of slit geometry pores and triangular geometry pores of different sizes, as an alternative to the classical Pure Slit Geometry Model (PSGM). Details of the MGM are thoroughly given and discussed in Azevedo et al. (2010).

In the present work,  $N_2$  adsorption isotherms at 77 K and  $CO_2$  adsorption isotherms at 273 K are measured for two controlled families of AC samples from peach stones and they are fitted with its respective family of adsorption isotherms obtained through the Grand Canonical Monte Carlo (GCMC) simulation method, using both the PSGM and the MGM. Textural characteristics of the samples, such as the specific surface area, the micropore volume and the PSD are obtained. The results are then discussed with the purpose of arriving to a consistent picture about the characterization of the material and provide some clues to answer the questions mentioned above. This characterization is proving to be helpful in the design and evaluation of gas separation processes based on the studied materials.

## 2 Experimental

### 2.1 Sample preparation

The activated carbons used in this study have been prepared in our laboratory by chemical activation with phosphoric acid using peach stones as a precursor, following the experimental conditions already described (Soares Maia et al. 2010), which we briefly review here. The samples were prepared by chemical activation with phosphoric acid as activating agent as it was reported previously. Initially, the precursor (peach stones) was crushed into granular form and sieved to get a uniform particle size (average size of 2.38 mm). Part of this material was washed with a 10% (weight) sulfuric acid solution for 2 hours and then the material was washed with distilled water so as to ensure total removal of acid (by pH check). The other part was washed only with distilled water. The samples were dried at 100 °C for 2 hours. Impregnation was carried out at 85 °C for 2 hours with phosphoric acid solutions at a low concentration (26% w/w,  $X_p = 0.2$ ), assuring that the solution had evaporated totally and that the activated agent had been totally incorporated to the carbon. After impregnation, the samples were dried and submitted to a one-step carbonization, with heating rates of 2 °C/min or 10 °C/min, under air or under nitrogen, until reaching 450 °C and staying at this final temperature for 2 hours. After carbonization, the samples were washed with distilled water up to pH 6 in order to thoroughly remove the remaining phosphoric acid. Finally, the samples were dried at 100 °C for 2 hours.

### 2.2 Experimental characterization

Porous texture analysis of all samples has been carried out by subatmospheric nitrogen and carbon dioxide adsorption at 77 K and 273 K, respectively, in Autosorb-1 MP apparatus (Quantachrome, U.S.A.) volumetric adsorption equipment. Specific surface areas were determined according to the BET method and micropore volumes were estimated using the Dubinin-Radushkevich (DR) equation (Rouquerol et al. 1999).

### 2.3 Theoretical characterization

We briefly review here the MGM developed in details in Azevedo et al. (2010) and used to fit the experimental isotherms for both gases. Two geometries are proposed in this model to represent the idealized porous structure of an AC, the slit and triangular geometry pores; only equilateral triangles are considered for the latter in order to keep the number of parameters to a minimum and in this case the pore size is given by the diameter of the circle inscribed in the triangular section of the pore. The gas-solid potential for the

slit geometry is given, as usual, by the superposition of two Steele potentials (Steele 1974), one per each infinite plate. For the triangular geometry, the gas-solid potential is obtained by summing the contributions of three semi-infinite plates. The potential of each semi-infinite plate is given in Bojan and Steele (1998). The values of all parameters included in the interaction potentials for N<sub>2</sub> and CO<sub>2</sub> adsorption are given in Table 1.

A collection of adsorption isotherms (the local isotherms) was obtained through the GCMC simulation method in the continuum, following the algorithm outlined by Valladares et al. (1998), both for the slit and the triangular geometries. Transition probabilities for each Monte Carlo attempt, displacement, adsorption and desorption of molecules, are given by the usual Metropolis rules. Equilibrium was generally achieved after 10<sup>7</sup> MC attempts, after which mean values were taken over the following 10<sup>6</sup> MC attempts for configurations spaced by 10<sup>3</sup> MC attempts in order to ensure statistical independence. This collection of isotherms can be used in three ways to fit a given experimental isotherm:

**Table 1** Values of potential parameters to both gases

| Parameter              | N <sub>2</sub> <sup>a</sup> | CO <sub>2</sub> <sup>b</sup> |
|------------------------|-----------------------------|------------------------------|
| $\varepsilon_{gs}/k_B$ | 53.22 K                     | 81.49 K                      |
| $\sigma_{gs}$          | 3.494 Å                     | 3.429 Å                      |
| $\varepsilon_{gg}/k_B$ | 101.5 K                     | 246.15 K                     |
| $\sigma_{gg}$          | 3.615 Å                     | 3.648 Å                      |

<sup>a</sup>Ravikovitch et al. (2000)

<sup>b</sup>Vishnyakov et al. (1999)

(a) pure slit pores; (b) pure triangular pores; (c) a mixture of slit and triangular pores, with an undetermined fraction  $x$  of slit pores.

A minimization method for the mean square error, with a regularization term, as described by Davies et al. (1999), was used to fit an experimental isotherm with the theoretical isotherm as explained in Azevedo et al. (2010).

### 3 Results and discussion

The nomenclature identifying the samples describes the particular activation procedure applied to each one of them. For example, A2a corresponds to a sample washed initially with water and carbonized at a temperature rate of 2 °C/min in ambient air atmosphere, while B10n corresponds to a sample pre-washed initially with sulfuric acid and afterwards with water and carbonized at a temperature rate of 10 °C/min in a nitrogen flux of 100 ml/min.

The specific surface areas calculated for the AC samples for both adsorbates are summarized in Table 2 and the pore volumes in the Table 3. As it was reported previously (Soares Maia et al. 2010), these values evidence the effect of the chemical impregnation at low concentration of the precursor by phosphoric acid on the characteristics of the resulting materials. In the case of specific surfaces obtained by CO<sub>2</sub> adsorption, as explained by Garrido et al. (1987), the concept of surface area of a microporous carbon does not have much physical meaning if micropore filling is taking place and at the same time a unambiguous value of density (and consequently of cross-sectional area) of the adsorbed molecule cannot be assigned. However, we can calculate and compare the theoretical values of surface areas

**Table 2** Specific surface areas (m<sup>2</sup>/g) of samples as estimated from the slit pore and mixed geometry models (Monte Carlo Simulations) for N<sub>2</sub> and CO<sub>2</sub> together with the values calculated by the BET equation, for N<sub>2</sub>

| Sample | Specific surface area (m <sup>2</sup> /g) |                     |         | Specific surface area (m <sup>2</sup> /g) |                     |
|--------|---|---------------------|---------|---|---------------------|
|        | Nitrogen                                  |                     |         | Carbon dioxide                            |                     |
|        | Slit pore geometry                        | Mixed pore geometry | BET eq. | Slit pore geometry                        | Mixed pore geometry |
| A2a    | 1171                                      | 644                 | 838     | 832                                       | 638                 |
| A10a   | 647                                       | 531                 | 772     | 670                                       | 709                 |
| A2n    | 697                                       | 545                 | 633     | 785                                       | 599                 |
| A10n   | 864                                       | 567                 | 1054    | 698                                       | 546                 |
| B2a    | 783                                       | 571                 | 957     | 713                                       | 529                 |
| B2n    | 817                                       | 642                 | 798     | 625                                       | 463                 |
| B10a   | 817                                       | 535                 | 775     | 561                                       | 411                 |
| B10n   | 827                                       | 1225                | 1019    | 766                                       | 581                 |

**Table 3** Micropore volumes ( $\text{cm}^3/\text{g}$ ) of samples as estimated from the slit pore and mixed geometry models (Monte Carlo Simulations) together with the values calculated by the DR equation

| Sample | Pore volume ( $\text{cm}^3/\text{g}$ )<br>Nitrogen |                           |        | Micropore volume ( $\text{cm}^3/\text{g}$ )<br>Carbon dioxide |                           |        |
|--------|--|---------------------------|--------|---|---------------------------|--------|
|        | Slit pore<br>geometry                              | Mixed<br>pore<br>geometry | DR eq. | Slit pore<br>geometry   | Mixed<br>pore<br>geometry | DR eq. |
|        |  |                           |        |   |                           |        |
| A2a    | 0.37   | 0.348                     | 0.34   | 0.29  | 0.23                      | 0.27   |
| A10a   | 0.32   | 0.328                     | 0.32   | 0.24  | 0.23                      | 0.21   |
| A2n    | 0.27   | 0.264                     | 0.26   | 0.28  | 0.21                      | 0.26   |
| A10n   | 0.49   | 0.482                     | 0.47   | 0.24  | 0.19                      | 0.22   |
| B2a    | 0.38   | 0.379                     | 0.38   | 0.24  | 0.20                      | 0.24   |
| B2n    | 0.34   | 0.334                     | 0.32   | 0.22  | 0.17                      | 0.22   |
| B10a   | 0.34   | 0.326                     | 0.32   | 0.18  | 0.16                      | 0.20   |
| B10n   | 0.44   | 0.421                     | 0.40   | 0.25  | 0.21                      | 0.26   |

using the calculated PSD of both models shown in Figs. 1 and 2. Figure 1 contains the PSDs for the samples which are washed only with distilled water (samples A), and Fig. 2 the PSDs for the samples which have a pre-treatment with sulfuric acid before the impregnation (samples B), both for carbon dioxide adsorption. Figure 3 shows the simulated theoretical isotherms for  $\text{CO}_2$  using the GCMC simulated using the slit geometry (a) and simulated using the triangular geometry (b). The isotherms generated for pores greater than  $15 \text{ \AA}$  become linearly dependent, determining the limit of the “reliability region”, but they still contribute to the overall adsorption amount. Based on this observation, as it was done by Jagiello and Thommes (2004), the integration limit in the integral equation representing the global adsorption isotherm should be extended above that sensitivity limit. In this work the upper integration limit was assumed to be approximately  $18 \text{ \AA}$ . It follows that the last interval corresponding to the range from  $15$  to  $18 \text{ \AA}$  in the PSDs shown in Figs. 1 and 2 really accumulates the contribution of all pores larger than  $15 \text{ \AA}$  (for this reason the area representing this contribution in the PSD is shadowed), an approximation that should be taken into account in the analysis of results, in particular when discussing the predicted specific surface and micropore volume of the samples. It is interesting to note that, in comparing the PSDs obtained for the two geometric models, the MGM and the PSGM, for  $\text{CO}_2$  (reported in Figs. 1 and 2) with those for  $\text{N}_2$  (reported in Soares Maia et al. 2010), the similarity between the MGM PSD and the PSGM PSD, for a given sample, is greater for  $\text{CO}_2$  adsorption than for  $\text{N}_2$  adsorption. This means that, at the temperatures used in this work,  $\text{CO}_2$  adsorption is less sensitive to the geometry than  $\text{N}_2$  adsorption. This fact is

consistent and can be understood by energetic arguments, in facts, from Table 1 we can see that the ratio between the gas-solid interaction energy and the thermal energy,  $\varepsilon_{gs}/k_B T$ , is  $0.7$  for  $\text{N}_2$  at  $77 \text{ K}$  and  $0.3$  for  $\text{CO}_2$  at  $273 \text{ K}$ , explaining the lower sensitivity of  $\text{CO}_2$  adsorption with respect to the pore geometry.

The values of the predicted specific surface for  $\text{N}_2$  and  $\text{CO}_2$  are compared with the BET values corresponding to  $\text{N}_2$  in Table 2, while the predicted micropore volumes are compared to DR values in Table 3.

As already discussed in Soares Maia et al. (2010) in the case of the characterization of these samples with  $\text{N}_2$  adsorption, with  $\text{CO}_2$  we find again that the MGM gives a more consistent picture for the characterization of the materials than the PSGM. A direct and simple way to compare the results for the two adsorbates is through the cumulative pore volume, as it is shown in Figs. 4 to 7. A suggestive result is that a better agreement between the  $\text{N}_2$  and  $\text{CO}_2$  PSDs is achieved through the MGM than through the classical PSGM for all samples. As we already mentioned, the question of whether the PSDs obtained through different adsorbates should be the same for a given sample is still controversial. Ravikovitch et al. (2000) and Jagiello and Thommes (2004) find similar PSDs for different gases for a kind of carbon fibers, while Blanco et al. (2010) find different PSDs for different gases adsorbed in AC monoliths. The present study seems to reinforce the idea that different adsorbates should generally provide different PSDs for the same sample. In facts, from Figs. 5 and 7 we see that only samples A2n and B10a yield truly similar MGM PSDs for different adsorbates, while for the other samples there are appreciable discrepancies of different magnitudes.

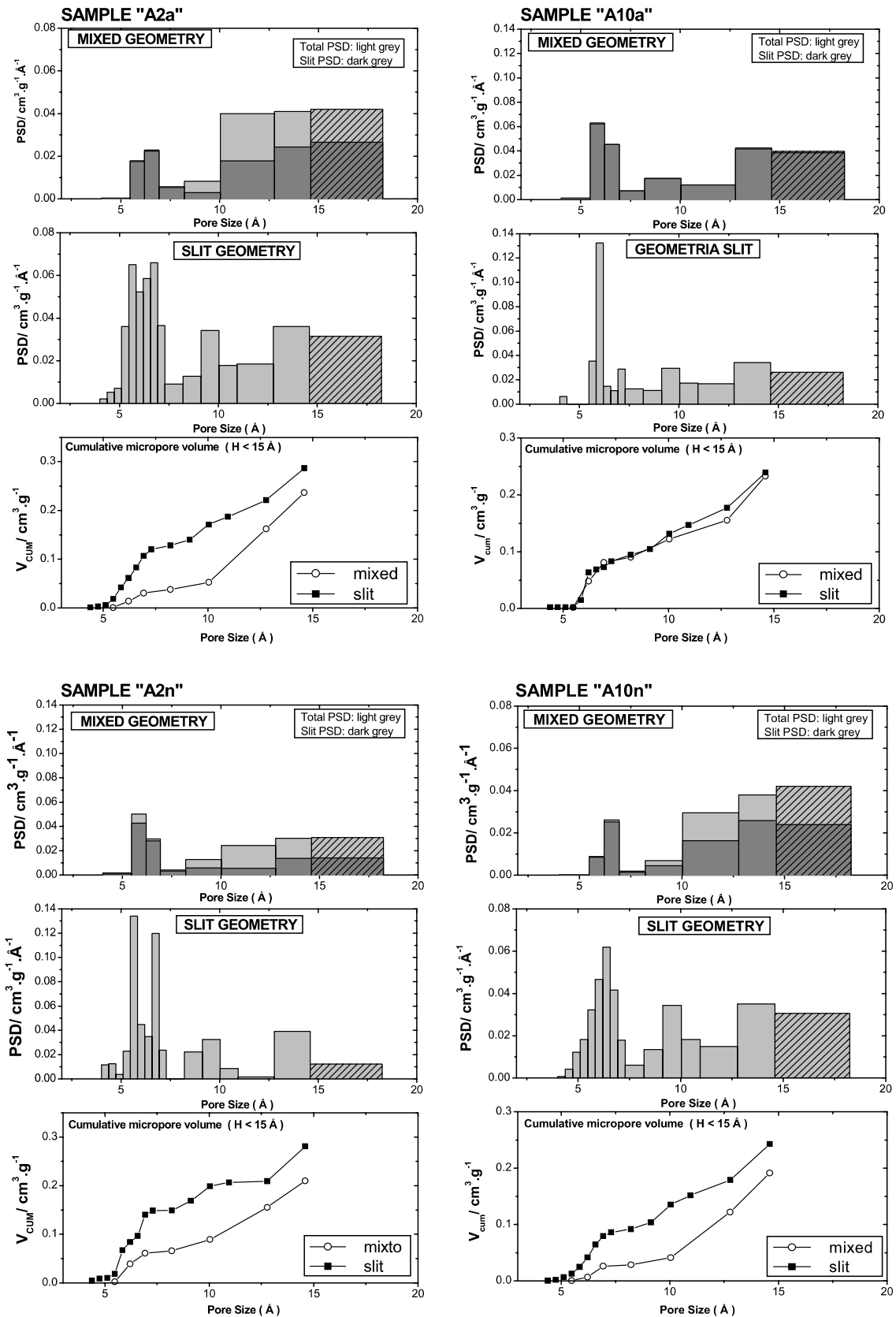
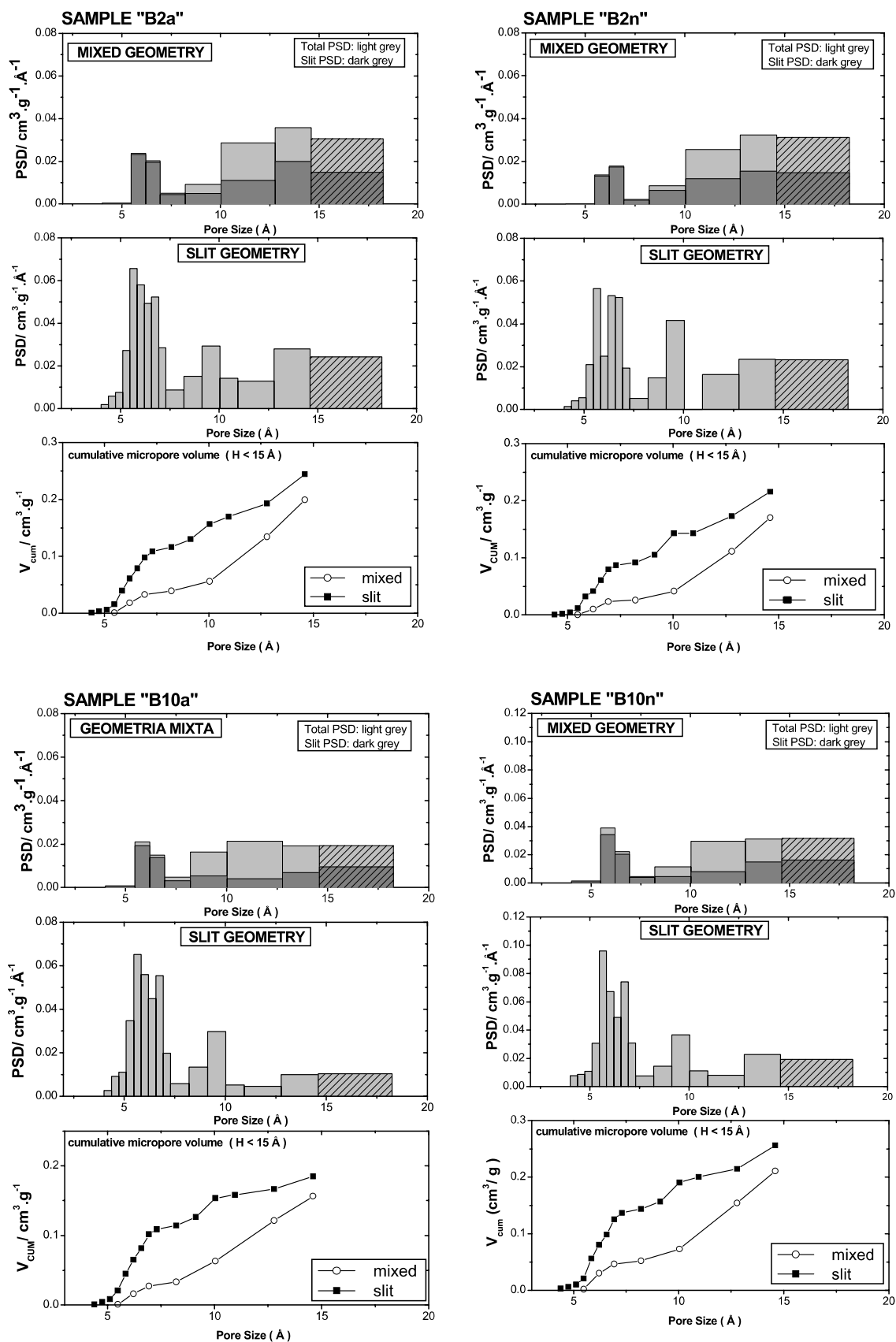
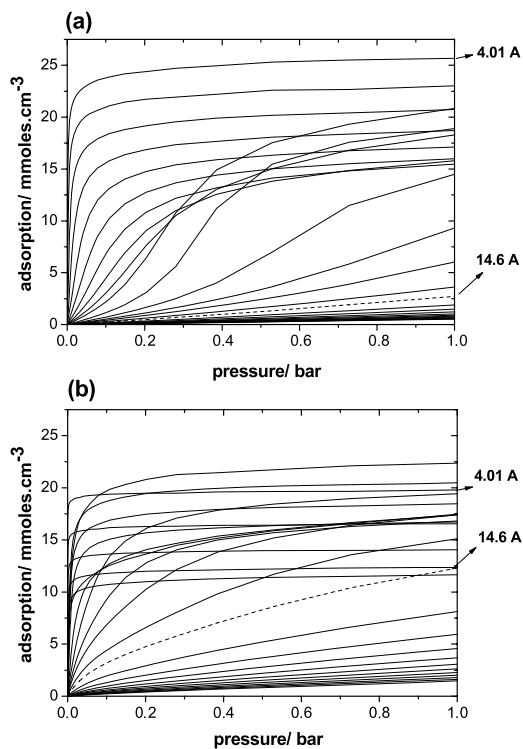


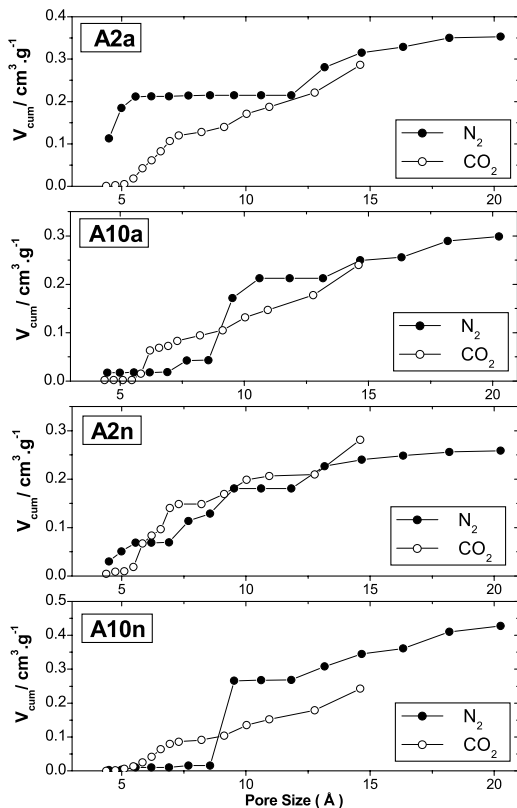
Fig. 1 Pore size distribution from CO<sub>2</sub> adsorption isotherms of samples "A" calculated using Monte Carlo Simulation



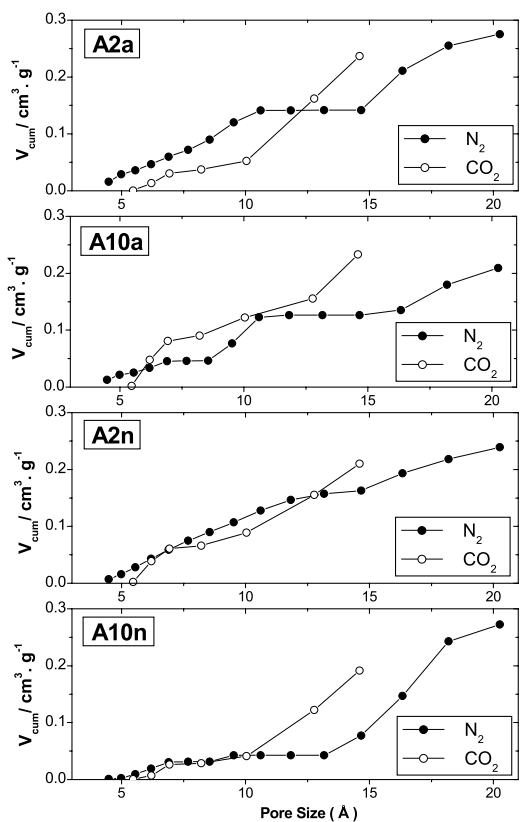
**Fig. 2** Pore size distribution from CO<sub>2</sub> adsorption isotherms of samples "B" calculated using Monte Carlo Simulation



**Fig. 3** GCMC isotherms of CO<sub>2</sub> adsorption at 273 K (a) simulated using the slit geometry and (b) simulated using the triangular geometry



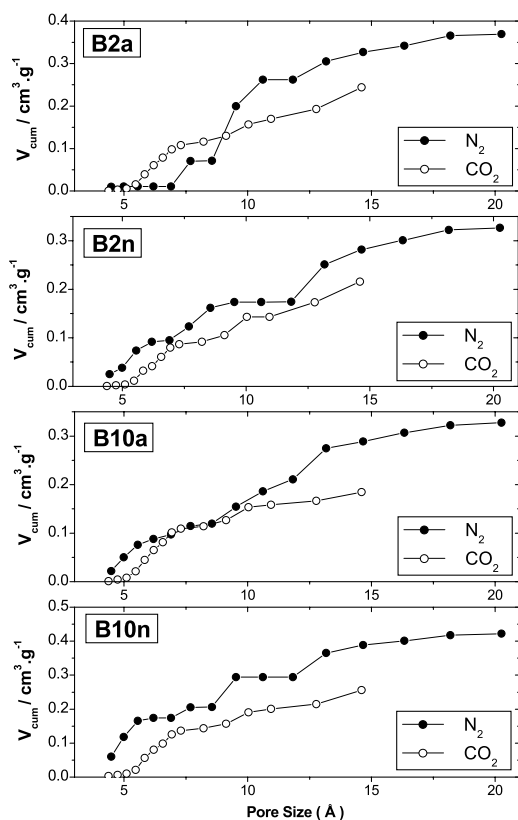
**Fig. 4** Cumulative pore volume distribution of samples “A” calculated using Pure Slit Geometry Model (PSGM)



**Fig. 5** Cumulative pore volume distribution of samples “A” calculated using Mixed Geometry Model (MGM)

It is also suggestive that these two samples with similar MGM PSDs present a quite flat distribution, a highly homogeneous distribution of pore sizes. Cazorla-Amorós et al. (1998) showed that the characteristic curves for N<sub>2</sub> and CO<sub>2</sub> adsorption superimpose on those samples in which N<sub>2</sub> adsorption is not restricted and therefore the adsorption mechanisms of both adsorbates are similar. They reported again that CO<sub>2</sub> adsorption applied down to subatmospheric pressures is especially important to complement N<sub>2</sub> adsorption at 77 K since it is sensitive to the narrow micropores not accessible to N<sub>2</sub>. Their analysis is in concordance with what we observe here in samples B (see Figs. 6 and 7), where the agreement between PSDs is better and evidences the effect of the pre-treatment of the precursor with sulfuric acid. The sulfuric acid degrades and redistributes the raw material biopolymers, triggering even more the development of larger micropores and mesopores. In this new structure, the phosphoric acid may act more efficiently to form micropores during the chemical activation (Rios et al. 2009).

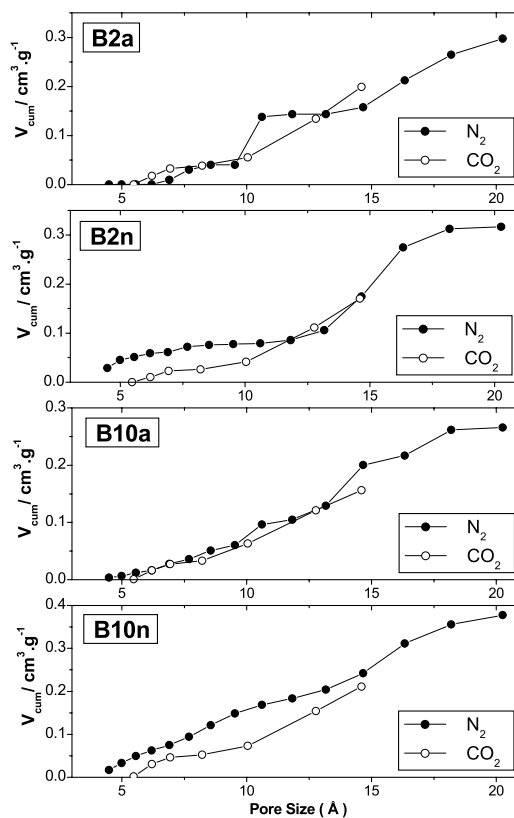
The greater consistency in the characterization of the two series of AC obtained through the MGM can also be observed by comparing the behavior of specific surfaces and micropore volumes for both adsorbates in Tables 2 and 3. However, the micropore volumes predicted



**Fig. 6** Cumulative pore volume distribution of samples “B” calculated using Pure Slit Geometry Model (PSGM)

by the MGM for CO<sub>2</sub> adsorption are always lower than the DR values and the corresponding values predicted by the PSGM (see Table 3). This discrepancy was to be expected and is due to the fact that the last interval of the PSDs for CO<sub>2</sub> adsorption (shaded area) includes contributions from pores of higher sizes and to the characteristic fact that this shaded area in the PSGM PSD is about half that corresponding to the MGM, which, as already established in previous studies, is always biased toward smaller sizes.

Finally, we performed a test to establish to what extent an adsorption isotherm calculated on the basis of the PSD obtained through N<sub>2</sub> adsorption can represent an adsorption isotherm for CO<sub>2</sub> adsorption. Figure 8 shows the comparison of CO<sub>2</sub> adsorption isotherms (in semi-logarithmic scale) calculated using the N<sub>2</sub> PSD, for the MGM, the PSGM and experimental data, in the cases where there is the worst agreement between the PSDs corresponding to the two gases: sample A2a (a) and sample B2a (c); and the cases where we have the best agreement: sample A2n (b) and sample B10a (d). Again, we see that the only case where the N<sub>2</sub> PSD can be used safely to predict the CO<sub>2</sub> adsorption isotherm is that corresponding to sample B10a.



**Fig. 7** Cumulative pore volume distribution of samples “B” calculated using Mixed Geometry Model (MGM)

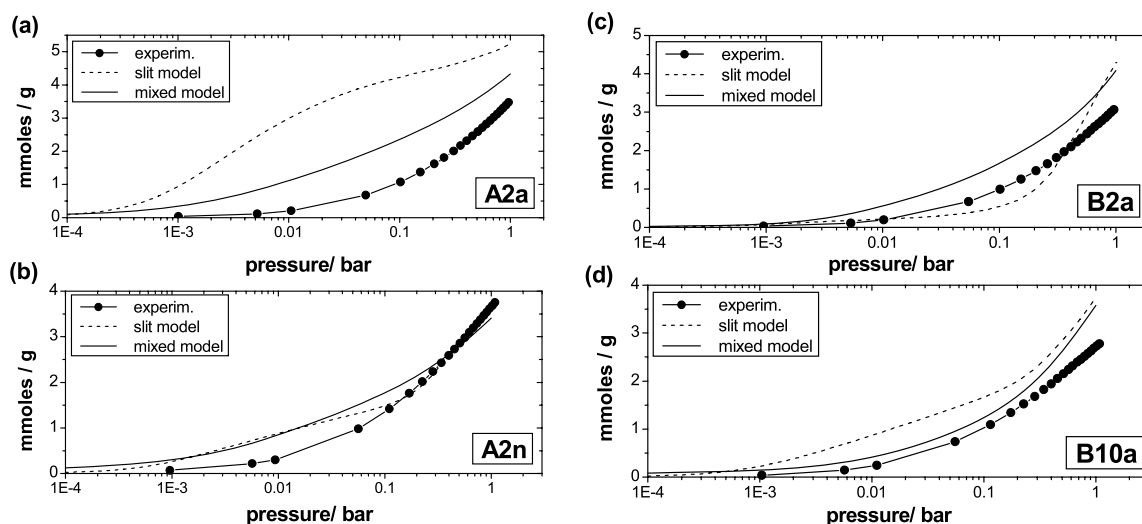
#### 4 Conclusions

We have studied two series of controlled AC samples both through N<sub>2</sub> and CO<sub>2</sub> adsorption in order to establish a consistent characterization of the material and further test the reliability of the recently proposed MGM. Through the analysis of the results presented above, we can conclude that:

- The MGM provides a more consistent characterization of the materials as compared with the classical PSGM.
- The PSDs of a given sample obtained through N<sub>2</sub> and CO<sub>2</sub> adsorption experiments are in general different, although the MGM predicts a greater similarity than the PSGM.
- The N<sub>2</sub> PSD cannot be used safely in general to predict the CO<sub>2</sub> adsorption isotherm on the same sample. This can only be done in the case of almost uniform PSDs.

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**Fig. 8** Comparison of CO<sub>2</sub> adsorption isotherms calculating using the N<sub>2</sub> PSD for the MGM and the PSGM, and the experimental data: (a) sample A2a, (b) sample A2n, (c) sample B2a and (d) sample B10a

## References

- Azevedo, D.C.S., Rios, R.B., López, R.H., Torres, A.E.B., Cavalcante, C.L. Jr., Toso, J.P., Zgrablich, G.: Characterization of PSD of activated carbons by using slit and triangular pore geometries. *Appl. Surf. Sci.* **256**, 5191–5197 (2010)
- Blanco, A.A.G., Alexandre de Oliveira, J.C., López, R., Moreno-Piraján, J.C., Giraldo, L., Zgrablich, G., Sapag, K.: A study of the pore size distribution for activated carbon monoliths and their relationship with the storage of methane and hydrogen. *Colloids Surf. A, Physicochem. Eng. Asp.* **537**, 74 (2010)
- Bojan, M.J., Steele, W.A.: Computer simulation in pores with rectangular cross-sections. *Carbon* **36**, 1417–1423 (1998)
- Cazorla-Amorós, D., Alcañiz-Monge, J., Casa-Lillo, M.A., Linares-Solano, A.: CO<sub>2</sub> as an adsorptive to characterize carbon molecular sieves and activated carbons. *Langmuir* **14**, 4589–4596 (1998)
- Davies, G.M., Seaton, N.A., Vassiliadis, V.S.: Calculation of pore size distribution of activated carbons from adsorption isotherms. *Langmuir* **15**, 8235–8245 (1999)
- Garrido, J., Linares-Solano, A., Martín-Martínez, J.M., Molina-Sabio, M., Rodríguez-Reinoso, F., Torregrosa, R.: Use of N<sub>2</sub> vs. CO<sub>2</sub> in the characterization of activated carbons. *Langmuir* **3**, 76–81 (1987)
- Huang, Z.H., Kang, F., Huang, W.L., Yang, J.B., Liang, K.M., Cui, M.L., Cheng, Z.: Pore structure and fractal characteristics of activated carbon fibers characterized by using HRTEM. *J. Colloid Interface Sci.* **249**, 453–457 (2002)
- Jagiello, J., Thommes, M.: Comparison of DFT characterization methods based on N<sub>2</sub>, Ar, CO<sub>2</sub>, and H<sub>2</sub> adsorption applied to carbons with various pore size distributions. *Carbon* **42**, 1227–1232 (2004)
- Lozano-Castelló, D., Cazorla-Amorós, D., Linares-Solano, A.: Usefulness of CO<sub>2</sub> adsorption at 273 K for the characterization of porous carbons. *Carbon* **43**, 1233–1242 (2004)
- Marsh, H., Rodríguez-Reinoso, F.: *Activated Carbon*. Elsevier, London (2006)
- Ravikovitch, P.I., Vishnyakov, A., Russo, R., Neimark, A.V.: Unified approach to pore size characterization of microporous carbonaceous materials from N<sub>2</sub>, Ar, and CO<sub>2</sub> adsorption isotherms. *Langmuir* **16**, 2311–2320 (2000)
- Rios, R.B., Silva, W.M., Torres, A.E.B., Azevedo, D.C.S., Cavalcante, C.L. Jr.: Adsorption of methane in activated carbons obtained from coconut shells using H<sub>3</sub>PO<sub>4</sub> chemical activation. *Adsorption* **15**, 271–277 (2009)
- Rodríguez-Reinoso, F., Molina-Sabio, M.: Textural and chemical characterization of microporous carbons. *Adv. Colloid Interface Sci.* **76–77**, 271–294 (1998)
- Rouquerol, F., Rouquerol, J., Sing, K.: *Adsorption by Powders and Porous Solids*. Academic Press, San Diego (1999)
- Soares Maia, D.A., Sapag, K., Toso, J.P., López, R.H., Azevedo, D.C.S., Cavalcante, C.L.C. Jr., Zgrablich, G.: Characterization of activated carbon from peach stones through the mixed geometry model. *Mic. Mes. Mat.* (2010, accepted)
- Steele, W.A.: *The Interaction of Gases with Solids Surfaces*. Oxford, Pergamon (1974)
- Valladares, D.L., Rodríguez-Reinoso, F., Zgrablich, G.: Characterization of active carbons: the influence of the method in the determination of the pore size distribution. *Carbon* **36**, 1491–1499 (1998)
- Vishnyakov, A., Ravikovitch, P.I., Neimark, A.V.: Molecular level models for CO<sub>2</sub> adsorption in nanopores. *Langmuir* **15**, 8736–8742 (1999)