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Extended poromechanics for adsorption-induced swelling prediction in double porosity media: modeling and experimental validation on activated carbon

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Abstract

Natural and synthesised porous media are generally composed of a double porosity: a microporosity where the fluid is trapped as an adsorbed phase and a meso or a macro porosity required to ensure the transport of fluids to and from the smaller pores. Zeolites, activated carbon, tight rocks, coal rocks, source rocks, cement paste or construction materials are among these materials.

In nanometer-scale pores, the molecules of fluid are confined. This effect, denoted as molecular packing, induces that fluid-fluid and fluid-solid interactions sum at the pore scale and have significant consequences at the macroscale, such as instantaneous deformation, which are not predicted by classical poromechanics. If adsorption in nanopores induces instantaneous deformation at a higher scale, the matrix swelling may close the transport porosity, reducing the global permeability of the porous system. This is important for applications in petroleum oil and gas recovery, gas storage, separation, catalysis or drug delivery.

This study aims at characterizing the influence of an adsorbed phase on the instantaneous deformation of micro-to-macro porous media presenting distinct and well-separated porosities. A new incremental poromechanical framework with varying porosity is proposed allowing the prediction of the swelling induced by adsorption without any fitting parameters. This model is validated by experimental comparison performed on a high micro and macro porous activated carbon. It is shown also that a single porosity model cannot predict the adsorption-induced strain evolution observed during the experiment. After validation, the double porosity model is used to discuss the evolution of the poromechanical properties under free and constraint swelling.

Keywords: Adsorption, swelling, double porosity media, poromechanical modelling

Introduction

Following the IUPAC recommendation (Sing et al., 1985; Thommes et al., 2015), the pore space in porous materials is divided into three groups according to the pore size diameters: macropores of widths greater than 50 nm, mesopores of widths between 2 and 50 nm and micropores (or nanopores) of widths less than 2 nm. Zeolites, activated carbon, tight rocks, coal rocks, source rocks, cement paste or construction materials are among these materials. In recent years, a major attention has been paid on these microporous materials because the surface-to-volume ratio (i.e., the specific pore surface) increases with decreasing characteristic pore size. Consequently, these materials can trap an important quantity of fluid molecules as an adsorbed phase. This is important for applications in petroleum and oil recovery, gas storage, separation, catalysis or drug delivery.

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28 For these microporous materials, a deviation from standard poromechanics (Biot, 1941; Coussy, 2004), is ex-
29 pected. In nanometer-scale pores, the molecules of fluid are confined. This effect, denoted as molecular packing,
30 induces that fluid-fluid and fluid-solid interactions sum at the pore scale and have significant consequences at the
31 macroscale, such as instantaneous deformation. A lot of natural and synthesised porous media are composed of a
32 double porosity: the microporosity where the fluid is trapped as an adsorbed phase and a meso or a macro porosity re-
33 quired to ensure the transport of fluids to and from the smaller pores. If adsorption in nanopores induces instantaneous
34 deformation at a higher scale, the matrix swelling may close the transport porosity, reducing the global permeability
35 of the porous system or annihilating the functionality of synthesised materials. In different contexts, this deformation
36 may be critical. For instance, *in situ* adsorption-induced coal swelling has been identified (Larsen, 2004; Pan and
37 Connell, 2007; Sampath et al., 2017) as the principal factor leading to a rapid decrease in CO₂ injectivity during coal
38 bed methane production enhanced by CO₂ injection. Conversely, gas desorption can lead to matrix shrinkage and
39 microcracking, which may help oil and gas recovery in the context of unconventional petroleum engineering (Levine,
40 1996). The effects of adsorbent deformation on physical adsorption has also been identified by Thommes and Cy-
41 chosz (2014) as one of the next major challenges concerning gas porosimetry in nano-porous non-rigid materials (e.g.
42 metal organic framework). In conclusion, there is now a consensus in the research community that major attention
43 has to be focused on the coupled effects appearing at the nanoscale within microporous media because they may have
44 significant consequences at the macroscale.

45 Experimentally, different authors tried to combine gas adsorption results and volumetric swelling data (see e.g. Gor
46 et al. (2017) for a review). The pioneering work of Meehan (1927) showed the effect of carbon dioxide sorption on
47 the expansion of charcoal but only mechanical deformation was reported and adsorption quantities were not mea-
48 sured. Later on, different authors (Briggs and Sinha, 1933; Levine, 1996; Day et al., 2008; Ottiger et al., 2008; Pini
49 et al., 2009; Hol and Spiers, 2012; Espinoza et al., 2014) performed tests on bituminous coal, because it is of utmost
50 importance in the context of CO₂ geological sequestration and coal bed reservoirs exploitation. However, most results
51 were not complete in a sense that adsorption and swelling experiments were not measured simultaneously (Meehan,
52 1927; Robertson and Christiansen, 2005) or performed on exactly the same coal samples (Ottiger et al., 2008). Other
53 authors presented simultaneous *in situ* adsorption and swelling results but the volumetric strain was extrapolated from
54 a local measurement – using strain gauges (Levine, 1996; Harpalani and Schraufnagel, 1990; Battistutta et al., 2010)
55 or LVDT sensors (Chen et al., 2012; Espinoza et al., 2014) – or by monitoring the silhouette expansion (Day et al.,
56 2008). Perrier et al. (2017) presented an experimental setup providing simultaneous *in situ* measurements of both
57 adsorption and deformation for the same sample in the exact same conditions, which can be directly used for model
58 validation. Gas adsorption measurements are performed using a custom-built manometric apparatus and deforma-
59 tion measurements are performed using a digital image correlation set-up. This set-up allows full-field displacement
60 measurements, which may be crucial for heterogeneous, anisotropic or cracked samples.

61 As far as modeling is concerned, molecular simulations are the classical tools at the nanoscale. Important efforts
62 have been involved in molecular simulations in order to characterise adsorption-induced deformation in nanoporous
63 materials (Vandamme et al., 2010; Brochard et al., 2012a; Hoang and Galliero, 2015) and these investigations showed
64 on few configurations that pressures applied on the pore surfaces may be very high (few hundred of MPa), depend-
65 ing on the thermodynamic conditions and on the pore sizes. Note that an alternative approach based on a non-local
66 density functional theory can be used to obtain highly resolved evolutions of pore pressure *versus* pore widths and
67 bulk pressure in slit-shaped pores for a large spectrum of thermodynamic conditions on the whole range of micropore
68 widths, even for complex fluids (Grégoire et al., 2018). However, if macroscopic adsorption isotherms may be recon-
69 structed in a consistent way from molecular simulations through the material pore size distribution (Khaddour et al.,
70 2014), molecular simulation tools are not tractable to predict resulting deformation at a macroscale due to the fluid
71 confinement in nanopores (pore sizes below 2 nm). Note that Kulasinski et al. (2017) proposed a molecular dynamic
72 study where macroscopic swelling may be reconstructed from water adsorption in mesoporous wood (pore sizes in
73 [4 – 10] nm). If adsorption is essentially controlled by the amount and size of the pores, the mechanical effect of the
74 pressure build up inside the pores due to fluid confinement requires some additional description about the topology
75 and spatial organization of the porous network which is not easy to characterize, for sub-nanometric pores especially.
76 Such a result motivates the fact that swelling is usually related to the adsorption isotherms instead of the pore pressure
77 directly, the mechanical effect of the pore pressure being hidden in the poromechanical description.

78 In this context, different enhanced thermodynamical or poromechanical frameworks have been proposed within
79 the last ten years to link adsorption, induced deformation and permeability changes (e.g Pan and Connell (2007);

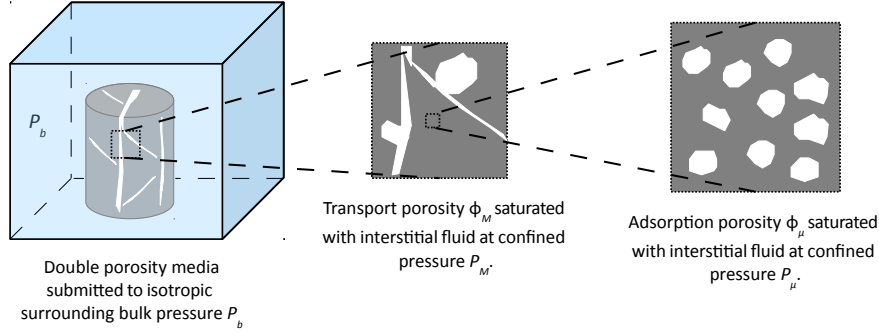


Figure 1: Schematic of a double porosity media.

80 Pijaudier-Cabot et al. (2011); Brochard et al. (2012b); Vermorel and Pijaudier-Cabot (2014); Perrier et al. (2015);
 81 Nikoosokhan et al. (2014)). For instance, Brochard et al. (2012b) (resp. Vermorel and Pijaudier-Cabot (2014)) pro-
 82 posed enhanced poromechanical frameworks where swelling volumetric deformation may be estimated as a function
 83 of the bulk pressure and a coupling (resp. a confinement) coefficient, which may be deduced from adsorption measure-
 84 ments. However, if these models are consistent with experimental results from the literature, they cannot be considered
 85 as truly predictive because the model parameters have to be identified to recover the experimental loading path. An
 86 incremental poromechanical framework with varying porosity has been proposed by Perrier et al. (2015) allowing the
 87 full prediction of the swelling induced by adsorption for isotropic nano-porous solids saturated with a single phase
 88 fluid, in reversible and isothermal conditions. This single porosity model has been compared with experimental data
 89 obtained by Ottiger et al. (2008) on bituminous coal samples filled with pure CH_4 and pure CO_2 at $T = 45^\circ\text{C}$ and a
 90 fair agreement was observed for these low porosity coals but these types of models have to be enhanced to take into
 91 account the intrinsic double porosity features of such materials.

92 This study aims at characterizing the influence of an adsorbed phase on the instantaneous deformation of micro-
 93 to-macro porous media presenting distinct and well separated porosities in term of pore size distribution. A model
 94 accounting for double porosity is proposed and validated by in-situ and simultaneous experimental comparisons.
 95 The novelty of the approach is to propose an extended poromechanical framework taking into account the intrinsic
 96 double porosity features of such materials capable of predicting adsorption-induced swelling for high porous materials
 97 without any fitting parameters.

98 1. An incremental poromechanical framework with varying porosity for double porosity media

99 In this section, an incremental poromechanical framework with varying porosity proposed by Perrier et al. (2015)
 100 for single porosity media is extended to double porosity media.

101
 102 We consider here a double porosity medium with distinct and separated porosities. The small porosity is called
 103 *adsorption porosity* (ϕ_μ) and the larger one *transport porosity* (ϕ_M). This medium is considered as isotropic with
 104 a linear poro-elastic behaviour and it is immersed and saturated by a surrounding fluid at bulk pressure P_b under
 105 isothermal conditions. Confinement effects may change the thermodynamic properties of the interstitial fluids in both
 106 porosities. The adsorption porosity is saturated by an interstitial fluid of density ρ_μ at pressure P_μ . The transport
 107 porosity is fully saturated by an interstitial fluid (single-phase) of density ρ_M at pressure P_M (see Fig. 1).

108 For saturated isotropic porous solids, in reversible and isothermal conditions and under small displacement-
 109 gradient assumptions, classical poromechanics may be rewritten for double porosity media Coussy (2004) :

$$d\tilde{G}_s = d\Psi_s + dW_s \quad (1)$$

$$= \underbrace{\sigma_{ij} : d\varepsilon_{ij} + P_M d\phi_M + P_\mu d\phi_\mu}_{d\Psi_s} + \underbrace{d(-P_M\phi_M - P_\mu\phi_\mu)}_{dW_s} \quad (2)$$

$$= \sigma_{ij} : d\varepsilon_{ij} - \phi_M dP_M - \phi_\mu dP_\mu. \quad (3)$$

110 In Eq. 1–3, $(\tilde{G}_s, \Psi_s, W_s)$ are respectively the Gibbs free energy, the Helmholtz free energy and the mechanical work
 111 of the skeleton. The state variables $(\varepsilon_{ij}, \phi_M, \phi_\mu)$ are respectively the infinitesimal strain tensor, the transport porosity
 112 and the adsorption porosity. The associated thermodynamical forces $(\sigma_{ij}, P_M, P_\mu)$ are respectively the Cauchy stress
 113 tensor and the fluid pore pressures in both porosities.

114
 115 For an isotropic linear poro-elastic medium, the state equations are then given by:

$$\left\{ \begin{array}{l} \sigma_{ij} = \frac{\partial \tilde{G}_s}{\partial \varepsilon_{ij}} \\ \phi_M = -\frac{\partial \tilde{G}_s}{\partial P_M} \\ \phi_\mu = -\frac{\partial \tilde{G}_s}{\partial P_\mu} \end{array} \right. , \quad \text{and then:} \quad (4)$$

$$\left\{ \begin{array}{l} d\sigma = K(\phi_M, \phi_\mu)d\varepsilon - b_M(\phi_M, \phi_\mu)dP_M - b_\mu(\phi_M, \phi_\mu)dP_\mu \\ d\phi_M = b_M(\phi_M, \phi_\mu)d\varepsilon + \frac{dP_M}{N_{MM}(\phi_M, \phi_\mu)} - \frac{dP_\mu}{N_{M\mu}(\phi_M, \phi_\mu)} \\ d\phi_\mu = b_\mu(\phi_M, \phi_\mu)d\varepsilon - \frac{dP_M}{N_{\mu M}(\phi_M, \phi_\mu)} + \frac{dP_\mu}{N_{\mu\mu}(\phi_M, \phi_\mu)} \end{array} \right. .$$

116 In Eq. 4, $(\sigma = \sigma_{kk}/3)$ and $(\varepsilon = \varepsilon_{kk})$ are respectively the total mean stress and the volumetric strain. $(K, b_M, b_\mu, N_{MM},$
 117 $N_{M\mu}, N_{\mu M}, N_{\mu\mu})$ are respectively the apparent modulus of incompressibility and six poromechanical properties, which
 118 depends on the two evolving porosities ϕ_M and ϕ_μ and on the constant skeleton modulus.

119
 120 Considering a single cylindrical porosity², homogenization models Halpin and Kardos (1976) yield to:

$$\left\{ \begin{array}{l} K(\phi) = \frac{K_s G_s (1-\phi)}{G_s + K_s \phi} \quad , \quad G_s = \frac{3K_s(1-2\nu_s)}{2(1+\nu_s)} \\ b(\phi) = 1 - \frac{K(\phi)}{K_s} \quad , \quad N(\phi) = \frac{K_s}{b(\phi) - \phi} \end{array} \right. . \quad (5)$$

121 In Eq. 5, ϕ is the porosity and (G_s, ν_s) are respectively the shear modulus and the Poisson ratio of the skeleton matrix.

122
 123 Practically and for high porosity media, an iterative process of homogenization is chosen to avoid discrepancies
 124 in the apparent properties estimation as noticed by Barboura (2007). The iterative process of homogenization for a
 125 cylindrical porosity is detailed in Appendix A. Full details on the iterative processes for both spherical and cylindrical
 126 porosities are presented in Perrier et al. (2015).

127
 128 Considering that the two porosities are distinct, well separated and both cylindrical, the iterative process can
 129 be used in two successive steps to determine the different modulus of incompressibility. Note that this two step
 130 homogenization process may be reversed as well to estimate the skeleton properties knowing the apparent ones:

$$\begin{aligned} (K, G) &= \mathcal{F}_n(\mathcal{F}_n(K_s, G_s, \phi_\mu), \phi_M) \\ \text{and } (K_s, G_s) &= \mathcal{R}_n(\mathcal{R}_n(K, G, \phi_M), \phi_\mu) . \end{aligned} \quad (6)$$

131 In Eq. 6, $(\mathcal{F}_n, \mathcal{R}_n)$ stand as the standard and the reverse iterative processes of homogenization defined in Eq. A.1 and A.2
 132 respectively. K_s and G_s (resp. K and G) are the skeleton (resp. apparent) incompressible and shear moduli.

133
 134 Based on stress/strain partitions (Coussy, 2004) and on the response of the medium saturated by a non-adsorbable

²This assumption is discussed in Perrier et al. (2015) where both spherical and cylindrical porosities are considered.

135 fluid (Nikoosokhan et al., 2013), the six poromechanical properties ($b_M, b_\mu, N_{MM}, N_{M\mu}, N_{\mu M}, N_{\mu\mu}$) may be identified:

$$136 \quad \left\{ \begin{array}{l} b_M = 1 - \frac{K}{K_\mu} \quad , \quad b_\mu = K \left(\frac{1}{K_\mu} - \frac{1}{K_s} \right) \\ \frac{1}{N_{MM}} = \frac{b_M - \phi_M}{K_\mu} \quad , \quad \frac{1}{N_{M\mu}} = \frac{1}{N_{\mu M}} = (b_M - \phi_M) \left(\frac{1}{K_\mu} - \frac{1}{K_s} \right) \quad , \\ \frac{1}{N_{\mu\mu}} = \frac{(b_\mu - \phi_\mu)}{K_s} + (b_M - \phi_M) \left(\frac{1}{K_\mu} - \frac{1}{K_s} \right) \end{array} \right. \quad (7)$$

$$137 \quad \text{with } K_\mu = \mathcal{F}_n(K_s, G_s, \phi_\mu) .$$

136 For a porous medium saturated by a fluid under isothermal conditions (isotropic surrounding/bulk pressure: P_b ,
137 density: ρ_b), $d\sigma = -dP_b$ and Eq. 4 yield to:

$$\left\{ \begin{array}{l} d\varepsilon = \frac{-dP_b}{K_s} \\ d\phi_M = \frac{-\phi_M}{K_s} dP_b \quad . \\ d\phi_\mu = \frac{-\phi_\mu}{K_s} dP_b \end{array} \right. \quad (8)$$

138 Therefore, classical poromechanics predicts a shrinkage of the porous matrix and a decrease of the porosity under
139 bulk pressure. This has been confirmed by experimental measurements (e.g. Reucroft and Patel (1986) on a natural
140 coal with a non-adsorbable gas).

141
142 Considering that the fluid is confined within both porosities, the thermodynamic properties (pressures: P_M, P_μ ,
143 densities: ρ_M, ρ_μ) of the interstitial fluid in the two porosities (ϕ_M, ϕ_μ) differ from the surrounding ones (P_b, ρ_b) but the
144 thermodynamic equilibrium imposes that the three fluids are chemically balanced (equality of the chemical potentials
145 μ_b, μ_M and μ_μ). Assuming that the Gibbs-Duhem equation ($dP = \rho d\mu$) still applies for both the surrounding fluid and
146 the interstitial ones, a macroscopic relation between the interstitial pore pressures and the surrounding one may be
147 derived similarly to the relation initially proposed by Vermorel and Pijaudier-Cabot (2014) and used in Perrier et al.
148 (2015) for single porosity media:

$$\left\{ \begin{array}{l} dP_M = \rho_M \frac{dP_b}{\rho_b} = \frac{dP_b}{1-\chi_M} \\ dP_\mu = \rho_\mu \frac{dP_b}{\rho_b} = \frac{dP_b}{1-\chi_\mu} \end{array} \right. \quad (9)$$

149 In Eq. 9, ($\chi_M = 1 - \frac{\rho_b}{\rho_M}$) and ($\chi_\mu = 1 - \frac{\rho_b}{\rho_\mu}$) are the confinement degrees in the transport and in the adsorption porosities
150 respectively, which characterize how confined is the interstitial fluid due to the number of adsorbate moles n_M^{ex} and n_μ^{ex}
151 that exceeds the number of fluid moles at bulk conditions in porosities ϕ_M and ϕ_μ respectively:

$$\left\{ \begin{array}{l} \chi_M = \frac{n_M^{ex}}{n_M^{tot}} \quad \text{with} \quad n_M^{tot} = n_M^{ex} + \frac{\rho_b V_{\phi_M}}{M} \\ \chi_\mu = \frac{n_\mu^{ex}}{n_\mu^{tot}} \quad \text{with} \quad n_\mu^{tot} = n_\mu^{ex} + \frac{\rho_b V_{\phi_\mu}}{M} \end{array} \right. \quad (10)$$

152 In Eq. 10, (V_{ϕ_M}, V_{ϕ_μ}) are the connected porous volume corresponding to the transport porosity ϕ_M and to the adsorption
153 porosities ϕ_μ respectively, n_M^{ex} and n_μ^{ex} are the number of adsorbate moles that exceeds the number of fluid moles at
154 bulk conditions and n_M^{tot} and n_μ^{tot} are the total number of moles of interstitial fluid in porosities ϕ_M and ϕ_μ respectively.
155 Generally, there is no way to link separately the two confinement degrees χ_M and χ_μ to quantities that can be measured
156 experimentally because the partition of the excess number of adsorbate moles n^{ex} , which can be measured experimen-
157 tally, within the two porosities is unknown ($n^{ex} = n_M^{ex} + n_\mu^{ex}$). However, assuming that the two scales of porosities are
158 well separated, one can consider that most of the adsorption phenomenon occurs in the adsorption porosity ($n_\mu^{ex} \gg$
159 n_M^{ex}) and that the interstitial fluid is not confined in the transport porosity:

$$\left\{ \begin{array}{l} \chi_\mu \approx \frac{n^{ex}}{n_\mu^{tot}} \quad \text{and} \quad dP_\mu = \frac{dP_b}{1-\chi_\mu} \\ \chi_M \approx 0 \quad \text{and} \quad dP_M = dP_b \end{array} \right. \quad (11)$$

160 Finally, a new incremental poromechanical framework with varying porosities for double porosity media is pro-
 161 posed:

$$\left\{ \begin{array}{l}
 d\varepsilon = \left(\frac{b_\mu}{1-\chi_\mu} + b_M - 1 \right) \frac{dP_b}{K} \\
 d\phi_\mu = \left[\underbrace{\left(\frac{b_\mu}{1-\chi_\mu} + b_M - 1 \right) \frac{b_\mu}{K}}_{T_1} + \underbrace{\frac{1}{N_{\mu\mu}(1-\chi_\mu)}}_{T_2} - \underbrace{\frac{1}{N_{\mu M}}}_{T_3} \right] dP_b \\
 d\phi_M = \left[\underbrace{\left(\frac{b_\mu}{1-\chi_\mu} + b_M - 1 \right) \frac{b_M}{K}}_{T_4} - \underbrace{\frac{1}{N_{\mu M}(1-\chi_\mu)}}_{T_5} + \underbrace{\frac{1}{N_{MM}}}_{T_6} \right] dP_b \\
 \chi_\mu = \frac{n^{ex}}{n_\mu^{tot}} \quad \text{with} \quad n_\mu^{tot} = n^{ex} + \frac{\rho_b V_{\phi_\mu}}{M} = n^{ex} + \frac{m_s \rho_b}{M \rho_s} \frac{\phi_\mu}{1-\phi_\mu-\phi_M}
 \end{array} \right. \quad (12)$$

162 In Eq. 12, $K(\phi_M, \phi_\mu)$ is given by Eq. 6, $(b_M, b_\mu, N_{MM}, N_{\mu M}, N_{\mu\mu})$ all depend on (ϕ_M, ϕ_μ) and are given by Eq. 7,
 163 (n^{ex}, P_b, ρ_b) are experimentally measurable and (m_s, M, ρ_s) are respectively the adsorbent sample mass, the molar
 164 mass of the adsorbed gas and the density of the material composing the solid matrix of the porous adsorbent.

165 2. Validation by experimental comparisons on a double porosity synthetic activated carbon

166 The experimental results obtained by Perrier et al. (2017) on a double porosity synthetic activated carbon (*Chemv-*
 167 *iron*) are used in this study for validation purpose. The main advantage of the proposed method is to provide simulta-
 168 neous *in situ* measurements of both adsorption and deformation for the same sample in the exact same conditions.

169
 170 The material and the adsorption-induced strain measurements are briefly recalled in section 2.1. The model input
 171 parameters are identified in section 2.2 and finally comparisons between experimental and model results are performed
 172 in section 2.3.

173 2.1. Material description and adsorption-induced strain measurements

174 In this section, the experimental results obtained by Perrier et al. (2017) on a double porosity synthetic activated
 175 carbon are briefly recalled. Full details may be found in Perrier et al. (2017).

176
 177 An activated carbon (*Chemviron*) is used as adsorbent material. The sample is a cylinder and its main character-
 178 istics are collected in Table 1. The geometrical dimensions have been measured with a caliper, the mass has been
 179 measured with a *Precisa* scale (XT 2220 M-DR), the specific pore surface has been measured with a gas porosimeter
 180 (*Micromeritics* ASAP 2020) according to the BET theory (Brunauer et al., 1938). The specific micropore volume has
 181 been estimated according to the IUPAC classification (Thommes et al., 2015) (pore diameter below 2 nm) based on
 182 a pore size distribution deduced from a low-pressure adsorption isotherm (N_2 at 77 K from 8.10^{-8} to 0.99 P/P_0 in
 183 relative pressure range) measured with the same gas porosimeter according to the HK theory (Horvath and Kawazoe,
 184 1983). The specific macropore volume has been estimated according to the IUPAC classification (Thommes et al.,
 185 2015) (pore diameter above 50 nm) based on a pore size distribution deduced from mercury intrusion porosimetry.
 186 Both porosimetry techniques show that there are almost no pore of diameters between 2 nm and 50 nm in this material.
 187 The two porosities are well separated in term of pore size distribution.

188
 189 The adsorbates, CO_2 and CH_4 , as well as the calibrating gas, *He*, are provided with a minimum purity of 99.995%,
 190 99.995% and 99.999% respectively.

191

Table 1: Main characteristics of the adsorbent and the adsorbates.

Property	Unit	Symbol	Value
Height	(cm)	h	1.922 ± 0.004
Diameter	(cm)	d	2.087 ± 0.002
Volume	(ml)	V_{ech}	6.57 ± 0.03
Adsorbent sample mass	(g)	m_s	4.137 ± 0.001
Solid matrix density	(kg/L)	ρ_s	2.4 ± 0.8
Specific pore surface	($\text{m}^2 \cdot \text{g}^{-1}$)	S_{BET}	1090 ± 10
Specific micropore volume	($\text{cm}^3 \cdot \text{g}^{-1}$)	v_{ϕ_μ}	0.51 ± 0.01
Adsorption porous volume	(cm^3)	V_{ϕ_μ}	2.115 ± 0.001
Adsorption porosity	(%)	ϕ_μ^0	32 ± 1
Specific macropore volume	($\text{cm}^3 \cdot \text{g}^{-1}$)	v_{ϕ_M}	0.66 ± 0.01
Transport porous volume	(cm^3)	V_{ϕ_M}	2.712 ± 0.001
Transport porosity	(%)	ϕ_M^0	41 ± 1
Total porosity	(%)	ϕ^0	73 ± 2
CO ₂ molar mass	($\text{g} \cdot \text{mol}^{-1}$)	M_{CO_2}	44.01
CH ₄ molar mass	($\text{g} \cdot \text{mol}^{-1}$)	M_{CH_4}	16.04

192 CO₂ and CH₄ excess adsorption isotherms are built step by step from gas adsorption measurements performed
 193 using a custom-built manometric set-up. Simultaneously adsorption-induced swelling strain are measured based on
 194 digital image correlation. Full details are provided in Perrier et al. (2017).

195
 196 Fig. 3 presents the results of these simultaneous measurements for an activated carbon filled with pure CO₂ and
 197 pure CH₄ at $T = 318.15$ K and $T = 303.15$ K respectively. Full-field deformation maps and collected experimental
 198 data are reported in Perrier et al. (2017).

199
 200 Fig. 3.a presents the results in term of excess adsorption/desorption isotherms. CO₂ and CH₄ gas sorption in ac-
 201 tivated carbon is a reversible phenomenon and no hysteresis is observed between adsorption and desorption paths as
 202 previously reported in the literature in Khaddour et al. (2014). Noting that adsorbed quantity amount increases when
 203 temperature decreases, Fig. 3.a shows that CO₂ is preferentially adsorbed in carbon compare to CH₄ as previously
 204 reported in the literature (Ottiger et al., 2008; Battistutta et al., 2010). This is the reason why CO₂ injection is used to
 205 increase CH₄ recovery in Enhanced Coal Bed Methane production.

206
 207 Fig. 3.b presents the results in term of adsorption-induced volumetric strain. CO₂ and CH₄ gas adsorption-induced
 208 deformation is a reversible phenomenon but a small hysteresis is observed between the adsorption and the desorption
 209 paths. This hysteresis is not linked to the adsorption-deformation couplings but is due to an elastic compaction of the
 210 carbon matrix grains (Perrier, 2015). Cycling effect and material compaction are detailed in (Perrier et al., 2017). For
 211 a given pressure, CO₂ adsorption produces more volumetric deformation than CH₄ adsorption, which is the source of
 212 the rapid decrease in CO₂ injectivity during coal bed methane production enhanced by CO₂ injection.

213 2.2. Identification of model input parameters

214 The input parameters of the incremental poromechanical framework with varying porosities for double porosity
 215 media presented in Eq. (12) are:

- 216 • The adsorbent sample mass (m_s), the molar mass of the adsorbed gas ($M_{\text{CO}_2}, M_{\text{CH}_4}$), the density of the material
 217 composing the solid matrix of the porous adsorbent (ρ_s), the initial transport porosity (ϕ_M^0) and the initial
 218 adsorption porosity (ϕ_μ^0), which are all given in Table 1.
- 219 • The surrounding fluid bulk pressure (P_b), the excess adsorbed quantities (n^{ex}) and the bulk density (ρ_b), which
 220 are both experimentally measured or deduced. From the experimental measurements of the excess adsorption
 221 isotherm (Fig. 3.a), a power-law fit is identified and used as an input in the incremental estimation of Eq. (12).
 222 From the bulk pressure and the temperature, the bulk density (ρ_b) of the surrounding fluid is estimated by its
 223 state equation using the AGA8 software (Starling, 1994).
- 224 • The skeleton incompressibility (K_s) and shear (G_s) moduli are deduced from the apparent ones from the two
 225 step homogenization reversed process presented in Eq. (6). The apparent properties are experimentally mea-
 226 sured using an ultra-sonic technique where longitudinal and transverse waves are generated by a piezo-electric
 227 source and detected by a laser Doppler vibrometer (Shen et al., 2016):

$$\begin{cases} K &= \rho_s(V_p^2 - \frac{4}{3}V_s^2) \\ G &= \rho_s V_s^2 \end{cases} . \quad (13)$$

228 In Eq. 13, (V_p, V_s) are respectively the velocities of the longitudinal and the transverse waves. With $V_p =$
 229 (302 ± 2) m.s⁻¹ and $V_s = (176 \pm 1)$ m.s⁻¹, we get $K = (120 \pm 15)$ MPa and $G = (75 \pm 8)$ MPa and then
 230 $K_s = (6.0 \pm 0.6)$ GPa and $G_s = (3.5 \pm 0.4)$ GPa.

231 Note that the experimental technique developed by Perrier et al. (2017) and allowing simultaneous measure-
 232 ments of adsorption-induced swelling may also be used to characterize K_s directly as previously reported by Hol
 233 and Spiers (2012). Indeed, if a non-adsorbable gas (such as helium) is used, the skeleton incompressible mod-
 234 ulus may be deduced from bulk pressure and volumetric shrinkage strain measurements using Eq. 8. Figure 2
 235 presents a typical result of K_s direct identification. An experimental value of $K_s = (6 \pm 1)$ GPa is then obtained,
 236 which is in good agreement with the latter one. Note that dynamic and static mechanical properties may differ

for a lot of materials so a perfect match is not expected here. However, for this material with a low rigidity, the difference between the static and the dynamic properties is relatively not important and it may stand within the measurement uncertainty.

As discussed in Perrier et al. (2017), activated carbon is subjected to cycling effect and material compaction. The process to produce the active carbon is composed of three phases: first the carbon is grinded, then it is activated, and finally it is compacted to obtain a cylindrical sample. During the first cycle of gas adsorption, there is a competition between the grain compaction shrinkage and the adsorption-induced volumetric swelling and a large hysteresis is observed because of the material compaction. This compaction is mostly irreversible and after the first cycle, the second and the third cycles are reversible. Fig. 3 presents the results in term of adsorption-induced volumetric strain obtained during the third cycle when the activated carbon is fully compacted and swelling strain fully reversible. The two other cycles are presented in Perrier et al. (2017). However, the ultra-sonic technique used to identify the apparent elastic properties has been performed on the sample before compaction and the skeleton elastic properties may differ after compaction. Therefore, a second direct K_s identification has been performed after the adsorption-induced swelling test and the value of $K_s = 7.0 \pm 0.8$ GPa is obtained. Assuming that the shear skeleton modulus is affected by the compaction in the same proportion of the incompressible one – *i.e.* assuming that the Poisson's ratio is not affected by the compaction – the following skeleton moduli are identified and further used in the comparisons with experimental data:

$$\begin{cases} K_s &= (7.0 \pm 0.8) \text{ GPa} \\ G_s &= (4.1 \pm 0.4) \text{ GPa} \end{cases} \quad (14)$$

2.3. Comparisons between experimental and model results

Fig. 3 presents also the results obtained with the double porosity adsorption-induced deformation model presented in part 1. All the parameters being identified in section 2.2, the volumetric strain induced by gas adsorption is estimated step by step as well as the evolutions of the transport and adsorption porosities and the poromechanical properties without any fitted parameters.

Fig. 3.b shows that the double porosity adsorption-induced deformation model presented in part 1 is capable to predict swelling induced by both CH_4 and CO_2 gas adsorption without any additional fitting parameters. The entry parameters in the model are those collected in Table 1, the skeleton elastic moduli corrected as explained in the latter section, and the adsorption isotherms. For this activated carbon, a swelling strain of $\approx 2\%$ is recovered for a CO_2 bulk pressure up to 46 bar and a swelling strain of $\approx 1.5\%$ is recovered for a CH_4 bulk pressure up to 107 bar.

Fig. 4 shows the same results in term of excess adsorption quantities versus adsorption-induced swelling. One can note that the relationship between excess adsorbed quantities and resulting swelling is not linear. Moreover, the two evolutions for the two different gases are close together showing that the volumetric swelling is directly linked to the excess adsorbed quantity.

Fig. 5 shows that for this challenging high micro and macro porous activated carbon, a single porosity model, as the one presented in Perrier et al. (2015), highly overestimates the swelling deformation induced by gas adsorption in this activated carbon. The coupling appearing between the evolving adsorption porosity and the evolving transport porosity limits the macroscopic swelling of the material. This can only be captured with a double porosity model.

2.4. Evolution of the poromechanical properties under free swelling

The proposed double porosity model being validated by experimental comparisons in the latter section, we study here the evolution of the poromechanical properties under this free swelling.

Fig. 6 presents the evolution of the confinement degree in the adsorption porosity under free swelling for an activated carbon filled with pure CO_2 and pure CH_4 at $T = 318.15$ K and $T = 303.15$ K respectively. At the early adsorption stage, the confinement degree is high (≥ 0.9) for both CO_2 and CH_4 . This is due to the fact that at the onset of adsorption, the interstitial fluid density is much higher than the bulk density ($\rho_b \ll \rho_\mu$). Upon swelling,

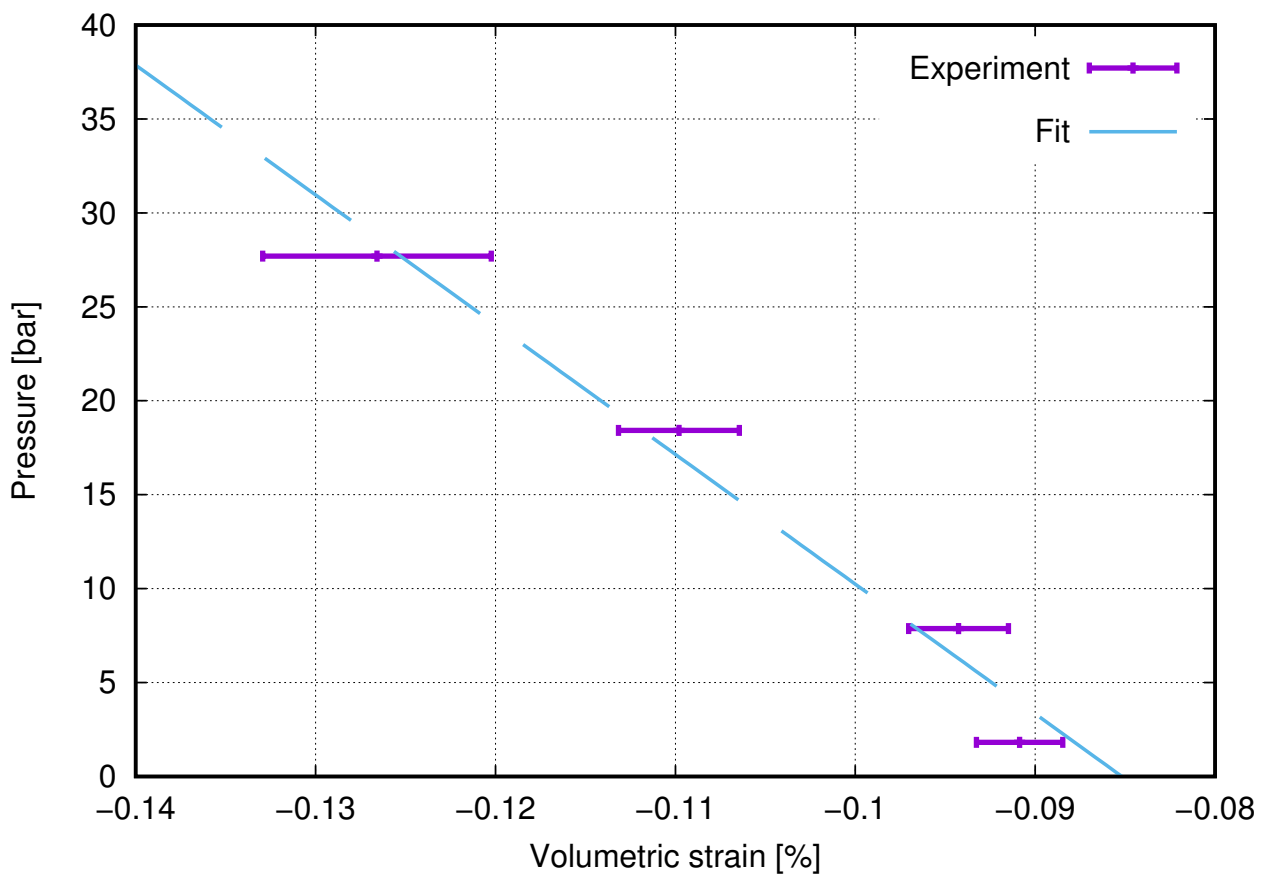
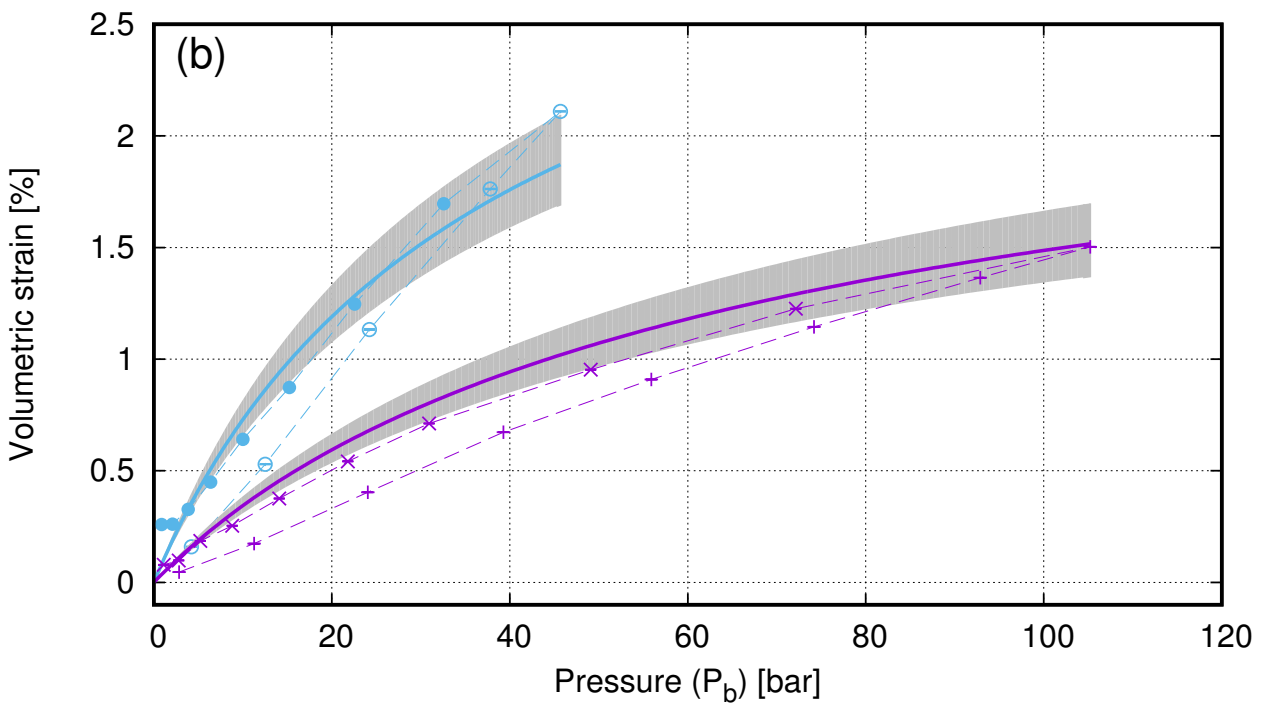
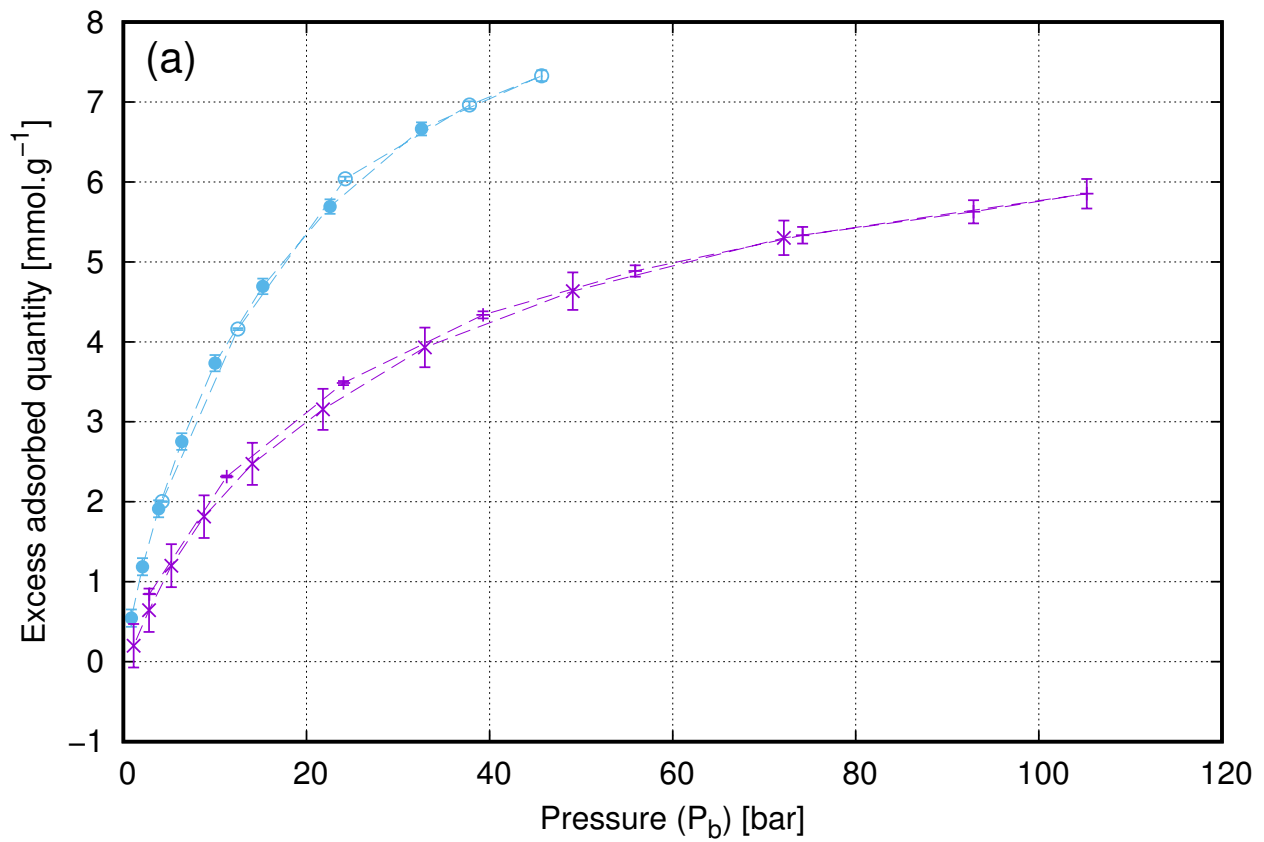


Figure 2: Activated carbon K_v direct identification based on Eq. 8 thanks to helium bulk pressure and volumetric shrinkage strain measurements (the slope provides directly K_v).



- | | | | |
|----------------------------------|--|----------------------------------|--|
| (1) CO ₂ – adsorption | | (1) CH ₄ – desorption | |
| (1) CO ₂ – desorption | | (2) Model – mean | |
| (1) CH ₄ – adsorption | | (2) Model – dispersion | |

(¹) Experiment (Perrier et al., 2017), (²) Model (this study).

Figure 3: Simultaneous adsorption and induced swelling measurements for an activated carbon filled with pure CO₂ and pure CH₄ at $T = 318.15$ K and $T = 303.15$ K respectively: (a) experimental excess adsorption isotherms; (b) comparison between experimental and modeling adsorption-induced swelling results.

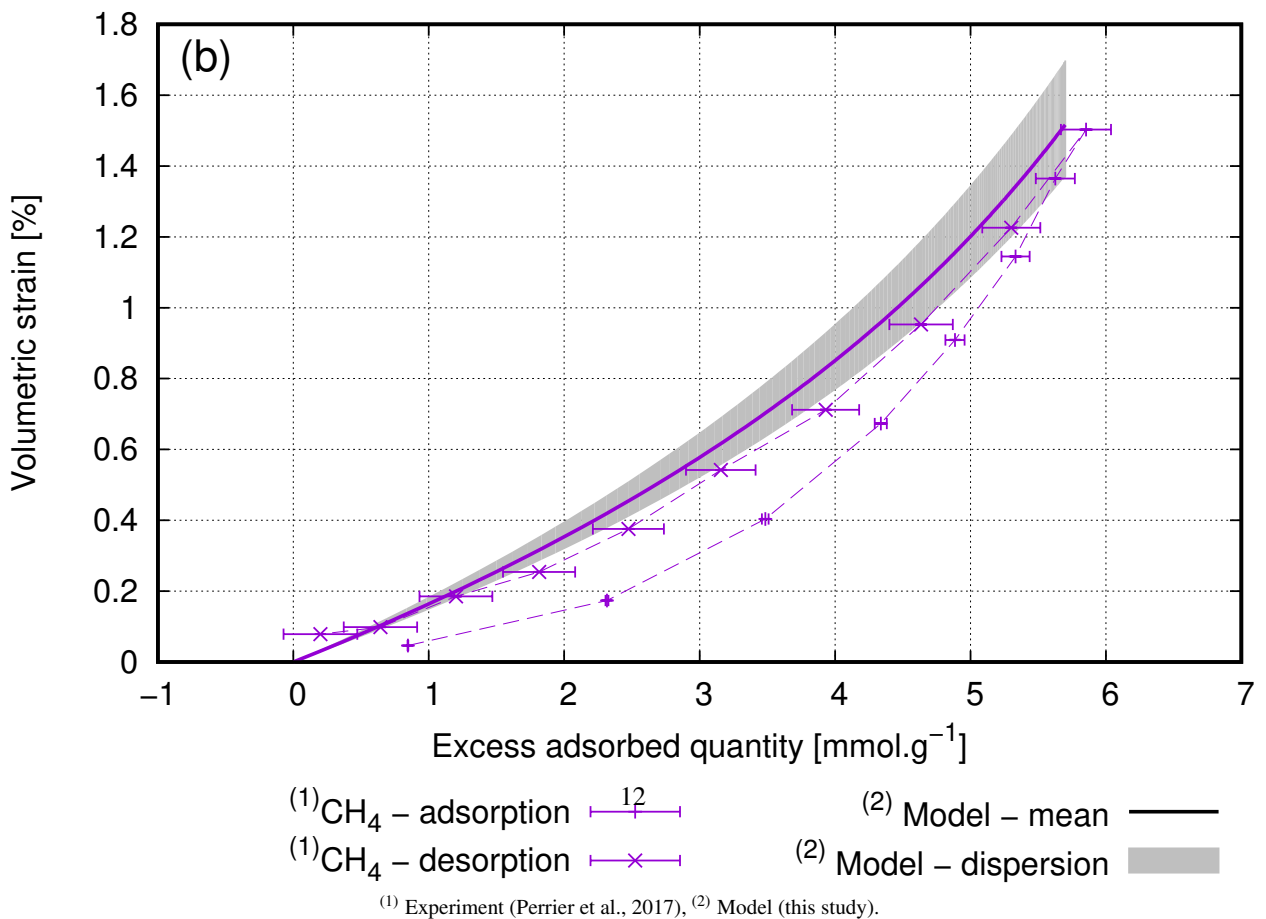
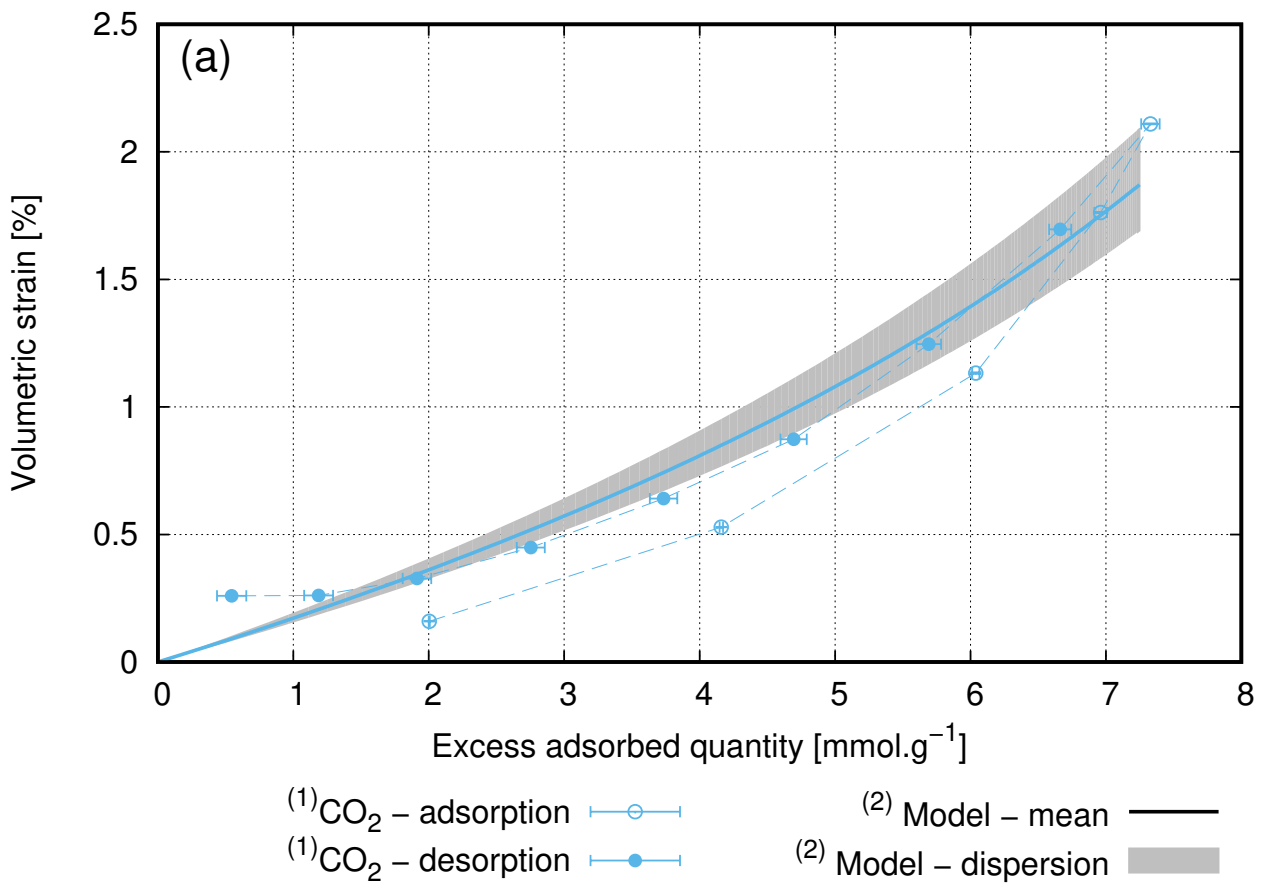


Figure 4: Comparison between experimental and modeling results in term of excess adsorption quantities versus adsorption-induced swelling for an activated carbon: (a) CO_2 at $T = 318.15 \text{ K}$; (b) CH_4 at $T = 303.15 \text{ K}$.

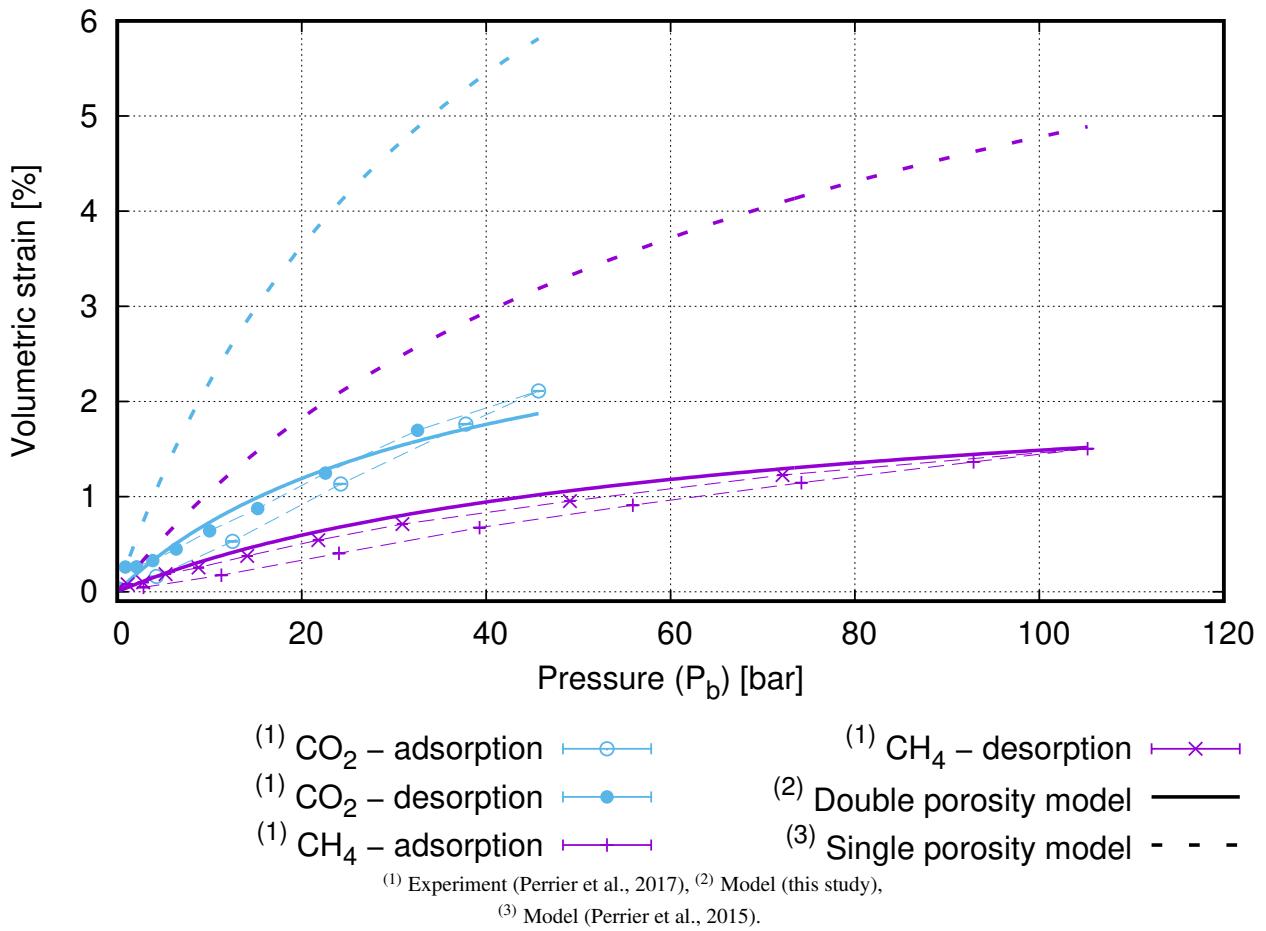


Figure 5: Comparison between the adsorption-induced swelling results provided by the single and the double porosity models for an activated carbon filled with pure CO₂ and pure CH₄ at $T = 318.15$ K and $T = 303.15$ K respectively.

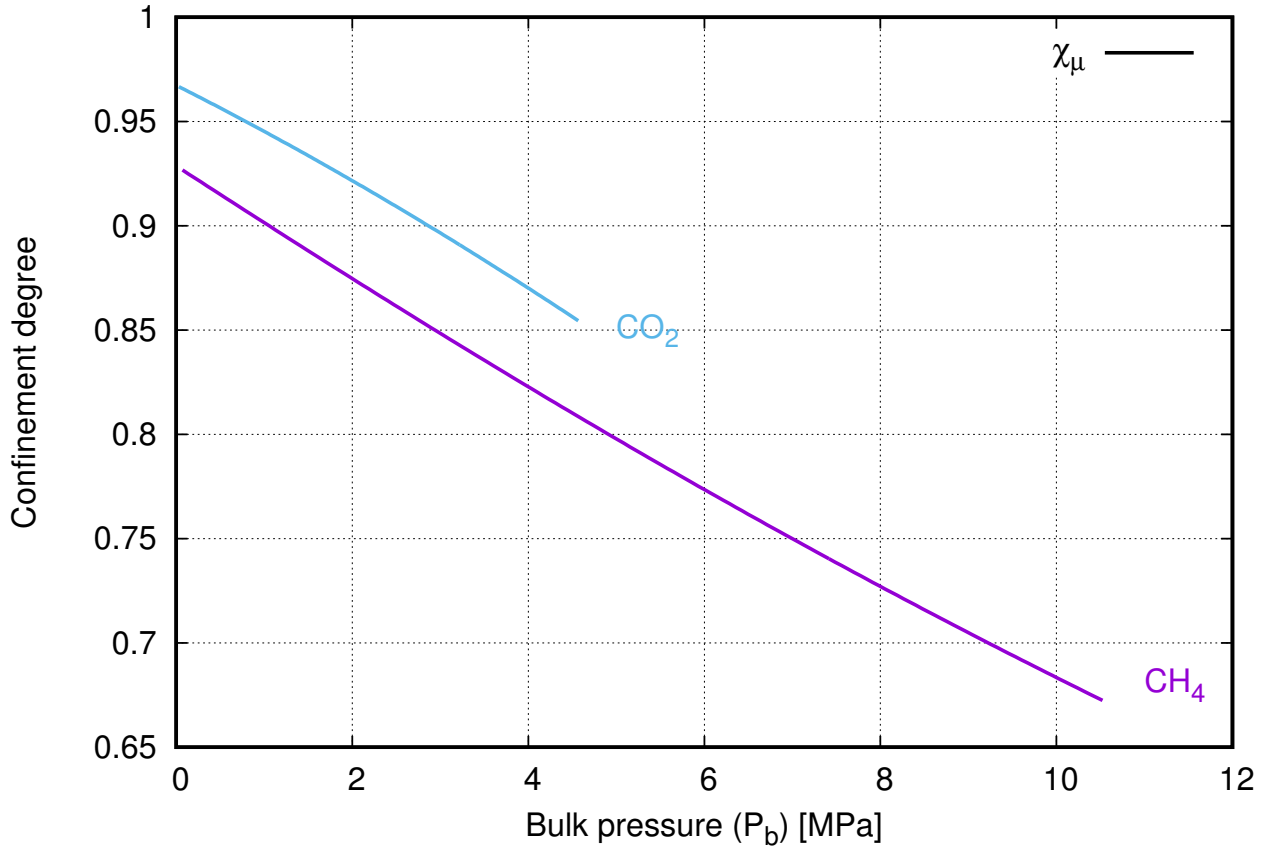
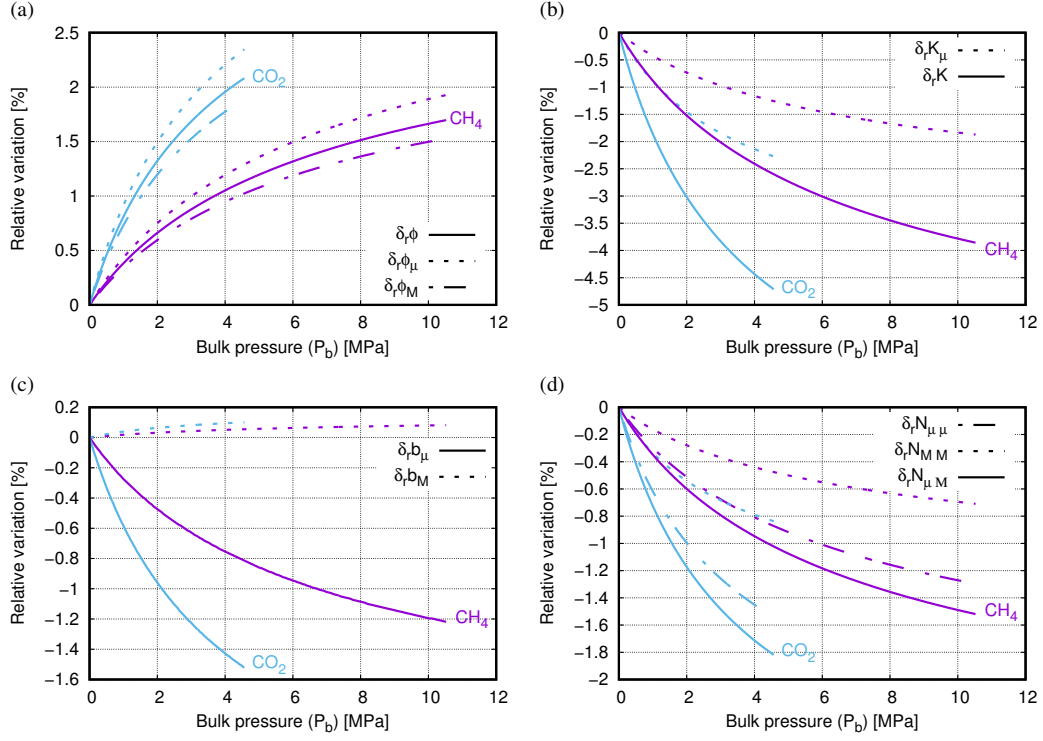


Figure 6: Evolution of the confinement degree in the adsorption porosity (χ_μ) under free swelling for an activated carbon filled with pure CO₂ and pure CH₄ at $T = 318.15$ K and $T = 303.15$ K respectively.

282 the confinement degree is decreasing for both CO₂ and CH₄. This may due to two main reasons: firstly, the ratio of
 283 the bulk density over the interstitial fluid density is increasing; secondly, the adsorption porosity is increasing due to
 284 the active carbon swelling, and therefore, the confinement of the fluid decreases. That way the functional $\frac{\phi_\mu}{1-\phi_\mu-\phi_M}$ in
 285 Eq. 12 is increasing even faster. Therefore the total number of adsorbed gas moles increases faster than the excess
 286 number of moles and the confinement degree is decreasing, the CO₂ interstitial fluid being more confined than the
 287 CH₄ one.

288 Figs. 7 presents the evolution of the poromechanical properties in term of relative variations under free swelling.
 289 Fig. 7.a shows that all porosities are increasing with increasing bulk pressure under free swelling and, for this activated
 290 carbon, a relative variation of total porosity of $\approx 2\%$ is recovered for a CO₂ bulk pressure up to 46 bar and a relative
 291 variation of $\approx 1.5\%$ is recovered for a CH₄ bulk pressure up to 107 bar. Due to the increase of porosities, Fig. 7.b
 292 shows that incompressible moduli are decreasing under free swelling, K decreasing faster than K_μ . Consequently, b_M
 293 is increasing and b_μ upon free swelling as shown in Fig. 7.c. The evolution of the coupling poromechanical properties
 294 N_{MM} , $N_{\mu\mu}$, $N_{\mu M}$ are more difficult to anticipate but Fig. 7.d shows that they are all decreasing upon swelling.

295 Even if it may be counter-intuitive, Fig. 7.a shows that, under free swelling, the transport porosity is not decreasing
 296 even if the adsorption porosity increases. It simply increases less than the adsorption porosity. Note that this cannot be
 297 generalised for other materials or thermodynamic conditions because this is due to the complex couplings appearing
 298 between the transport and the adsorption porosities in Eq. 12. For the conditions considered here, Fig. 8 shows that,
 299 whatever the bulk pressure, the different contributions of the terms (T_1 to T_6) in Eq. 12 lead to a positive derivative of
 300 both porosities in respect to the bulk pressure, and therefore both porosities increases upon swelling (see Eq. 12 for
 301 T_1 to T_6 term expressions).



where $\delta_r X = \frac{X - X^0}{X^0}$ is the relative variation of X .

Figure 7: Evolution of the poromechanical properties in term of relative variations under free swelling for an activated carbon filled with pure CO_2 and pure CH_4 at $T = 318.15 \text{ K}$ and $T = 303.15 \text{ K}$ respectively.

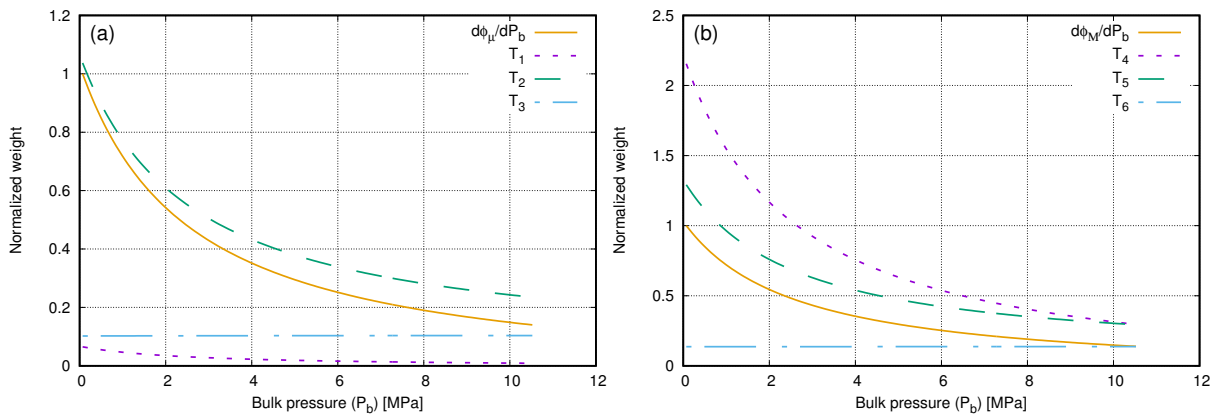


Figure 8: Relative contribution of the terms (T_1 to T_6) in the derivative of adsorption (ϕ_μ) and transport (ϕ_M) porosities in respect to the bulk pressure (see Eq. 12 for T_1 to T_6 term expressions). Normalized weight are estimated in respect to the derivative initial values.

3. Case-study of constrained swelling

In this section, one case-study of constrained swelling is considered. The volumetric strain is then assumed to be equal to zero and Eq. 12 may be rewritten as:

$$\left\{ \begin{array}{l} d\varepsilon = 0 \\ d\phi_\mu = \left(\frac{1}{N_{\mu\mu}(1-\chi_\mu)} - \frac{1}{N_{\mu M}} \right) dP_b \\ d\phi_M = \left(-\frac{1}{N_{\mu M}(1-\chi_\mu)} + \frac{1}{N_{MM}} \right) dP_b \\ \chi_\mu = \frac{n^{ex}}{n_\mu^{tot}} \quad \text{with} \quad n_\mu^{tot} = n^{ex} + \frac{\rho_b V_{\phi_\mu}}{M} = n^{ex} + \frac{m_s \rho_b}{M \rho_s} \frac{\phi_\mu}{1-\phi_\mu-\phi_M} \end{array} \right. \quad (15)$$

Figs. 9 presents the evolution of the poromechanical properties in term of relative variations under constrained swelling. Fig. 9.a shows that the total porosity and the transport porosity are now decreasing whereas the adsorption porosity still increases. Indeed, and for the conditions considered here, Fig. 10 shows that, whatever the bulk pressure, T_7 and T_8 in Eq. 15 lead to a positive derivative of the adsorption porosity in respect to the bulk pressure, whereas T_9 and T_{10} in Eq. 15 lead to a negative derivative of the transport porosity. Figs. 9.b to 9.d show the corresponding evolution of the other poromechanical properties with increasing bulk pressure. Fig. 11 shows the evolution of the total mean stress under constraint swelling. The volumetric strain being imposed equal to zero, the continuum is submitted to compressive total mean stresses.

Concluding remarks

- A new incremental poromechanical framework with varying porosity has been proposed allowing the prediction of the swelling induced by adsorption. Within this framework, the adsorption-induced strain are incrementally estimated based on experimental adsorption isotherm measurements only. The evolution of the porosity and the evolutions of the poromechanical properties, such as the apparent incompressible modulus, the apparent shear modulus, the Biot modulus and the Biot coefficient, are also predicted by the model.
- A double porosity model has been proposed for which the adsorption porosity and the transport porosity are distinguished. These two scales of porosity are supposed to be well separated and a two steps homogenization process is used to estimate incrementally the evolution of the poromechanical properties, which couple the evolutions of both porosities.
- An existing custom-built experimental set-up has been used to test the relevance of this double porosity model. A challenging high micro and macro porous activated carbon has been chosen for this purpose. An adsorption porosity of $32.2 \pm 0.2\%$ and a transport porosity of $41.6 \pm 0.2\%$ have been characterized as well as its apparent and skeleton elastic properties. *In situ* adsorption-induced swelling has been measured for pure CO_2 and pure CH_4 at $T = 318.15 \text{ K}$ and $T = 303.15 \text{ K}$ respectively and the corresponding model responses have been estimated. It has been shown that the double porosity model is capable to predict accurately the swelling induced by both CH_4 and CO_2 gas adsorption without any fitting parameters. Conversely, it has been shown that a single porosity model highly overestimates the swelling deformation induced by gas adsorption for this high micro and macro porous activated carbon. The coupling appearing between the evolving adsorption porosity and the evolving

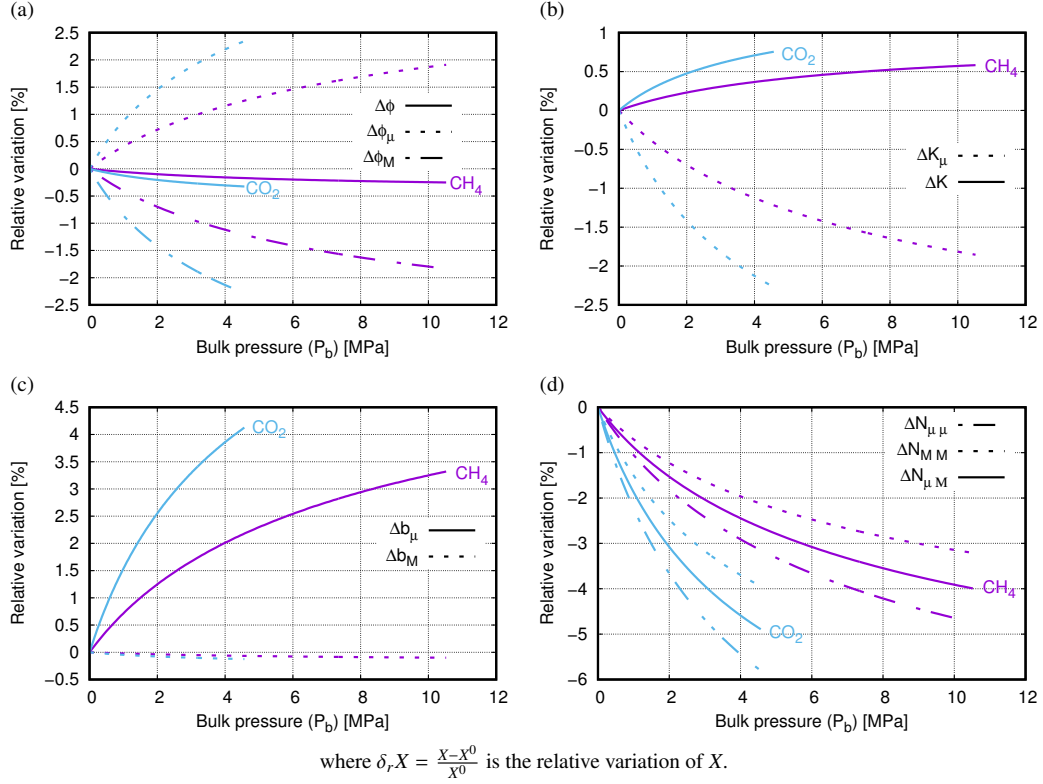


Figure 9: Evolution of the poromechanical properties in term of relative variations under constrained swelling for an activated carbon filled with pure CO₂ and pure CH₄ at $T = 318.15$ K and $T = 303.15$ K respectively.

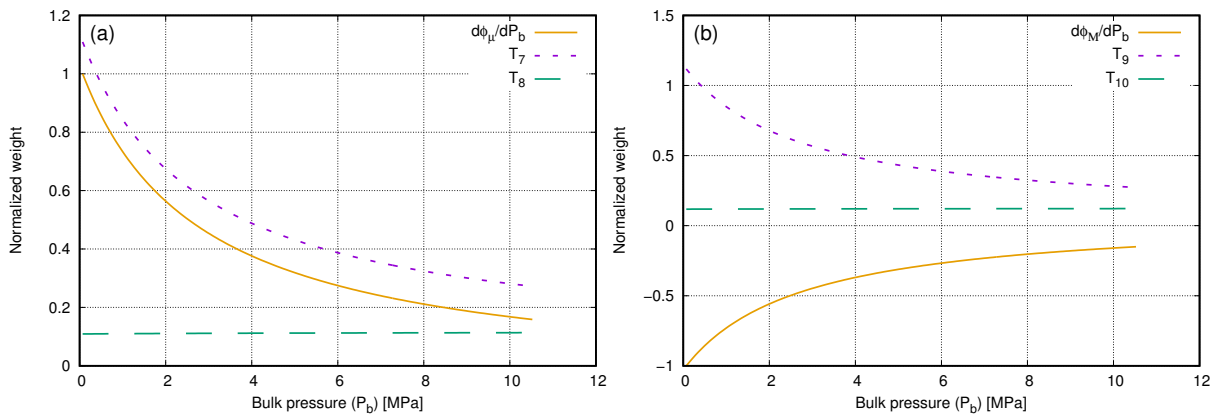


Figure 10: Relative contribution of the terms (T_7 to T_{10}) in the derivative of adsorption (ϕ_μ) and transport (ϕ_M) porosities in respect to the bulk pressure (see Eq. 15 for T_7 to T_{10} term expressions). Normalized weight are estimated in respect to the derivative initial values.

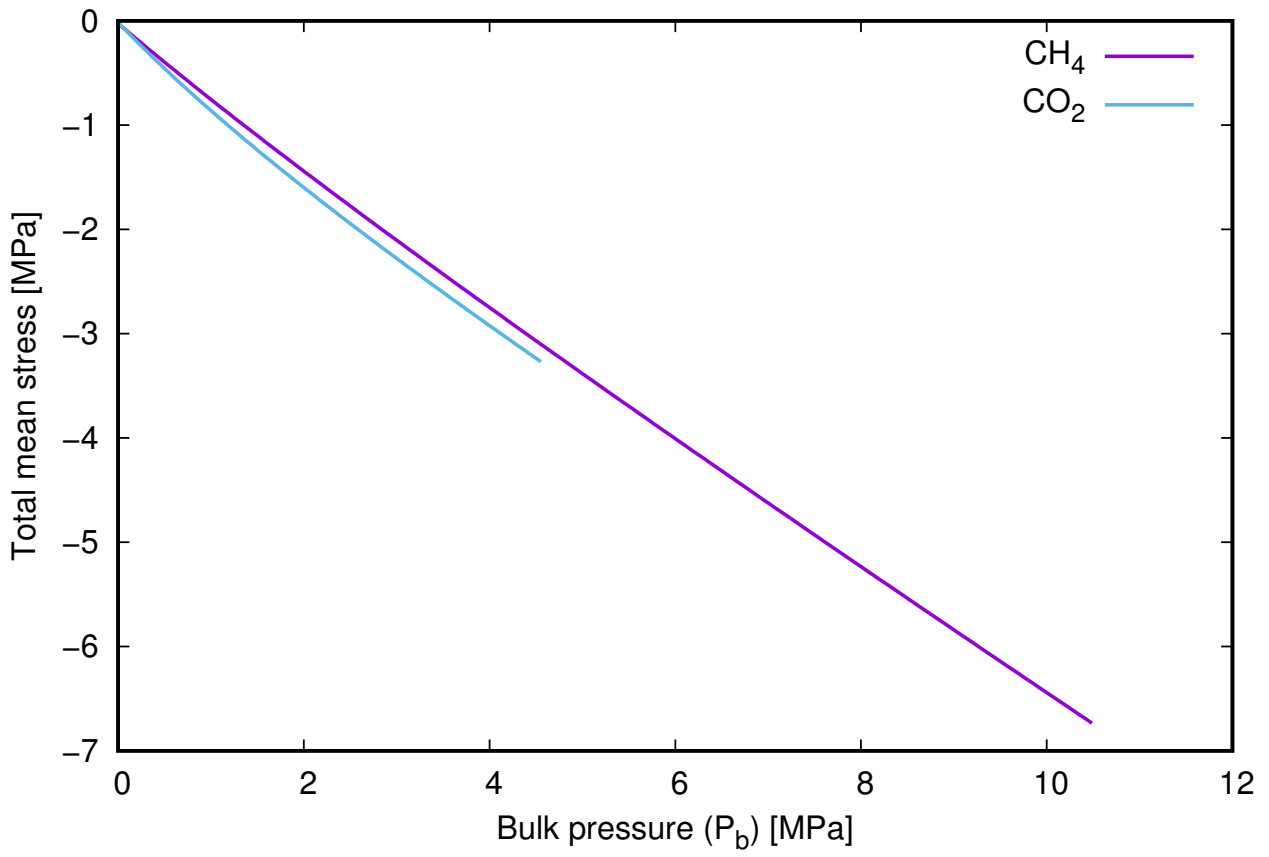


Figure 11: Total mean stress evolution under constrained swelling.

332 transport porosity limits the macroscopic swelling of the material. This can only be captured with a double
 333 porosity model.

- 334 • After validation, the double porosity model has been used to discuss the evolution of the poromechanical prop-
 335 erties under free and constraint swelling. The case-study of constraint swelling consists here in assuming a
 336 global volumetric strain equal to zero. It has been shown that for the considered material, all porosities are in-
 337 creasing with increasing bulk pressure under free swelling, whereas the total porosity and the transport porosity
 338 are decreasing when the adsorption porosity still increases under constraint swelling.

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346 Appendix A. Iterative process of homogenization

347 Following Smaoui-Barboura Barboura (2007), an iterative homogenization process may be applied for the linear
 348 homogenization functions used for a cylindrical porosity (Eq. 5)³.

349 Considering a given cylindrical porosity ϕ , the local skeleton properties (K_s, G_s) and a given number of increment
 350 n , the global homogenized properties (K_m, G_m) are determined step by step using the following scheme:

$$\begin{aligned}
 (K_m, G_m) &= \mathcal{F}_n(K_s, G_s, \phi) \text{ with:} \\
 \left[\begin{array}{l}
 K^{(0)} = K_s \quad , \quad G^{(0)} = G_s \quad , \quad \Delta\phi = \frac{\phi}{n} \quad , \quad \phi^{(i)} = \frac{\Delta\phi}{1-\phi+i\Delta\phi} \\
 \left\{ \begin{array}{l}
 K^{(i)} = \mathcal{H}_K(\phi^{(i)}, K^{(i-1)}, G^{(i-1)}) \\
 G^{(i)} = \mathcal{H}_G(\phi^{(i)}, K^{(i-1)}, G^{(i-1)})
 \end{array} \right. \\
 K_m = K^{(n)} \quad , \quad G_m = G^{(n)}
 \end{array} \right. , \tag{A.1}
 \end{aligned}$$

$$\text{where: } \left\{ \begin{array}{l}
 \mathcal{H}_K(\phi, K_s, G_s) = K_s - \frac{\phi K_s}{1-(1-\phi)\left(\frac{K_s}{K_s+G_s}\right)} \\
 \mathcal{H}_G(\phi, K_s, G_s) = G_s - \frac{\phi G_s}{1-(1-\phi)\left(\frac{K_s+2G_s}{2K_s+2G_s}\right)}
 \end{array} \right. .$$

351 Moreover, the latter iterative process may be reversed to determine step by step the local skeleton properties

³For a full description on the iterative processes for both spherical and cylindrical porosities see Perrier et al. (2015).

352 (K_s, G_s) knowing the homogenized properties (K_m, G_m) and a given number of increment n :

$$(K_s, G_s) = \mathcal{R}_n(K_m, G_m, \phi) \text{ with:}$$

$$\left[\begin{array}{l} K^{(0)} = K_m \quad , \quad G^{(0)} = G_m \quad , \quad \Delta\phi = \frac{\phi}{n} \quad , \quad \phi^{(i)} = \frac{\Delta\phi}{1-\phi+i\Delta\phi} \\ \left\{ \begin{array}{l} K^{(i)} = \mathcal{H}_K(\phi^{(i)}, K^{(i-1)}, G^{(i-1)}) \\ G^{(i)} = \mathcal{H}_G(\phi^{(i)}, K^{(i-1)}, G^{(i-1)}) \end{array} \right. \quad , \\ K_s = K^{(n)} \quad , \quad G_s = G^{(n)} \end{array} \right. \quad (A.2)$$

$$\text{where: } \left\{ \begin{array}{l} \mathcal{H}_K(\phi, K_s, G_s) = K_s + \frac{\phi K_s}{1-(1-\phi)\left(\frac{K_s}{K_s+G_s}\right)} \\ \mathcal{H}_G(\phi, K_s, G_s) = G_s + \frac{\phi G_s}{1-(1-\phi)\left(\frac{K_s+2G_s}{2K_s+2G_s}\right)} \end{array} \right. .$$

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