Cyclotetrabenzil-Based Porous Organic Polymers with High Carbon Dioxide Affinity

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Abstract Porous organic polymers (POPs) incorporating macrocyclic units have been investigated in recent years in an effort to transfer macrocycles' intrinsic host-guest properties onto the porous networks to achieve complex separations. In this regard, highly interesting building blocks are presented by the family of cyclotetrabenzoin macrocycles with rigid, well-defined, electron-deficient cavities. This macrocycle shows high affinity towards linear guest molecules such as carbon dioxide, thus offering an ideal building block for the synthesis of CO₂philic POPs. Herein, we report the synthesis of a POP through the condensation reaction between cyclotetrabenzil and 1,2,4,5-tetraamino-nobenzene under ionicothermal conditions using the eutectic zinc chloride/sodium chloride/potassium chloride salt mixture at 250 °C. Notably, following the condensation reaction, the macrocycle favors three-dimensional (3D) growth rather than two-dimensional one while retaining the cavity. The resulting polymer named 3D-mPOP, showed a highly microporous structure with a BET surface area of 1142 m² g⁻¹ and a high carbon dioxide affinity with a binding enthalpy of 39 kJ mol⁻¹. Moreover, 3D-mPOP showed very high selectivity for carbon dioxide in carbon dioxide/methane and carbon dioxide/nitrogen mixtures.

Key words macrocycles, porous polymers, host-guest chemistry, ionicothermal synthesis, CO₂ capture

Introduction

The environmental impact of greenhouse gas emissions is an ever-growing concern, primarily due to the continuously rising atmospheric levels of carbon dioxide (CO₂), which have surpassed 400 ppm. In addition to lowering the world’s reliance on fossil fuel energy, technologies to capture CO₂ will be needed to minimize the environmental impact of this gas. In this regard, porous materials have gained tremendous attention. Light-weight porous organic polymers (POPs) with high surface areas, structural tunability, chemical stability, scalability and ease of preparation are intriguing candidates to tackle this problem. The CO₂ affinity of a POP is determined by two main parameters: (a) the size of the pores, which should be in the ultramicropore (~0.7 nm) to micropore range (<2 nm) and (b) the presence of heteroatoms such as nitrogen that can enhance dipole-quadrupole interactions with CO₂. Shape-persistent macrocycles and cages can offer well-defined binding sites for CO₂ molecules and facilitate its efficient capture and separation. In this direction, POPs containing macrocycle or cage-building blocks have gained significant interest in recent years and have already found applications in water/air purification, natural gas purification, adsorption of toxic pollutants and as battery electrodes. The macrocycles including cyclodextrins, calix[4]arenes, resorarenes, and pillar[5]arenes have already been integrated into the POPs. Recently, Miljanić and coworkers reported a facile and a scalable approach for the preparation of cyclotetrabenzoin macrocycles and their esters. Cyclotetrabenzoazin esters feature a well-defined, electron-deficient cavity, which is shown to be selective towards linear guest molecules such as terminal alkynes, organic nitriles, CS₂, and CO₂, and a surface area greater than 500 m² g⁻¹ in the case of cyclotetrabenzoazin acetate. It has also been reported that larger guests such as benzonitrile and phenyl acetylene do not fit in the cavity. The oxidation of cyclotetrabenzoazin to the corresponding octaketone dubbed cyclotetrabenzoazin (labeled as octaketone in Scheme 1a) enabled further derivatization through a condensation reaction with 1,2-phenylenediamines to form pyrazine linkages. Interestingly, whereas the acetylated...
cyclotetrabenzoic largely retains the square-grid structure of the parent cyclotetrabenzoic, steric hindrance generated by pyrazine linkages forced the macrocycle to adopt a saddle-shaped three-dimensional (3D) structure, with pyrazine linkages arranged in an alternating manner, thus offering a unique platform for the synthesis of fully sp²-hybridized 3D-POPs.¹⁵

Results and Discussion

The cyclotetrabenzoic itself is highly insoluble due to the strong intermolecular hydrogen bonding interactions.¹⁵ Upon its treatment with nitric acid, it is oxidized to the corresponding cyclotetrabenzil octaketone, which has a much higher solubility as it is no longer a hydrogen bond donor.¹⁴ The X-ray diffraction (XRD) crystal structure of octaketone shows a geometry that resembles a chair. One pair of rings is facing each other, with an interplanar distance of 7.64 Å, while the other pair finds themselves in parallel planes (interplanar distance: 4.23 Å) but offset from each other. The neighboring carbonyl groups are almost perpendicular to each other, with O=C–C=O dihedral angles of 82.1° and 88.3°. In the extended packing diagram of this compound, noticeable are short (2.34 Å) contacts between carbonyl oxygens on one molecule and aromatic hydrogens on the neighboring molecule. The condensation reaction between octaketone and 1,2-phenylenediamine in ethanol affords the corresponding pyrazine-functionalized model compound, whose structure is highly distorted into a 3D structure resembling a saddle, as evidenced from the single-crystal X-ray structure. Within the central macrocycle, one pair of aromatic planes is almost parallel (7.2° interplanar angle), while the other shows significant twisting with an interplanar angle of 80.6°. The planes of the appended quinoxaline moieties on the opposite sides of this model compounds form a V-shape with interplanar angles of 69.7° and 73.8°.

There are only a handful of fully sp²-hybridized organic linkers (such as e.g. cyclooctatetraene), which are at the same time synthetically accessible and deplanarized enough to offer a 3D arrangement, though none of these linkers features an intrinsic pore. Inspired by these results, we targeted the synthesis of a macrocycle-containing 3D POP, 3D-mPOP, by reacting octaketone with 1,2,4,5-tetraaminobenzene under ionothermal conditions using a ZnCl₂/KCl/NaCl eutectic salt mixture (Scheme 1c) at 250 °C.¹⁶ Since the eutectic salt mixture has a lower melting point than ZnCl₂, it enables the polymerization reaction to proceed at lower temperatures, which is critical to avoid partial carbonization. The formation of 3D-mPOP was verified by Fourier-transform infrared (FTIR) and X-ray photoelectron spectroscopy (XPS) analyses (Figure 1a, b). FTIR spectra revealed the formation of pyrazine linkages as evidenced by the C=N stretching band at 1669 cm⁻¹. We also observed a residual C=O stretching at 1696 cm⁻¹.¹⁷ The –NH₃⁺ stretching band of 1,2,4,5-tetraaminobenzene tetrahydrochloride (TABH) at 2466 cm⁻¹ also disappeared, further indicating the successful formation of pyrazine linkages. We also observed the characteristic aromatic =C–H stretching and bending modes at 3000 and 1413 cm⁻¹, respectively (Figure 1a). The XPS N1s spectrum revealed the –C=N– and –C=N– peaks at 398.8 and 400.2 eV, respectively, which were in a perfect agreement with those of pyrazine moieties.¹⁸ Moreover, the C 1s spectrum revealed three different carbon binding energies at 284.5, 285.5 and 286.8 eV, representing the characteristic –C=C–/–C=–, –C=N–, and –C=N– signatures, respectively (Figure 1b).¹⁹ As a control sample, the model compound was synthesized under the same reaction conditions by reacting octaketone with 1,2-diaminobenzene in an 85% yield (see Figure S1 for the characterization data).¹⁴ The powder XRD analysis of the 3D-mPOP revealed its amorphous nature (Figure S2). In addition, the chemical structure of the 3D-mPOP was verified by solid-state cross-polarization magic-angle
spinning $^{13}$C NMR analysis. The solid-state $^{13}$C NMR spectrum of 3D-mPOP is (Figure S3) found to be in good agreement with that of the model compound. In line with the FTIR data, we observed the presence of terminal carbonyl moieties at 194 ppm. Elemental analysis (EA) was performed to determine the elemental composition of 3D-mPOP (Table S1). The EA data showed 76.7% of C, 14.8% of N and 5.2% of H, in good agreement with the calculated data. We attributed the slight deviation in the C and N contents to the presence of water molecules trapped within the pores, as verified by the presence of a broad peak at 3300 cm$^{-1}$ in the FTIR spectrum (Figure 1a). Thermogravimetric analysis (TGA) data showed that the synthesized polymer is stable up to 350 °C under both air (Figure 1c) and N$_2$ (Figure S4) atmosphere. The initial mass loss is attributed to the removal of trapped solvents and water. Complete removal of the salts can be verified by TGA under air where 100% mass loss is obtained at 1000 °C (Figure 1c).

The porosity and pore structure of 3D-mPOP and the model compound were analyzed with $N_2$ sorption measurements at 77 K (Figure 2a). The surface area was calculated from adsorption isotherms using the Brunauer–Emmett–Teller (BET) theory and the pressure ranges were determined from the Rouquerol plots (Figure S5). 3D-mPOP showed a Type I isotherm showing a highly microporous structure. On the contrary, the model compound showed a Type III adsorption isotherm indicating a nonporous or macroporous structure (Figure 2a). While 3D-mPOP has a BET surface area of 1142 m$^2$ g$^{-1}$, that of the model compound was found to be only 31 m$^2$ g$^{-1}$ (Figure 2a and Table 1). The scanning electron micrographs (SEMs) revealed an interconnected pore structure presumably due to the templating effect of the salts (Figure S6). The nonlocal density functional theory (NLDFT) pore size distribution analysis showed the presence of two types of micropores with respective sizes of 5.4 and 11.4 Å (Figure 2b). The 5.4 Å-sized pore corresponds to the center of the distorted pyrazine-based macrocycle cavity and the 11.4 Å-sized pore corresponds to the extrinsic pores formed after the polymerization. The H4 hysteresis in the desorption branch at $P/P_0 = 0.4$ points to the presence of mesopores and a slit-like pore structure.

The microporous structure of 3D-mPOP was further examined by CO$_2$, CH$_4$, and N$_2$ uptake (Figure 2c) experiments. The CO$_2$ gas uptake at 273 K was found to be 2.29 mmol g$^{-1}$, followed by 0.51 mmol g$^{-1}$ for CH$_4$, and almost no uptake of N$_2$ (0.14 mmol g$^{-1}$). These results clearly demonstrate (Table 2) the CO$_2$-philicity of the 3D-mPOP, which is likely arising from the cycloketetrabenzoazinc macrocycle, which was shown to be a good host for the various linear molecules including CO$_2$. The isosteric heat of adsorption ($Q_{st}$) for CO$_2$ was calculated from the
adsorption isotherms obtained at 273, 298, and 323 K (Figure S7). The $Q_{st}$ value for CO$_2$ was found to be in the range of 32.2–39.2 kJ mol$^{-1}$ (Figure 2d). Notably, the $Q_{st}$ value of 39.2 kJ mol$^{-1}$ at zero coverage clearly shows that the affinity of the 3D-mPOP towards CO$_2$ is dictated by the macrocyclic units. Moreover, the calculated $Q_{st}$ value is highly favorable as the adsorption is physical, which results in easier regeneration. Given the high affinity of 3D-mPOP
towards CO₂, we decided to evaluate the CO₂ selectivity over N₂ and CH₄. The gas selectivity of 3D-mPOP was investigated by measuring the corresponding gas uptake isotherms at 273 K up to 1 bar. The initial steep increase in the case of CO₂ (Figure 2c) is attributed to the high affinity of the macrocyclic units for this guest. High CO₂ uptake at low partial pressures \((P/P_0 = 0.15)\) is highly relevant, especially for flue gas separation. In order to calculate the mixed gas selectivity from single-component gas adsorption isotherms, we used the ideal adsorbed solution theory (IAST), which is quite useful to evaluate the mixed gas selectivity for various porous materials.

3D-mPOP showed an excellent CO₂/N₂ (15:85) IAST selectivity of 137 under flue gas conditions at 1 bar. We also evaluated the performance of 3D-mPOP for natural gas (CO₂:CH₄, 5:95) and land fill gas (CO₂:CH₄, 50:50) separation (for performance comparison, see Table S2). The IAST CO₂/CH₄ selectivities of 3D-mPOP for natural gas and land fill gas turned out to be 22 and 18, respectively (Figure 3) at 273 K, 1 bar. These values are significantly higher compared to the pillar[5]arene-based polymers and comparable to the POPs incorporating highly CO₂-philic organic cages. Moreover, 3D-mPOP also performed better than representative POPs such as BILPs and azo-COPs thus clearly demonstrating the impact of the macrocycle (for a detailed comparison, see Table S2). High CO₂ selectivity of the 3D-mPOP over N₂ and CH₄ is attributed to the strong affinity of the macrocycle towards the linear guest molecules as well as to the larger kinetic diameter of N₂ (3.64 Å) and CH₄ (3.80 Å) compared to CO₂ (3.30 Å). These values clearly demonstrate the potential of 3D-mPOP for CO₂ removal from land fill gas and natural gas mixtures as well as CO₂ scrubbing.

Conclusions

We demonstrated the potential of cyclotetra benzil as a functional organic building block to form fully sp²-hybridized 3D polymer networks. Moreover, the high apparent affinity of the cyclotetra benzil host towards the linear guest molecules was successfully transferred to the polymer network to achieve highly efficient CO₂ capture, with high selectivity over N₂ and CH₄. This study also underlines the potential of macrocycles and cages as building blocks for the synthesis of POPs for complex separations thanks to their highly selective host–guest interactions.

Experimental Section

All the chemicals and solvents were used as purchased without any further purification. Dry solvents were
purchased from Sigma-Aldrich or Acros Chemicals. The NaCl (99.95%) and KCl (99.95%) were purchased from Carl-Roth. The ZnCl₂ (99.95% trace metal basis), TABH (98%), and 1,2-phenylenediamine (98%) were purchased from Sigma-Aldrich. The hydrochloric acid solution (36.5%) was purchased from Honeywell Chemicals. All manipulations involving water and air-sensitive chemicals were carried in a glovebox under an argon atmosphere. The degassing and reactions under inert atmosphere were carried out using standard Schlenk line techniques. Silica gel chromatography was performed on 230–400 mesh silica gel (Silicyl). Thin layer chromatography was performed using Merck 60 F₂₅₄ silica/alumina gel plates. FTIR spectra were recorded on a PerkinElmer Frontier spectrometer equipped with PIKe GladiATR module. The solution-phase NMR spectra were recorded using a Bruker Avance III 500 MHz spectrometer using deuterated solvents. The solid-state CP MAS ¹³C NMR spectrum was recorded using a Bruker Avance Neo 400 MHz spectrometer using 7 kHz spinning rate and with a 5.0 s relaxation delay. The NMR spectra were calibrated based on the deuterated solvent peak. The XRD patterns were obtained using a STOE STADI-P system using Cu Kα incident beam. The samples were scanned between 2° and 60° of 2θ. The XPS measurements were carried out using a PHI VersaProbe II scanning XPS microprobe (Physical Instruments AG, Germany). Analysis was performed using a monochromatic Al Kα X-ray source of 24.8 W power with a beam size of 100 µm. The spherical capacitor analyzer was set at 45° with respect to the sample surface. Field emission SEM images were obtained on a Cressington 208HR sputter coater in order to avoid charging.

Procedures

The octaketone was prepared according to the previously reported literature procedure. The 3D-mPOP was synthesized by the ionothermal method using a eutectic salt mixture composed of NaCl, KCl, and ZnCl₂ salts. The mixture of 79.3 mg of octaketone (0.15 mmol), 85.2 mg of TABH (0.30 mmol), 18.4 mg of NaCl (0.315 mmol), 59.3 mg of KCl (0.795 mmol), and 169.7 mg of ZnCl₂ (1.245 mmol) was finely ground in a mortar. The resulting solid mixture was then transferred into a Pyrex ampule (18 mL) and evacuated under vacuum for 45 min before being flame-sealed. The ampule was heated in an oven at 250 °C for 48 h. After the completion of the polymerization, the contents of the ampule were washed with acetone (100 mL), THF (100 mL), methanol (100 mL), and water, respectively. Finally, the polymer was stirred in 500 mL of a 0.1M HCl solution for 5 d at RT before subsequent purification by Soxhlet extraction using methanol to yield 65.6 mg (66.2%) of 3D-mPOP as a black powder.

The model compound was synthesized using the same procedure in 85% yield as a brown powder. The ¹H NMR (CDCl₃, 500 MHz): δ 8.18 (dd, J = 5.8, 3.2 Hz, 8 H), 7.79 (dd, J = 5.8, 3.2 Hz, 8 H), 7.59 (s, 16H) ppm. The ¹³C NMR (CDCl₃, 125 MHz): δ 152.40, 141.62, 139.36, 130.65, 130.35, 129.53 ppm.

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Supporting Information

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Primary Data

Crystal structure data for octaketone have been deposited with the Cambridge Crystallographic Data Centre under code CCDC-2069402.

References


