Catalytic Solvolytic and Hydrolytic Degradation of Toxic Methyl Paraoxon with La(catecholate)-Functionalized Porous Organic Polymers

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Supporting Information

ABSTRACT: Two robust catechol-functionalized porous organic polymers (catPOPs) with different Td-directing nodes were synthesized using a cobalt-catalyzed acetylene trimerization (CCAT) strategy. Postsynthesis metallation was readily carried out with La(acac)₃ to afford catalytically active La-functionalized catPOPs for the solvolytic and hydrolytic degradation of the toxic organophosphate compound methyl paraoxon, a simulant for nerve agents.

KEYWORDS: porous organic polymers, catechol, catalysis, organophosphates, lanthanum

INTRODUCTION

Over the past decade, porous organic polymers (POPs) have emerged as a new class of materials with promising applications in gas storage,¹⁻⁷ chemical separation,³⁻¹¹ and heterogeneous catalysis.¹²⁻¹⁷ The directed assembly of one or more rigid organic building blocks into a microporous network using stable organic bonds can afford chemically and thermally stable materials with both highly accessible internal surface areas and a wide range of chemical functionalities.⁷ Of particular interest to us is the design of POPs suitable for applications that combine molecular recognition and catalysis. Specifically, the integration of coordinatively unsaturated metal ions into POPs should afford micropore environments that are capable of binding and transforming small-molecule substrates.¹⁷ Together with the known ability of nanometer-sized cavities to sequester reactants and enhance their in-pore concentrations beyond that in solution,¹⁸,¹⁹ this should lead to enhanced catalysis.

While metal ions have been incorporated into POPs possessing bipyridyl ligands and used for catalysis,¹⁶,²⁰ this strategy necessitates the use of charge-compensating anions, which can fill valuable pore volumes and block coordination sites.¹²,¹³,¹⁵,¹⁶ To generate POPs that can stabilize metal ions featuring high degrees of unsaturation, we have focused instead on the use of negatively charged ligands as building blocks. In addition to porphyrin-based systems,¹³ we have been able to integrate catechol-bearing building blocks into POPs and successfully form POP-stabilized monocatecholated metal complexes with a series of divalent metals (Cu II, Mg II, Mn II, and Zn II) that demonstrate enhanced hydrogen sorption capabilities²¹ and removal of toxic chemicals.²² The dianionic catecholate ligands offset the cationic charges of divalent metal ions while their isolation inside the POP micropore precludes the formation of stable bis- and tris-chelation motifs that are the dominant species in a homogeneous environment.²³ The result is metal centers with empty or labile coordination environments (solvents or water) that can be used to bind and recognize small molecules.

Given our interest in the solvolytic degradation of phosphate triesters and its relevance in the decomposition of toxic organophosphate-based nerve agents,¹⁹,²⁴ we reasoned that a Lewis-acidic metal ion bound inside a catechol-functionalized POP would be a potent, reusable catalyst for these reactions.²⁵,²⁶ While both Al III and Zn II complexes have been used in the supramolecularly catalyzed methanolysis of phosphate esters,¹⁹,²⁴ we choose to incorporate La III ions into our catechol POPs (catPOP) given its strong oxophilic nature and its ability to coordinate up to 9 ligands.²⁷ We hypothesized that (monocatecholate)La moieties stabilized inside a POP cavity would be able to bind phosphate triesters together with a large number of hydroxylated reagents, such as methanol and water, inside a micropore and accelerate its solvolytic decomposition. In addition to the dianionic catecholate ligand, the third anionic ligand of the La III ion (i.e., MeO⁻ or HO⁻) or other protonated ligands (MeOH or H₂O) can serve as a pool of nucleophiles in the solvolysis/hydrolysis of the coordinated phosphate ester. We note that the high activity of La III ion in the hydrolytic cleavage of DNA²⁸ and solvolysis of phosphate triesters,²⁹⁻³¹ has been demonstrated.
Scheme 1. Synthesis of Catechol-Containing POPs \(A_2B_1\) and \(A_2C_1\) Using a Cobalt-Catalyzed Acetylene Trimerization Strategy (CCAT) and Their Subsequent Metallation with La\(^{III}\) Ions

“The POPs shown above are idealized representations of a completely formed network. However, different substitution patterns (1,3,4 vs 1,3,5) may be present as well as olefins/dienes and unreacted acetylene groups because of incomplete polymerization. For the \(A_2B_1\) composition, solid-state \(^{13}\)C NMR analysis suggested that this material is free of olefin/diene groups. See the Supporting Information by Weston et al.\(^{21}\) for additional discussion.”

2. EXPERIMENTAL SECTION

Synthesis of Polymers. POP \(A_2B_1\) was synthesized following a previously reported procedure.\(^{21}\)

**POP \(A_2C_1\).** In a nitrogen-filled glovebox, a 5 mL microwave vial (capacity designates the amount of solution that can be safely loaded) equipped with a magnetic stir bar was charged with monomers \(A^{35}\) (38 mg, 0.18 mmol) and \(C^{35}\) (54 mg, 0.09 mmol) in the same optimal ratio found for \(A_2B_1\).\(^{21}\) This mixture was dissolved in dry 1,4-dioxane (4 mL) and \(\text{Co}_2(\text{CO})_8\) (30 mg, 0.09 mmol) was added. The solution was stirred for 5 min prior to being sealed and removed from the glovebox. The reaction mixture was then stirred at 110 °C in a silicone oil bath for 3 h, during which time a black precipitate formed. Upon cooling to room temperature, the microwave vial was opened and the precipitate was isolated by filtration, washed with \(H_2O\) (30 mL), and stirred in conc. aqueous hydrochloric acid (10 mL) for 2 h. The remaining black polymer was washed with \(H_2O\) (30 mL) and MeOH (30 mL), dried over dynamic vacuum, and activated under a stream of nitrogen at 150 °C for 12 h to afford \(A_2C_1\) (80 mg, 97%).

**Representative Procedure for the Metallation of Polymers.** **POP \(La_2A_2B_1\).** \(A_2B_1\) (100 mg) was added to a solution of \(La(\text{acac})_3\) (260 mg, 0.57 mmol) in MeOH (10 mL) and stirred at 50 °C for 18 h. The suspension was filtered and the solid polymer was extracted for 12 h with MeOH using a Soxhlet apparatus. The remaining material was filtered and activated under a stream of nitrogen at 150 °C for 12 h.

**Representative Procedure for the Methanolysis of \(p\)-Nitrophenyl Dimethyl Phosphate (PNPDMP) by \(La_2A_2C_1\) under Shaking Conditions.** On the benchtop, PNPDMP (19 mg, 25 mM), \(La_2A_2C_1\) (4 mg, 6 mol % La\(^{III}\)) and 4-ethylmorpholine buffer solution (93 mM, 30 vol % EtOH, pH 10, 3 mL)\(^{34}\) were placed in a 2 dram vial. The reaction vial was sealed with a Teflon-lined cap and allowed to shake at 200 rpm and 60 °C in a Thermolyne Type 17600 aluminum heating block (Thermolyne, Dubuque, IA) mounted on a Thermolyne Type 65800 shaker (Thermolyne, Dubuque, IA). Periodically, the reaction vial was removed from the shaker and quickly opened for aliquot (100 \(\mu\)L) sampling before being put back on the shaker. The sampled aliquot was diluted with MeOH to 25 mL in a volumetric flask and analyzed by UV–vis spectroscopy. The conversion of PNPDMP as a function of reaction time was obtained by monitoring the increase of absorbance of \(p\)-nitrophenol at 311 nm.

**Hydrolysis of \(p\)-Nitrophenyl Dimethyl Phosphate (PNPDMP) by \(La_2A_2C_1\) under Shaking Conditions.** On the benchtop, PNPDMP (19 mg, 25 mM), \(La_2A_2C_1\) (4 mg, 6 mol % La\(^{III}\)) and 4-ethylmorpholine buffer solution (93 mM, 30 vol % EtOH, pH 10, 3 mL)\(^{34}\) were placed in a 2 dram vial. The reaction vial was sealed with a Teflon-lined cap and allowed to shake at 200 rpm and 60 °C in a Thermolyne Type 17600 aluminum heating block (Thermolyne, Dubuque, IA) mounted on a Thermolyne Type 65800 shaker (Thermolyne, Dubuque, IA). Periodically, the reaction vial was removed from the shaker and quickly opened for aliquot (100 \(\mu\)L) sampling before being put back on the shaker. The sampled aliquot was diluted with the buffer solution to 25 mL in a volumetric flask and analyzed by UV–vis spectroscopy. The conversion of PNPDMP as a function of reaction time was obtained by monitoring the increase of absorbance of the \(p\)-nitrophenolate ion at 406 nm.

3. RESULTS AND DISCUSSION

In exploring the use of La-functionalized catPOPs for phosphate ester hydrolysis, we wanted to investigate how the substrate accessibility of the micropore reaction environment, and thus its catalytic activity, can be tuned by incorporating different organic linkers. Previously,\(^{21}\) we have demonstrated that the copolymerization of an orthoester-protected 1,4-diethyl-2,3-dihydroxybenzene\(^{35}\) (see Scheme S1 in the SI for its synthesis) with a \(T_1\)-directing \(tetraakis(4-ethyl)methane monomer\(^{36}\) (see Scheme S2 in the SI for its synthesis) in different monomer ratios resulted in a family of porous polymers with tunable surface areas and pore size distributions. One member of this family (\(A_2B_1\), Scheme 1, \(R = \text{Carbon} \)) was then metallated with divalent metals that readily bind small molecules such as \(H_2\).\(^{21}\) For the degradation of large phosphate ester substrates, we hypothesized that using the larger \(T_1\)-
directing tetrakis(4-ethyl)adamantyl monomer to afford the corresponding La-functionalized catPOPs with close to a 1:1 catechol:metal stoichiometry. Although the nonmetallated POPs show a small difference in BET surface areas, LaA2C1 shows a surprisingly ~2.5-fold higher surface area over LaA2B1 (650 vs 265 m²/g) and a 3-fold higher methanol uptake at 0.80 \( P_{(\text{pore})}/P_{(\text{relative})} \) (Figure S18 in SI). Given that the pore diameters are similar for both materials, (Figures S14 and S15 in the SI, pore size distributions were calculated using nitrogen and argon measurements respectively) the larger surface area of LaA2C1 indicates its greater pore accessibility, which should make it a better catalyst for the solvolysis/hydrolysis of a phosphate triester. Although the BET-derived pore size distributions of these two materials are quite similar (Figures S14 and S15 in the SI), the la leaching differences can be explained if the local environments around the La(catecholate) moieties are different enough to cause instability. Supporting this speculation is the observation that the acac counterion is not visible in the solid-state IR of the metastable LaA2B1 and LaA2C1. (see Table 2). After Soxhlet extraction with THF, LaII content as determined by ICP-OES analysis of the product solutions leached from LaA2B1 during the reaction, in contrast to the negligible leaching in the case of LaA2C1 (Table 2). Although the BET-derived pore size distributions of these two materials are quite similar (Figures S14 and S15 in the SI), the leaching differences can be explained if the local environments around the La(catecholate) moieties are different enough to cause instability. Supporting this speculation is the observation that the acac counterion is not visible in the solid-state IR spectra of LaA2B1, but is observable in that for LaA2C1 (see section S13 in the SI).

The degree of LaII leaching was further corroborated by monitoring the catalytic activities of the solution phases in the methanolysis of PNPDMP by LaA2C1 and LaA2B1. After each reaction reached 30% conversions (~2 h for LaA2C1 and ~3 h
for La$_{A2}$B$_1$, the POP particles were removed by filtering and the PNPDMP concentrations in the solutions were further monitored. The background-corrected rate of methanolysis is ~1.7-fold higher in the filtrate for La$_{A2}$B$_1$ than that for La$_{A2}$C$_1$ (Figure S12 in the SI), which is consistent with the former containing a larger amount of leached La$^{III}$ ions. The activity in the filtrate is much less than that for an equivalent amount of La(acac)$_3$ (see section S6 in the SI), suggesting that the leached La$^{III}$ is a much less-active form than La(acac)$_3$ monomer.

Motivated by the promising catalytic activity of La$_{A2}$C$_1$, we examined its recyclability in the methanolysis of PNPDMP (Table 2). Surprisingly, the initial methanolysis rate drops significantly with each cycle, even though little leaching of La$^{III}$ is observed. This phenomenon can be attributed to a number of factors: (1) the substrate/products are retained in the pores during catalysis, thus blocking new substrate from entering; (2) the framework of the POP is degraded/relaxed, which inhibits substrate access to the catalytic sites; or (3) the encapsulated La(catecholate) moieties are degraded into less-active forms during catalysis.

To evaluate the possibility that substrate/products may be clogging the pores, La$_{A2}$C$_1$ was Soxhlet-extracted with THF for 24 h after the third cycle. Surprisingly, evaluation of the filtrate by UV–vis spectroscopy revealed a significant amount of “adsorbed” PNPDMP substrate (2.7 mg from 6.6 mg of isolated materials, or a 2.4 substrate:La molar ratio). While we cannot determine if the adsorbed substrate is bound to the oxophilic La$^{III}$ ion, its sequestration in the pores might be limiting transport between the pores and the external solution, thereby contributing to the reduction in catalytic activity. Unfortunately, the catalytic activity of the Soxhlet-extracted La$_{A2}$C$_1$ did not improve, as the initial rate for the “fourth” cycle was only 4× faster than that for the uncatalyzed reaction.

To evaluate factors 2 and 3, we “aged” La$_{A2}$C$_1$ in methanol at 60 °C and in the absence of PNPDMP for four days, and then remeasured its surface area by N$_2$ gas adsorption (see Section S8 in the SI). To our surprise, the BET surface area greatly decreased (650 m$^2$/g as-synthesized vs 180 m$^2$/g aged, Figure 3). However, conducting the same aging experiment on the nonmetallated POP A$_2$C$_1$ produced no significant change in surface area (1170 m$^2$/g as-synthesized vs 1080 m$^2$/g aged). This result led us to conclude that the degradation of supported La(catecholate) moieties into less-active forms must be an important contributor to the successive decrease in catalysis rate. Although we do not know the exact nature of the degradation products, it is conceivable that the La$^{III}$ ion could be cleaved from the catechol in the presence of MeOH to form less active species that are trapped in the micropores.

As both A$_2$C$_1$ and La$_{A2}$C$_1$ can take up a significant amount of water vapor (see Figure S19 in SI, section 14), we hypothesize that La$_{A2}$C$_1$ would be active in the hydrolysis of PNPDMP, which is a more practical route toward the destruction of nerve agents. Under pH 10 buffered conditions and in 30 vol % EtOH, which helps to solubilize the nerve agent simulant, the hydrolysis of PNPDMP in the presence of La$_{A2}$C$_1$ is 12 times faster than the uncatalyzed reaction (Figure 4). In contrast to the catalyzed methanolysis of PNPDMP, La$_{A2}$C$_1$ retains significantly more catalytic activity over three cycles of hydrolysis: the initial rate only drops 40% after the first cycle and remains the same for the second and third cycles, showing good recyclability (Table 3). Soxhlet extraction of the La$_{A2}$C$_1$ catalyst after each cycle revealed essentially no trapping of water vapor (see Figure S19 in SI, section 14), we hypothesize that La$_{A2}$C$_1$ would be active in the hydrolysis of PNPDMP, which is a more practical route toward the destruction of nerve agents.

<table>
<thead>
<tr>
<th>catalyst</th>
<th>cycle</th>
<th>observed rate (M s$^{-1}$)$^b$</th>
<th>La$^{III}$ leaching (%)$^c$</th>
<th>relative rate vs uncat reaction</th>
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<tr>
<td>La$_{A2}$B$_1$</td>
<td>1</td>
<td>$1.1 \times 10^{-6}$</td>
<td>0.1</td>
<td>12</td>
</tr>
<tr>
<td>La$_{A2}$C$_1$</td>
<td>1</td>
<td>$1.1 \times 10^{-6}$</td>
<td>0.1</td>
<td>12</td>
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<tr>
<td></td>
<td>2</td>
<td>$6.7 \times 10^{-7}$</td>
<td>0.1</td>
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<tr>
<td></td>
<td>3</td>
<td>$6.7 \times 10^{-7}$</td>
<td>0.2</td>
<td>7</td>
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</table>

$^a$Reaction conditions: PNPDMP (25 mM), [La$^{III}$] (1.5 mM, 6 mol %), 4-ethyl morpholine buffer solution (93 mM, 30 vol % EtOH, pH 10), 60 °C. $^b$Initial rates were measured up to 10% conversion and corrected against background reactions. $^c$Percentage of the initial metal loading.
of the substrate (see section S11 in the SI) and the amount of La leaching from La\textsubscript{A2}C\textsubscript{1} is again negligible. Together, these data suggest that under the basic buffered aqueous conditions, transport of the substrates through the cavities of La\textsubscript{A2}C\textsubscript{1} is more facile and the La\textsuperscript{III} sites are more stable against decomposition. The basic aqueous environment of the solution must have preferentially solubilized both the substrate and the acidic hydrolyzed products, keeping them from clogging the pores. Interestingly, PNPDMP hydrolysis by acidic hydrolyzed products, keeping them from clogging the must have preferentially solubilized both the substrate and the decomposition. The basic aqueous environment of the solution with La\textsuperscript{III} ions to a transport of the substrates through the cavities of La\textsubscript{A2}C\textsubscript{1}.

4. SUMMARY AND CONCLUSIONS

In summary, two robust catechol-functionalized POPs with different \( T_2 \)-directing nodes can be synthesized and metallated with La\textsuperscript{III} ions to afford catalytically active materials for the solvolytic and hydrolytic degradation of toxic organophosphates. Most notably, POP La\textsubscript{A2}C\textsubscript{1}, with its higher accessible surface area, has significantly enhanced rates in the methanolytic decomposition of PNPDMP relative to the carbon-noded POP La\textsubscript{A2}B\textsubscript{1}. Presumably, the higher specific surface area of the former increases its pore accessibility to the substrates and thus increases reaction rates. While there is minimal leaching of La\textsuperscript{III} ions from the pores of POP La\textsubscript{A2}C\textsubscript{1}, La(catecholate) degradation appears to be more significant in methanol; the significant decrease in methanolysis rate of La\textsubscript{A2}C\textsubscript{1} after each recycling experiment can, in part, be attributed to this problem. In addition, the choice of reaction media is an important consideration in the decomposition of PNPDMP; when the external medium does not solvate this substrate and its products well, preferential sequestration of PNPDMP: when the external medium does not solvate this media is an important consideration in the decomposition of.

ACKNOWLEDGMENTS

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REFERENCES

(25) We note that Cohen and coworkers have incorporated protected-catechol struts into a derivative of UMCMI-1 de novo, removed the protecting groups, and then metallated the free catechol groups with Fe(II). However, the metallated MOF was not demonstrated for catalytic capability. See: Tanabe, K. K.; Allen, C. A.; Cohen, S. M. Angew. Chem., Int. Ed. 2010, 49, 9730–9733.


(35) This compound was synthesized from commercially available 1,2-dimethoxybenzene (6 steps, 24% overall yield).

(36) This compound was synthesized from commercially available tetraphenylmethane (3 steps, 41% overall yield).

(37) This compound was synthesized from commercially available 1-bromoadamantane (4 steps, 50% overall yield).

