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Polynuclear alkoxy–zinc complexes of bowl-shaped macrocycles and their use in the copolymerisation of cyclohexene oxide and CO₂†

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The reactions between alcohols and the tetranuclear ethyl–Zn complexes of an ortho-phenylene-bridged polypyrrole macrocycle, Zn₄Et₄(L¹)₁ and the related anthracenyl-bridged macrocyclic complex, Zn₄Et₄(THF)₄(L²)₂ have been studied. With long-chain alcohols such as n-hexanol, the clean formation of the tetranuclear hexoxide complex Zn₄(OC₆H₁₃)₄(L¹)₃ occurs. In contrast, the use of shorter-chain alcohols such as i-propanol results in the trinuclear complex Zn₃(μ₂-OiPr)₂(μ₃-OiPr)(HL¹)₄ that arises from demetalation; this complex was characterised by X-ray crystallography. The clean formation of these polynuclear zinc clusters allowed a study of their use as catalysts in the ring-opening copolymerisation (ROCP) reaction between cyclohexene oxide and CO₂. In situ reactions involving the pre-catalyst 1 and n-hexanol formed the desired polymer with the best selectivity for polycarbonate (90%) at 30 atm CO₂, whilst the activity and performance of pre-catalyst 2 was poor in comparison.

Introduction

Multidentate macrocycles are attractive as ligands for di- and polynuclear complexes of transition- and f-block metals as they can control both the basic coordination chemistry and the relative spatial positioning of metals within the macrocyclic framework, so providing a pre-organised chemical environment.1–4 This ligand design strategy can deliver a diversity of physical and reaction properties in the resulting complexes leading to, for example, clustering and aggregation,5–14 catalytic activity,15–28 molecular magnetism,29 allosteric constructs,30,31 and molecular sensing.32–35

We have been studying macrocycles in which two donor compartments comprising two dipyrromethane and two Schiﬀ-base nitrogen donors (i.e. an N₄-donor set) are separated by rigid aryl backbones (e.g. L¹ and L², Fig. 1).36,37 On metalla- tion, the resulting dinuclear complexes adopt Pac-Man structures (e.g. A, Fig. 1) that promote a diversity of chemistry within the dinuclear molecular cleft, including dioxygen reduction catalysis,38–41 halide sensing,42 and uranyl reduction and oxo-group functionalisation.43–50 We have also exploited a steric variation of the meso-substituent (H instead of alkyl, L¹ and L², Fig. 1) which results in the adoption of bowl-shaped structures on metalla- tion, hinging at the meso-carbon instead of the aryl groups.51 Importantly, using this latter ligand variant allows for the isolation of higher nuclearity complexes such as the tetranuclear zinc alkyl macrocyclic complexes 1 and 2.

Fig. 1 Schiﬀ-base pyrrole macrocycles with varying meso-substituents and aryl linkers and the formation of generic dinuclear complexes of Pac-Man structures.
and 2 (Scheme 1); these complexes undergo subsequent protonolysis reactions with water to form tetranuclear Zn-oxo and hydroxo clusters.\(^2\)

The straightforward syntheses of 1 and 2, and their facile hydrolysis, provides an opportunity to study the ring opening copolymerisation (ROCOP) of carbon dioxide and epoxides to produce aliphatic polycarbonates.\(^5\) ROCOP catalysts are often isolated Lewis-acidic metal–alkoxide complexes or are pre-catalysts that are activated by alcohols to form metal alkoxides in situ.\(^7\) Furthermore, homogeneous zinc catalysts are attractive for ROCOP as the metal is redox inert and sustainable.\(^8\) Zinc clusters formed by alcoholysis/hydrolysis of organo-zinc species act as ROCOP catalysts but have very slow rates.\(^9\) Highly active zinc β-diketiminate (BDI) catalysts were reported,\(^7\) with the best forming dimers under the polymerisation conditions.\(^2\) Dinuclear zinc macrocyclic complexes are also highly active and operate under low pressures of carbon dioxide.\(^5\) While higher nuclearity zinc catalysts have been reported, it is not yet understood if dinuclear catalysts are optimum.\(^9\) As such, we reasoned that the tetra-nuclear alkyl–zinc macrocyclic complexes 1 and 2 could be activated by alcoholysis and that the resulting zinc alkoxide complexes could act as catalysts for ROCOP of CO\(_2\) and epoxides.

Results and discussion

Multinuclear Zn\(^{II}\) complexes considered for ROCOP catalysis

The two tetranuclear Zn–alkyl complexes [Zn\(_4\)Et\(_2\)](L), where L is either the ortho-phenylene-bridged macrocycle \(L_1\) (1) or the anthracenyl-bridged macrocycle \(L_2\) (2), were prepared as previously described (Scheme 1).\(^2\) These complexes are inert towards insertion of CO\(_2\), but undergo protonolysis reactions with four equivalents of \(n\)-hexanol to generate Zn–alkoxide complexes. Specifically, the alkoxide complex, [Zn\(_4\)[\(\mu^5\)-OC\(_6\)H\(_{13}\)]\(_4\)](L\(_1\)) \((3)\) was isolated, in 84% yield, from the reaction of 1 with four equivalents of \(n\)-hexanol in THF (Scheme 1). The reaction proceeds immediately as evident from the ethane gas evolution observed. The \(^1\)H NMR spectrum of 3 implies that it is fully symmetric with a single set of resonances for the macrocycle that are shifted in comparison with 1 (Fig. S1†); in C\(_6\)D\(_6\), the imine protons appear as a single resonance at 8.07 ppm, and the meso-protons appear at 6.38 ppm. Importantly, the ethyl resonances, that appear at 1.32 and 0.42 ppm for 1 in C\(_6\)D\(_6\), are absent from the spectrum of 3. Instead, there are a number of overlapping resonances between 1.89 and 0.57 ppm assigned to the new hexyl alkoxide ligands. Two triplet resonances, at 3.83 and 3.70 ppm, each showing integral values consistent with four protons are assigned to the methylene groups adjacent to the Zn–O bond. The distinct chemical shifts indicate that the alkoxide ligands bridge between two metals, with two alkoxides bridging between imine-donors and the other two bridging between pyrrole donors; the structurally characterised and analogous Zn–hydroxide complex, [Zn\(_4\)[\(\mu^5\)-OH]\(_4\)](L\(_1\)), also displayed similarly equivalent macrocycle resonances yet two distinct hydroxide environments.\(^5\) Furthermore, the \(^19\)F NMR resonance for the ortho-F groups is severely broadened due to restricted rotation of that group; such broadening is typically observed for bowl-shaped tetranuclear complexes.\(^5\) As such, the NMR data support the protonolysis of 1 to form 3 which is a bowl-shaped, tetranuclear Zn–(μ-alkoxide) complex.

Protonolysis reactions between 1 and alcohols other than \(n\)-hexanol are not straightforward. The reaction of 1 with isopropanol occurs readily, evolving gas from the THF solution, to yield the new trinuclear complex, [Zn\(_3\)(μ-OPr)][Zn\(_3\)(μ-OPr)](HL\(_1\)) \((4)\), Scheme 1). The \(^1\)H NMR spectrum of 4 in d\(_8\)-THF at 300 K shows a number of broad resonances consistent with the formation of a symmetric product and with the successful loss of the ethyl groups from 1 (Fig. S3†). The broad NMR resonances suggests the complex has a fluxional solution structure and so a VT-NMR study was undertaken. At 213 K, the spectrum is sharper and consistent with an asymmetric macrocyclic ligand environment, with each of the four inequivalent imine proton resonances showing signals at 8.86, 8.68, 8.48 and 8.40 ppm (Fig. S4†). Notably, a resonance at 11.98 ppm is only observable at this temperature and is assigned to a single pyrrole N–H proton. In addition, only three iso-propoxy ligands are seen, with the ipso-protons appearing as a single, broad resonance centred at 4.29 ppm, and the six individual methyl groups well resolved between 1.45 and 0.66 ppm. At 330 K, broad, thermally averaged resonances are seen, with the imine protons appearing as a single resonance at 8.36 ppm, whilst the three iso-propoxide ipso-protons resonate at 4.11 ppm; the associated methyl protons, with integral values of 18 protons per macrocycle, show a signal at 1.02 ppm.

Large, red, block crystals of 4 were grown from a benzene solution and the solid-state structure was determined by X-ray crystallography. Complex 4 is a trinuclear complex (Fig. 2) and adopts a highly distorted bowl-structure with a bite-angle of 102° between the two N\(_3\)-donor compartments of the macrocycle. This bite-angle is small in comparison with other bowl-
shaped complexes of the same ligand, for example, its Cu
analogue (Cu3(τ-py)3(L3)), 152°.51 This small bite-angle is attributed to coordination of the ligand to an L-shaped, trinuclear Zn-iso-propoxide cluster, which resembles a cubane in which two vertices are removed.94-96 In this cluster, the Zn centres are bridged by two μ3-alkoxide ligands (O2 and O3) and one μ1-alkoxide ligand (O1). Each Zn centre is four-coordinate with highly distorted tetrahedral coordination geometries, with bond angles ranging from 81.58(8)° to 143.47(9)°; in order to accommodate this cluster an imine group (N5) from one of the imino-pyrrole chelates is non-coordinating. The inter-metallic bond lengths that describe the edges of the cluster are regular 3.0071(5) Å (Zn1–Zn3) and 2.8213(6) Å (Zn2–Zn3). The Zn–O bond lengths that describe the edges of the cluster are regular and are in the range 1.920(2) Å to 2.143(2) Å. However, the cluster is distorted, with inequivalent bond angles in the hinge, of 121.4(1)° [Zn2–O1–Zn1] and 111.21(8)° [O3–Zn3–O2].

The reaction between 1 and four equivalents of phenol occurs readily and results in the formation of a complex that displays a similar 1H NMR spectrum to that of 4 (Fig. S5†). A single N–H proton resonance is seen at 11.76 ppm (at 300 K) which indicates that a similar demetallation reaction has occurred to form [Zn2(OPh)2(HL3)]. In an attempt to introduce a kinetic barrier towards demetallation, the reaction between 1 and 2,6-di-tert-butyl-phenol was investigated. No reaction is seen at room temperature, with the 1H NMR spectrum of 1 unchanged in the presence of the di-substituted phenol. However, after heating at 90 °C for 24 h, the 1H NMR spectrum shows that while partial protonolysis had occurred, no N–H proton is seen, consistent with the reaction avoiding demetallation side-processes (Fig. S6†). Nonetheless, the triplet resonance at 6.91 ppm, assigned to the para-proton of phenoxide co-ligands, shows an integral value consistent with there being only two phenoxides per macrocycle. There is also a quartet at 0.55 ppm and its integral is consistent with there being two ethyl ligands per macrocycle. Thus, the product is the tetranuclear complex [Zn4(OE6H3–Bu2–2,6)i(OEt2L3)]. Although zinc-phenoxide complexes are able to initiate ROCOP,97 this heteroleptic complex was not investigated further as the mixture of co-ligands would likely complicate initiation processes. Overall, the attempted protonolysis reactions resulted in only 3 as an isolated catalyst suitable for the ROCOP and only n-hexanol was considered as an acceptable alcohol for the in situ generation of catalytic systems using 1 and 2.

Demetalation of a tetranuclear Zn-iso-propoxide complex, that presumably forms initially, would yield one equivalent of Zn(OiPr)2 per equivalent of 4. The relative instability of the tetranuclear zinc complex suggests that combining 1 or 2 with iso-propanol will not be an effective initiating system as the desired multinuclear zinc alkoxide complex will be contaminated by the homoletic zinc alkoxide. Indeed, homoletic zinc alkoxide complexes are known to catalyse the formation of ether linkages in ROCOP reactions.98 Demetalation was not observed during the reaction of 1 with n-hexanol, which may be a result of the longer-chain alkoxide ligands imparting kinetic stability. The pKₐ for n-hexanol is predicted at 16.6 in water99 and is essentially identical to that of iso-propanol (pKₐ = 16.5 in water).100 Therefore, whilst demetalation occurs through protonolysis of the Zn–pyrrole bond, the formation of 4 is not attributed to a difference in acidity of the alcohol.

Polymerisation catalysis
Ring-opening copolymerisation reactions were conducted using complex 1 reacted in situ with four equivalents of n-hexanol, with a catalyst loading of 0.1 mol%, in neat cyclo-hexene oxide (CHO), under 1 bar pressure of CO₂, at 80 °C for 24 h (Table 1, entry 1). Four equivalents of the alcohol (0.4 mol%) were added immediately before the mixture was exposed to carbon dioxide. The catalytic activity was low, with a TOF of 9 h⁻¹. The polymer formed has a low molar mass (Mₙ = 4400 g mol⁻¹) and broad dispersity (D = 1.67). Analysis of the polymer composition using 1H NMR spectroscopy showed that the majority of linkages are ether, with only 7% carbonate linkages. Complex 1 was also tested, under 1 bar CO₂, using four equivalents of methanol as the alcohol (Table 1, entry 2). By analogy to the stoichiometric reactions with iso-propanol, it was proposed that a trinuclear Zn–methoxide complex would form and this species shows a low catalytic activity (TOF = 13 h⁻¹). The resulting poly(ether-carbonate) shows a high proportion of ether linkages, moderate molar mass (Mₙ = 15 300 g mol⁻¹) and broad dispersity (D = 2.69), the latter indicative of slow or multiple initiation reactions.

In order to increase the proportion of carbonate linkages for the catalyst system comprising 1/n-hexanol, the CO₂ pressure was increased (Table 1, entries 3 and 4, Fig. S8†). Using 30 bar pressure of CO₂, both the activity (TOF = 21 h⁻¹) and the selectivity for carbonate linkages increased (carbonate linkages = 56%). In line with the greater conversion, the resulting polymer shows a higher molar mass (Mₙ = 18 100 g mol⁻¹) but the dispersity remains very broad (D = 3.03). When the reaction pressure is increased further to 50 bar, the catalyst activity, conversion of epoxide, and carbonate selectivity all decrease. This may be a result of gas expansion which is known to occur under such sub-critical conditions and which effectively dilutes the catalyst concentrations.101
As part of attempts to improve the polymerisation selectivity, polymerisations were conducted in toluene solutions to reduce the overall epoxide concentration and hence slow sequential enchainment reactions (Table 1, entries 5, 6, Fig. S9f). Overall, the absolute catalyst concentration was the same as in the previous reactions conducted in neat epoxide but its relative loading compared to epoxide is increased. Polymerisations conducted in toluene solution at 1 bar CO2 pressure were unsuccessful (Table 1, entry 6), but at 30 bar pressure polymerisation occurs to form a polymer with significantly increased carbonate linkages (Table 1, entry 5). However, the ROCOP activity is reduced compared to reactions in neat epoxide, for example the TOF decreased from 21 h−1 (10 M) to 15 h−1 (5 M) (Table 1, entries 3 and 5). The polymerisation control is very poor forming a polymer with an exceptionally broad dispersity (Mn = 11 000 g mol−1; D = 14). To investigate further, the evolution of polycarbonate molar mass vs. conversion was analysed (Table S1, Fig. S11f). At low conversions, bimodal molar mass distributions are seen showing a characteristic very high molar mass peak ([Mn] = 194 000 g mol−1; D = 1.89) and a lower molar mass peak (Mn = 2400; D = 3.00). The higher molar mass peak did not increase particularly as polymerisation progressed whereas the lower peak shows a clear increase in molar mass vs. conversion. Aliquots were taken and the 1H NMR spectra show the formation of both carbonate and ether linkages throughout the reaction. It is tentatively proposed that the higher molar mass peak is due to uncontrolled and rapid formation of polyether, whilst the lower molar mass peak arises from ROCOP to form predominantly polycarbonate. Nonetheless, a more detailed analysis is precluded by the very broad molar mass distributions that clearly signal problems with relative initiation rates and number of active sites.

Polymerisations were also conducted under a range of similar conditions using the catalyst system formed from 2 (Table 1, entries 7–9). Under all conditions, its activity is very low, although the carbonate selectivity could be somewhat increased at higher pressures. The isolated hexyl alkoxide complex 3 shows similar performance to the catalyst system formed using 1 and n-hexanol, and is consistent with 3 being the true initiating species formed during alcoholysis of 1. The polycarbonate product, formed using 3, shows a similar molecular weight (Mn = 7400 g mol−1) and very broad dispersity (D > 13) to that formed using the catalyst system of 1/hexyl alcohol. Finally, ROCOP reactions using propylene oxide and carbon dioxide (50 bar) were unsuccessful with all catalysts. Overall, the activity values for all catalysts are at the lower end in this field and cannot compete with leading catalysts, such as the di-zinc carboxylates coordinated by β-diketiminate or macrocyclic ancillary ligands.77–88

Conclusions

The result of reactions between the tetrannuclear ethyl zinc complex 1 and alcohols is highly dependent on the alcohol used. While reaction with n-hexanol provides the isolable tetranuclear Zn hexyl-alkoxide complex 3, use of isopropanol results in demetallation and the formation of the trinuclear Zn complex 4. Reactions between 1 and phenol similarly result in demetallation, while the use of the more sterically hindered alcohol HOCH2H2(−Bu)-2,6 maintains the nuclearity of the complex but limits the protonolysis reaction, with two ethyl groups untouched. Complex 1 showed some activity and selectivity as a catalyst in ring-opening copolymerisation of cyclohexene oxide and carbon dioxide, with optimised conditions of 30 atm pressure of CO2, 0.1 mol% catalyst loading, 80 °C and in 5 M cyclohexene oxide (diluted in toluene). These conditions enabled the production of polycarbonates with 90% selectivity for carbonate linkages and with a TOF of 15 h−1. However, the polymers produced have very broad molar mass distributions suggesting that multiple catalytic
sites are present which exhibit poor reaction control. The analogous anthracenyl-bridged complex 2 showed even lower activity and a similar lack of polymerisation control. While higher nuclearity macrocyclic zinc complexes have potential as catalysts in ROCOP reactions, the complexes used in this study appear too labile, with facile demetalation occurring under reaction conditions, making them unsuitable as catalysts. This highlights the need for improved ligand design and complex stability towards alcohols to prepare more active and selective catalysts for ROCOP reactions.

Conflicts of interest
There are no conflicts to declare.

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