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Modulating the Activity and Selectivity of an Immobilized Ruthenium-Porphyrin Catalyst using a Fluorous Solvent

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Abstract: A ruthenium porphyrin catalyst with styrene side chains was incorporated into a highly cross-linked polymer by co-polymerization with ethylene glycol dimethacrylate in the presence of a chloroform porogen. Oxidation reactions catalyzed by the resulting polymer were accelerated when perfluoromethylcyclohexane (PFMC) was used as a co-solvent. Moreover, the PFMC co-solvent was found to change the substrate selectivity of the catalytic reactions. Both effects could be explained by a PFMC-induced partitioning of substrates and oxidant into the polymeric, catalyst containing matrix.

Keywords: fluorous solvent; immobilization; oxidation; polymers; porphyrin; ruthenium

Introduction

Macroporous, highly cross-linked organic polymers are increasingly being used as supports for immobilized transition metal catalysts.[1] These materials display a number of favorable characteristics. First of all, they typically show a high surface area (50–500 $m^2 g^{-1}$) and a distribution of pores[2] that ensure efficient access to catalysts within the polymer. Catalytic transformations are thus not restricted to sites on the exterior surface of the polymer particle. Secondly, the high content of cross-links results in a permanent pore structure, which allows the use of polar[3] *and* non-polar solvents for catalysis. This is in contrast to lightly cross-linked supports such as Merrifield resins, for which swelling is necessary for access to the interior volume.[4] Finally, highly cross-linked organic polymers are amenable to molecular imprinting. In the case of immobilized metal catalysts, this technique can be used to modulate the microenvironment and thus the activity and selectivity of the catalyst in a controlled fashion.[5,6]

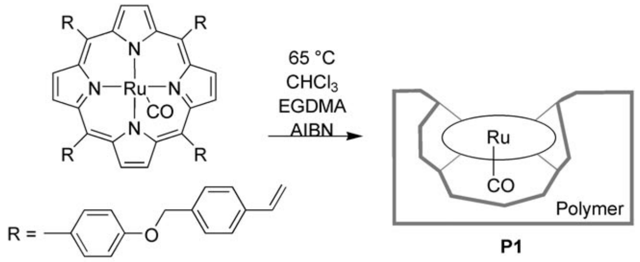
An interesting feature of highly cross-linked poly(acrylates) is their ability to act as potent sorbents for polar organic compounds dissolved in fluorinated solvents. For example, when a homopolymer of ethylene glycol dimethacrylate (EGDMA) was suspended in a solution of 9-anthracenemethanol in perfluoromethylcyclohexane (PFMC):hexane (1:1), a strong partitioning of the alcohol into the polymer was observed and quantified.[7] For less polar substances such as anthracene, the partitioning was lower indicating that fluorophobic effects are the likely cause. Permanently porous networks are uniquely effective in this context since poor solvents collapse lightly cross-linked materials into impenetrable gels.

The consequences of a strong partitioning of some analytes into poly-EGDMA is a high local concentration within the pores of the polymer. This leads to the intriguing possibility that the activity of a catalyst embedded in such a support may be enhanced by a favorable substrate concentration gradient when fluorinated solvents are employed.[8] First results with an immobilized rhodium(I) catalyst suggested that this was indeed possible; the rates for a hydrogenation reaction were found to increase with the fluorous content of the solvent.[9,10] In the following we provide evidence that such rate enhancements are likely to be a more general phenomena for catalysts immobilized in highly cross-linked polymers.[11] Oxidation reactions catalyzed by a poly-EGDMA-supported ruthenium complex are shown to be faster in PFMC-containing solvents. Furthermore, it is demonstrated that differential partitioning propensities of various substrates can predictively influence the substrate selectivity of the reactions.

Results and Discussion

Recently, we have shown that the co-polymerization of vinyl-substituted ruthenium porphyrin complexes with a large excess of EGDMA can be used to generate potent heterogeneous catalysts.[6a,12] For the oxidation of alcohols and alkanes by 2,6-dichloropyridine *N*-oxide (Cl_2pyNO), these catalysts were found to be significantly more active than the corresponding homogeneous catalysts. A likely explanation for this enhanced activity is the site-isolation of the catalyst within the highly cross-linked polymeric support. Due to the low concentration of the porphyrin complex in the polymer (0.25 mol% with respect to the cross-linking monomer), destructive self-oxidation reactions as observed for homogeneous catalysts[13] are prohibited.

In a continuation of these studies, we have investigated whether fluorous solvent-induced partitioning effects can be used to modulate the activity and selectivity of such catalysts. For this purpose, we prepared the polymeric catalyst **P1** by AIBN initiated co-polymerization of complex **1**[6a] with EGDMA ([**1**]:[EGDMA]=1:400) in the presence of chloroform as the porogen (Scheme 1). The resulting dark-red polymer **P1** was ground in a mortar, washed extensively with acetone and finally dried in vacuum. The nearly colorless washing solutions indicated a quantitative incorporation of the metallomonomer **1** in the polymeric EGDMA matrix. From N_2 adsorption isotherms, a Brunauer–Emmett–Teller (BET) surface area for **P1** of 409 $m^2 g^{-1}$ and an average pore size of 54 Å were determined.



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P1

Scheme 1. Synthesis of the polymeric catalyst **P1** by co-polymerization of complex **1** with EGDMA.

To investigate the influence of a fluorous solvent on the catalytic activity of polymer **P1**, we followed the time course of the oxidation of 1-indanol using 1 mol% Ru and Cl_2pyNO as the oxidant. The amount of polymer that was required was calculated based on the assumption that the metallomonomer **1** was incorporated quantitatively. A mixture of benzene and hexane with various amounts of PFMC (0, 10, 20 and 40%) was employed as the solvent. At the reaction temperature of 55°C, all solvent mixtures form a monophasic system. The conversion for the first 1.25 h of these reactions is depicted in Figure 1. A pronounced increase in catalytic activity was observed upon increasing the concentration of PFMC. After 1.25 h, the conversions for reactions with 0 and 40% PFMC differed by a factor of 10.5. A short induction period was evident from the time course of the reactions. This could be explained by noting that the immobilized Ru(CO) complex is only a catalyst precursor, from which the catalytically active Ru=O species must be generated.[14]

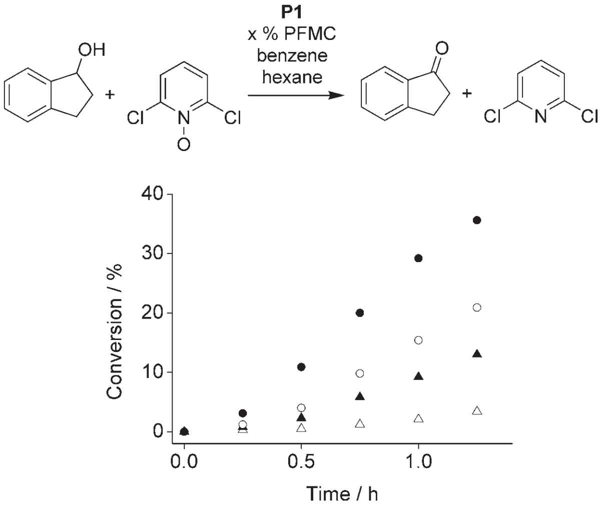

Figure 1. Oxidation of 1-indanol by Cl_2pyNO with the polymeric catalyst **P1** in solvents containing various amounts of PFMC (△: 0%; ▲: 10%; ○: 20%; ●: 40%). The reactions were performed in mixtures of benzene, hexane and PFMC at 55°C with a substrate/Cl_2pyNO/catalyst molar ratio of 100:100:1. The data points represent averaged values from two independent experiments.

A priori, the observed rate enhancements could be due to a PFMC-induced partitioning of the alcohol and/or the *N*-oxide into the polymeric matrix. To gain further insight, we performed oxidation reactions with different starting concentrations of *N*-oxide or 1-indanol. These experiments showed that the reactions are approximately first order with respect to the *N*-oxide and zero order with respect to indanol. The increased rates can therefore be explained by an increased local concentration of the oxidant, a partitioning of the alcohol is thus not expected to accelerate the reaction. Although control experiments with the homogeneous catalyst **1** were not possible due to catalyst precipitation in PFMC-containing solvent mixtures,[15] the data suggest that the ~10-fold increase in rate on going from 0 to 40% PFMC results from a fluorophobic induced ~10-fold increase in the local concentration of the oxidant.

Next, we investigated the oxidation of indane in a mixture of benzene/hexane containing 0 and 40% PFMC. This reaction proceeded in a two-step fashion to give first indanol, which could be further oxidized to indanone. At the beginning of the reaction, both products were present in comparable amounts. Interesting differences, however, were found for the relative amounts of these products for the two reaction conditions. At a total conversion of ~5%, indanol was the dominant reaction product in reactions performed in benzene/hexane. On the other hand, when the solvent contained 40% PFMC, it was indanone that was dominant (Figure 2). These results are explainable by the higher partition efficiency of the polar indanol as compared to indane. Since the product determining step (not turnover limiting) involves a direct competition between catalyst and indane or indanol, the relative concentration of these substrates will directly influence the selectivity, even though the overall reaction is zero order in substrate. In the 40% PFMC case, the local concentration of the more polar indanol in the catalyst phase is higher, which leads to a more favorable reaction cross-section. The inversion in product distribution is therefore a direct consequence of their polarity differences rather than their inherent chemical reactivities.

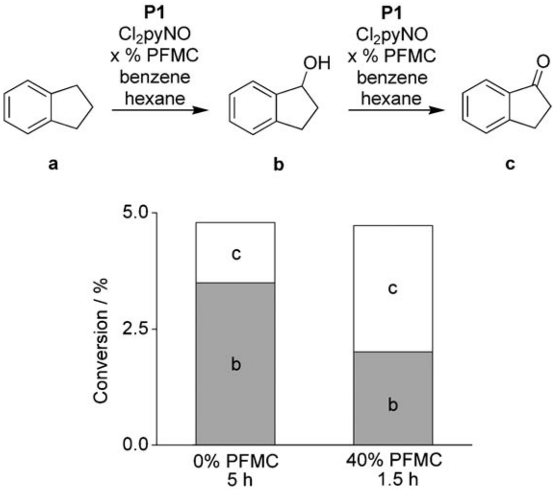

Figure 2. Oxidation of indane by Cl_2pyNO with the polymeric catalyst **P1** in solvents containing 0% or 40% of PFMC. The reactions were performed in mixtures of benzene, hexane and PFMC at 55°C with a substrate/Cl_2pyNO/catalyst molar ratio of 100:200:1. The data represent averaged values from two independent experiments.

We have additionally investigated this effect in the oxidation of three substrate mixtures with variable differences in polarity. In all cases, equimolar amounts of two secondary alcohols were oxidized to the corresponding ketones using again solvent mixtures of benzene/hexane containing 0 and 40% PFMC. The results are summarized in Figure 3.

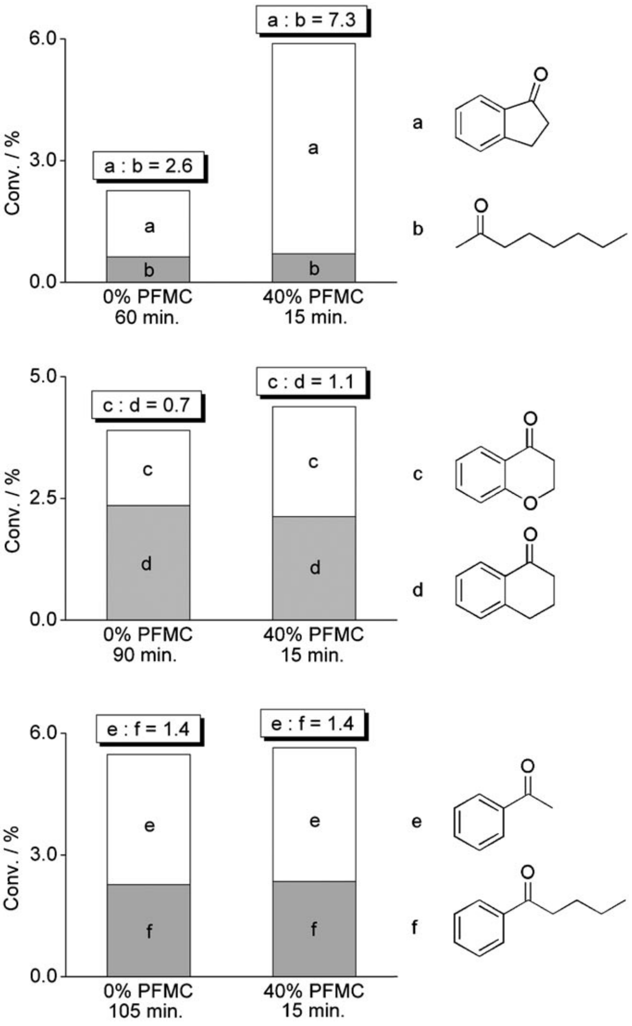

Figure 3. Simultaneous oxidation of two different secondary alcohols by Cl_2pyNO with the polymeric catalyst **P1** in solvents containing 0% or 40% of PFMC. The yields and the ratios of the ketone products are given. The reactions were performed in mixtures of benzene, hexane and PFMC at 55°C with a substrate/substrate/Cl_2pyNO/catalyst molar ratio of 100:100:100:1. The data points represent averaged values from two independent experiments.

In reactions with the substrates 1-indanol and 2-octanol, we observed a strong preference for the oxidation of indanol when PFMC was used as the co-solvent. At 15 and 60 min, respectively, 2-octanone was formed in approximately equal amounts. For reactions with PFMC, however, more than twice as much indanone was formed when compared to the reaction performed in benzene/hexane. This finding is in agreement with the observation that non-aromatic hydrocarbons of low polarity have a small partitioning efficiency.[7] A similar but less pronounced trend was observed for reactions with 1-tetralol and 4-chromanol. In the presence of PFMC, the selectivity for the more polar chromanol increased. No differences in selectivity were observed for 2-phenylethanol and 2-phenylpentanol, two substrates of rather similar overall polarity.

Conclusions

We have shown that oxidation reactions catalyzed by the immobilized ruthenium porphyrin catalyst **P1** are significantly accelerated in the presence of the fluorinated solvent PFMC. This rate acceleration is explained by invoking a consequently heightened local concentration of the Cl_2pyNO oxidant, which is an integral component in the turnover-limiting step (rate $\propto$ [Cl_2pyNO]). Additionally, it is demonstrated that this change in solvent also affects the substrate selectivity of the catalytic reaction. The rate enhancements and change in selectivity are taken as evidence supporting the notion that fluorous solvent-induced partitioning effects can strongly influence reactions with catalysts that are immobilized in highly cross-linked organic polymers. The fact that heterogeneous catalysts of this kind not only tolerate fluorinated solvents but may actually function better in such solvents is a finding that may be of interest for various applications involving fluorous solvents.[16]

Experimental Section

General Remarks

The syntheses of complex **1** and polymer **P1** were performed as described in ref.[6a] The BET measurements were carried out by QUANTACHROME GmbH, Odelzhausen, on a QUANTACHROME AUTOSORB-3 instrument. The adsorption measurements were performed with N_2 at a sample temperature of $-196\,°C$. Prior to the measurements, the samples were dried under vacuum at 100 °C for 2 h. The average pore diameter was calculated form the pore volume and the BET surface area using assuming a cylindrical pore model. The GC analyses were performed with a Varian 3800 spectrometer using a CP-Sil 8 CB column (30 m).

Catalytic Oxidations

The substrate ($6.25 \cdot 10^{-3}$ mmol) was added to a suspension of the polymer **P1** (10.0 mg, $6.25 \cdot 10^{-5}$ mmol Ru) in different solvent mixtures (A: 4.90 mL benzene, 0% PFMC; B: 2.90 mL benzene + 1.50 mL hexane + 0.50 mL PFMC = 10% PFMC; C: 2.40 mL benzene + 1.50 mL hexane + 1.00 mL PFMC = 20% PFMC; D: 1.40 mL benzene + 1.50 mL hexane + 2.00 mL PFMC = 40% PFMC). The mixture was placed in an oil bath and tempered at 55 °C for 30 min. The reaction was then started by addition of 100 μL of a stock solution containing Cl_2pyNO (51.2 mg, $3.12 \cdot 10^{-1}$ mmol) in benzene (5.0 mL). Samples (100 μL) were removed at regular intervals, filtered and poured in vials containing 1 mL of diethyl ether (in order to obtain a monophasic solution) and analyzed by GC. For the competition experiments, two substrates were added at the same time ($6.25 \cdot 10^{-3}$ mmol each).

Determination of the Reaction Order

To determine the reaction order of the oxidation of 1-indanol by Cl_2pyNO in the presence of 40% PFMC, a series of reactions with constant concentrations of Cl_2pyNO (12.5 mM) and catalyst (25 μM), but varying concentrations of 1-indanol (2.50 to 6.25 mM) was performed. The initial rates of the reactions as a function of the 1-indanol concentration were found to be constant (TOF = $139 \pm 3\ h^{-1}$; calculated from the yield after 20 min). This indicates a zero-order dependence with respect to the substrate. In addition, a series of reactions with constant substrate (1.25 mM) and catalyst (12.5 μM) concentrations but varying Cl_2pyNO concentrations (625 μM to 2.50 mM) was carried out. A first order dependence of the initial rates as a function of the Cl_2pyNO concentration was observed.

Acknowledgements

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