

Markedly enhanced recyclability of osmium catalyst in asymmetric dihydroxylation reactions by using macroporous resins bearing both residual vinyl groups and quaternary ammonium moieties†

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Markedly enhanced recyclability of osmium catalyst in asymmetric dihydroxylation has been achieved by using osmylated macroporous resins bearing both residual vinyl groups and quaternary ammonium moiety.

Os-Catalysed asymmetric dihydroxylation (AD) of olefins is undoubtedly one of the most efficient synthetic methods for chiral vicinal diols, which could be key intermediates in the synthesis of chiral drugs, natural products and fine chemicals, *etc.*¹ However, the high cost of the catalysts (osmium and the cinchona alkaloid ligands) as well as the high toxicity and volatility of the osmium component have made their large-scale industrial applications difficult. To overcome this drawback, much effort has been devoted to the development of effective immobilization of the osmium component. Early attempts to immobilize OsO₄ on solid-supported alkaloid ligands failed due to severe osmium leaching.² Recently, Kobayashi *et al.* reported that microencapsulated OsO₄ in a polymer matrix can be used as a recyclable osmium catalyst.³ However, high loading (5 mol%) of osmium was required in a typical dihydroxylation reaction. Very recently, another approach to immobilise K₂OsO₄·2H₂O has been achieved by using an ion-exchange technique on solid supports bearing quaternary ammonium moieties (Fig. 1).⁴ In terms of catalyst recycling, these immobilization techniques seem successful, however, turn over number (TON) is much lower compared to that of the homogeneous AD reactions. In homogeneous cases, 0.2 mol% of osmium is enough to complete most of the reactions. We recently reported that OsO₄ could be simply immobilised by osmylation onto resins bearing residual vinyl groups such as Amberlite XAD-4 or XAD-7 (Fig. 1).⁵ These air-stable and non-volatile osmylated

resins exhibited excellent catalytic activity in the asymmetric dihydroxylation of olefins, and could be recycled. Even when only 0.2 mol% of osmium was used, the resins could be reused three times. Unfortunately, leaching of OsO₄ into solution has been found upon reuse. Thus, there is still a demand driven by economic and environmental considerations, to develop more efficient immobilization methods for recovery and reuse of osmium catalyst.

In this communication we report that use of macroporous resins bearing both residual vinyl groups and quaternary ammonium moieties provides a simple and highly practical approach to the recycling of osmium catalyst. As depicted in Scheme 1, the resins possessing both residual vinyl groups and ammonium moiety might immobilize osmium tetroxide as well as osmate ion dissolved in solution and, thus, enhance the recyclability of osmium catalyst in asymmetric dihydroxylation.

The osmium complex of the resin bearing both residual vinyl groups and quaternary ammonium moieties (abbreviated as *VinylAmm* resin) was prepared by the suspension polymerisation of divinylbenzene and 4-vinylbenzyl chloride at an 80:20 ratio, followed by a reaction of the resulting the macroporous copolymer **1** (0.91 mmol Cl per g) with triethylamine yielding the *VinylAmm* resin (0.50 mmol N per g) and the subsequent osmylation of the *VinylAmm* resin with OsO₄ according to the procedure⁵ reported by us (Scheme 2). The Os complex of *VinylAmm* resin was then analysed by elemental analysis, UV, IR, XRF, UV-DRS and XPS (see supplementary information†). Os content in the resins was determined by UV and XRF (X-ray Fluorescence Spectrometer) analysis (0.18 mmol/g of Os). In the XPS (X-ray Photoelectron Spectroscopy) spectrum of this resin, Os 4f_{7/2} lines appeared at ~53 eV and ~50 eV.⁶ Based on these values, it is clear that the osmium tetroxide is reduced to Os(VI) monoglycolate and Os(IV) bisglycolate in the reaction with vinyl groups of resins.

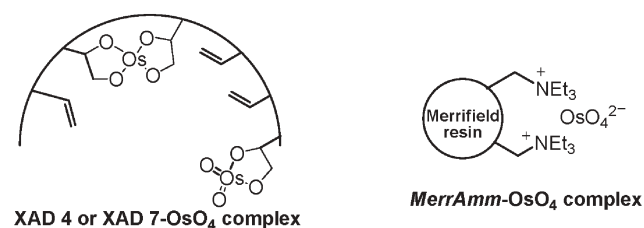
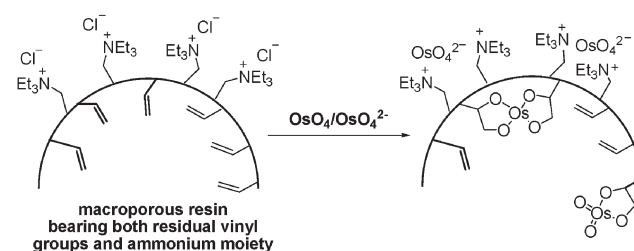


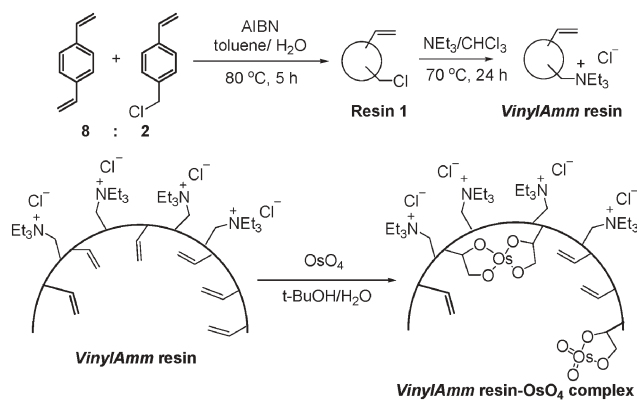
Fig. 1



Scheme 1

† Electronic supplementary information (ESI) available: experimental procedure and spectroscopic data. See <http://www.rsc.org/suppdata/cc/b504223b/>

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Scheme 2 Preparation of *VinylAmm*-OsO₄ complex.

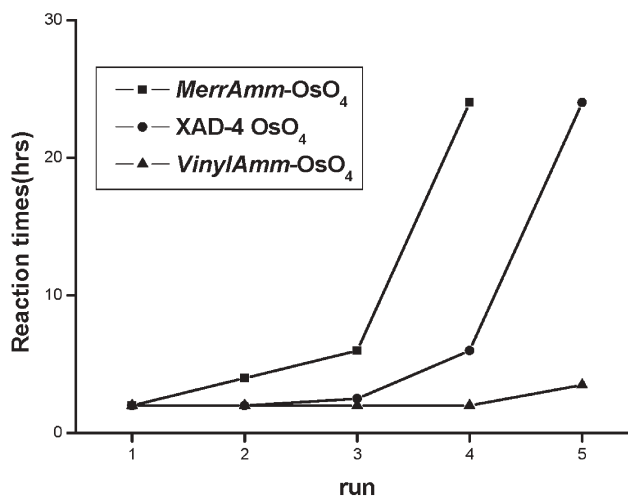


Fig. 2 Reaction time upon reuse.

To investigate catalytic performance of the osmylated resin, *VinylAmm* resin-OsO₄, the AD reaction of styrene was first carried out under the standard K₃Fe(CN)₆ conditions in the presence of *VinylAmm*-OsO₄ (1 mol%) and (DHQ)₂PHAL (1 mol%). The reaction using this solid Os catalyst was completed within 30 min to give the desired diol in excellent yield (93%) with 95% ee (entry 1 in Table 1). Even using 0.2 mol% catalyst, the reaction went very smoothly, affording the diol after 2 h in excellent yield and ee (entry 2 in Table 1). This solid osmium catalyst, *VinylAmm*-OsO₄, was then applied to the oxidation of other olefins. As shown in the entries 3–6 in Table 1, in all cases, the *VinylAmm* resin-Os catalyst exhibited a similar activity and enantioselectivity compared with those of homogeneous OsO₄.

To investigate the recyclability of the *VinylAmm* resin-OsO₄, the AD reactions of styrene were next carried out using 1 mol% of osmium catalyst and the results obtained here were compared with those obtained with the solid osmium catalyst reported in the literature (XAD 4-OsO₄ and *MerrAmm*-OsO₄, Fig. 1). For these experiments, *VinylAmm* resin-OsO₄ was loaded onto a commercially available small cylindrical container with mesh wall (MicroKan[®]) in order to minimise grinding of resins through

Table 1 Asymmetric dihydroxylation using *VinylAmm*-OsO₄ complex^a

Entry	Substrate	Time/h	Yield (%)	Ee (%)
1	Styrene	0.5	93	95
2 ^b	Styrene	2	94	93
3	<i>trans</i> -Stilbene	8	94	>99
4	β -Methylstyrene	1.5	97	95
5	Methyl <i>trans</i> -cinnamate	3.5	92	>99
6	1-Phenyl-1-cyclohexane	4.5	93	94

^a Experimental conditions: see supplementary information).

^b (DHQ)₂PHAL (0.5 mol%) and *VinylAmm*-OsO₄ (0.2 mol%).

stirring during the reaction. The black-coloured resins were recovered by simple filtration after the reaction. The XPS analysis of the recovered resin showed clearly that these recovered resins contain osmium species of +VI and +IV oxidation states (see supplementary information[†]). The alkaloid ligand was also almost quantitatively recovered by simple acid/base extraction. The recovered resins along with the replenished chiral ligand were subjected to further AD reactions of styrene. As shown in Table 2 and Fig. 2, the *VinylAmm* resin-OsO₄ maintained its catalytic activity for almost five cycles. On the other hand, the catalytic activity of the resins having only residual vinyl groups (*i.e.*, XAD 4-OsO₄) or having only ammonium moieties (*i.e.*, *MerrAmm*-OsO₄) decreased upon reuse significantly, causing increased turnover time. The difference of recyclability of each solid catalysts was shown to be more significant, when the reduced amounts (0.2 mol%) of osmium catalyst was used. Whereas Os-complex of *MerrAmm* resin and XAD-7 lost their catalytic activity after their first and third runs, respectively (*MerrAmm* resin: 2 h, 93%, 94% ee (1st run), 24 h, <10%, 82% ee (2nd run); XAD-7: 4 h, 98%, 93% ee (1st run), 6 h, 94%, 93% ee (2nd run), 15 h, 73%, 91% ee (3rd run), our solid osmium catalyst, the *VinylAmm* resin-OsO₄, exhibited much better recyclability than the above-mentioned solid osmium catalysts (5 h, 98%, 94% ee (1st run), 7 h, 93%, 94% ee (2nd run), 9 h, 98%, 93% ee (3rd run), 24 h, 94%, 92% ee (4th run)).

Considering all these results, osmium anchored to the *VinylAmm* resin is highly exposed to the oxidant, and once oxidised, it become free to react more readily with alkenes in solution. After the oxidant and starting alkenes are consumed, not only can the residual osmium tetroxide form new bonds with less accessible resin-bound vinyl groups but the osmate ion dissolved in

Table 2 Recyclability of solid Os-catalysts (1 mol%) in AD of styrene^a

Solid Os-catalyst	Run 1 (time, yield, ee)	Run 2 (time, yield, ee)	Run 3 (time, yield, ee)	Run 4 (time, yield, ee)	Run 5 (time, yield, ee)
<i>VinylAmm</i> -OsO	2h, 94%, 95% ee	2h, 91%, 95% ee	2h, 93%, 95% ee	2h, 90%, 95% ee	3.5h, 90%, 95% ee
XAD 4-OsO ₄ ^b	2h, 93%, 95% ee	2h, 92%, 95% ee	2.5h, 90%, 95% ee	6h, 88%, 95% ee	24h, 88%, 95% ee
<i>MerrAmm</i> -OsO ₄	2h, >99%, 96% ee	4h, >99%, 96% ee	6h, >99%, 96% ee	24h, <10%, 94% ee	

^a Recycling experiment conditions: see supplementary information ^b see Ref. 5. ^c This resin was prepared according to the procedure reported by Choudary *et al.*^{4b}

solution can also form complexes with the quaternary ammonium salts onto resin. This means that the synergic effect of both functionalities in the *VinylAmm* resin can markedly enhance the recyclability of the osmium catalyst in asymmetric dihydroxylation.

In conclusion, as we assumed, the synergic effect of both functionalities in the *VinylAmm* resin can markedly enhance the recyclability of osmium catalyst in asymmetric dihydroxylation. Although osmium leaching with the *VinylAmm* resin–OsO₄ was still found,⁷ causing increased turnover time upon reuse, to the best of our knowledge, our result is the most successful work reported until now on the solid osmium-mediated asymmetric dihydroxylation of olefins (total TONs = 1915!). Optimisation studies on this type of resin which can minimise osmium leaching, are currently in progress.

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