Asymmetric Hydroformylation of Olefins in a Highly Cross-Linked Polymer Matrix

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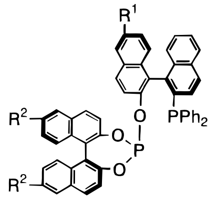
During the past two decades, intensive efforts have been devoted to develop polymer-supported chiral catalysts in order to introduce the advantages of heterogeneous catalysts, such as easy separation from the products and facile recovery for recycling, into homogeneous catalyst systems.[1−3] Immobilization of catalysts on polymer-supports often causes significant decrease of catalytic activity or selectivity of the reactions due to the slower diffusion of substrates in the polymer matrix.[4] Further decrease of catalytic activity or selectivity is expected to arise from utilizing a higher degree of cross-linking of the polymer-supports, although it is desirable to facilitate the treatments. Here, we report asymmetric hydroformylation of olefins using polymer-immobilized chiral phosphine−phosphite−Rh(I) complexes. Even in a highly cross-linked polymer matrix, the highest levels of catalytic activity and selectivity of the reaction were maintained.

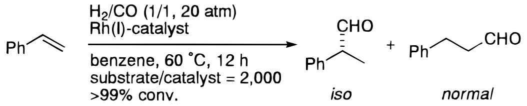
We recently developed homogeneous asymmetric hydroformylation of a wide variety of substrates catalyzed by Rh(I) complexes of chiral phosphine−phosphite, (*R,S*)-BINAPHOS (**1a**).[5] This system serves as the first example of the truly efficient catalysts of asymmetric hydroformylation for practical use. In this study, a vinyl group is introduced to **1a** so that the resulting ligand can be copolymerized with styrene derivatives. Thus, ligands **1b**−**d** have been prepared in which one, two, and three vinyl groups, respectively, are incorporated into **1a**.[6]



	R^1	R^2
1a:	H	H
1b:	-CH=CH$_2$	H
1c:	H	-CH=CH$_2$
1d:	-CH=CH$_2$	-CH=CH$_2$

The vinyl-BINAPHOSs, **1b**−**d**, were subjected to a radical copolymerization with styrene derivatives. Divinylbenzene is commercially available as a mixture of 1,2-, 1,3-, and 1,4-divinylbenzene and 3- and 4-ethylstyrene. In this work, divinylbenzenes of 55% content were used without further purification. Initiated by 2,2′-azobis(2,4-dimethylpentanenitrile) (V-65), a 3:97 mixture of **1b** and the divinylbenzenes was copolymerized in toluene (Scheme 1). Hereafter, this polymer is abbreviated as PS-**1b**.[7] This is a polymer with an extremely high degree of cross-linking, compared to polystyrene with less than 10% of cross-linking that is employed in most conventional studies.[1,3a−f] Other vinyl-BINAPHOSs were copolymerized in the same manner. The polymer-supported ligands were dispersed in benzene in the presence of Rh(acac)(CO)$_2$, and the mixtures were dried in vacuo. The resulting yellow solids, (PS-**1b**−**d**)−Rh(acac), were used as catalysts.

Asymmetric hydroformylation of styrene was examined under carbon monoxide and hydrogen (total pressure of 20 atm, CO/H$_2$ = 1:1) employing the (PS-ligand)−Rh(acac) complexes as catalysts in benzene at 60 °C (eq 1). The representative results are summarized in Table 1. All runs were repeated at least three times to ensure the reproducibility of the data. The reaction was completed after 12 h in all runs and the range of error for both the *i*-/*n*- ratio and enantiomeric excess (ee) was estimated to be ±<5%. Thus, with (PS-**1b**)−Rh(acac), 2-phenylpropanal and 3-phenylpropanal were obtained in an 84:16 ratio and the enantiomeric excess of the *iso*-aldehyde was 89% (*R*) (run 2). The highest level of catalytic activity, i.e., quantitative conversion to aldehydes with substrate/catalyst ratio of 2000, is maintained. This result is comparable to that obtained with the homogeneous system, Rh(acac)(**1a**) (run 1). Reduction of the cross-linking degree resulted in no significant change in the selectivities (run 3). With (PS-**1c**)−Rh(acac), the regio- and enantioselectivities of the reaction were essentially the same as with Rh(acac)(**1a**) and (PS-**1b**)−Rh(acac) (run 7). In contrast, however, lower ee was observed with (PS-**1d**)-Rh(acac) (run 8).



(1)

Because the present polymer catalyst hardly swells in benzene or hexane (run 4), easy handling and recovery−reuse have been achieved as shown in Figure 1. After the reaction was completed in a pressure bottle, the yellow polymer catalyst settled at the bottom of the bottle. The colorless supernatant suggests that the release of the Rh catalyst from the solids is negligible. The liquid phase containing the products was simply removed via a syringe, and the remaining solid catalyst was charged with an olefin solution and H$_2$/CO to give the aldehydes without any loss of productivity or selectivity (run 5 and 6).[8]

Another preparative route to the polymer-supported catalyst is the polymerization of a Rh(I) complex of the ligands. Thus, at first, ligand **1b** was treated with Rh(acac)(CO)$_2$ to form Rh(acac)-(**1b**). Copolymerization of Rh(acac)(**1b**) with divinylbenzenes

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(6) See Supporting Information for synthesis of vinyl-BINAPHOSs **1b**−**d** and copolymerization of these ligands with divinylbenzene (55% content).

(7) The polymeric ligands PS-**1b**−**d** and complexes (PS-**1b**−**d**)−Rh(acac) and PS-[Rh(acac)(**1b**−**d**)] were all insoluble in organic solvents such as benzene, THF, CH$_2$Cl$_2$, CHCl$_3$, DMSO, and DMF. For this reason, molecular weight of the polymers could not be determined.

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Scheme 1

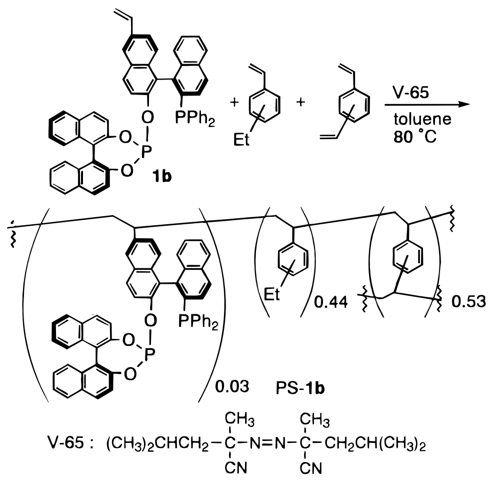


Table 1. Asymmetric Hydroformylation of Styrene Catalyzed by Polymer-Supported (*R*,*S*)-BINAPHOSs[a]

run	catalyst	*i*-/*n*-	ee (%)	run	catalyst	*i*-/*n*-	ee (%)
1	Rh(acac)(**1a**)	89:11	92	7	(PS-**1c**)−Rh(acac)	89:11	89
2	(PS-**1b**)−Rh(acac)	84:16	89	8	(PS-**1d**)−Rh(acac)	88:12	68
3[b]	(PS-**1b**)−Rh(acac)	83:17	89	9	PS-[Rh(acac)(**1b**)]	85:15	90
4[c]	(PS-**1b**)−Rh(acac)	80:20	81	10	PS-[Rh(acac)(**1c**)]	90:10	87
5[d]	(PS-**1b**)−Rh(acac)	84:16	89	11	PS-[Rh(acac)(**1d**)]	87:13	85
6[d]	(PS-**1b**)−Rh(acac)[e]	79:21	86				

[a] A solution of styrene (6.20 mmol) in benzene (0.35 mL) was treated with carbon monoxide (10 atm) and hydrogen (10 atm) in the presence of the polymer catalyst (3.1×10^{-3} mmol of Rh) at 60 °C for 12 h. The conversion of styrene to aldehydes (>99% for all the runs), and the *i*-/*n*- ratios were determined by ^{1}H NMR. The enantiomeric excesses were determined by GLC analysis (Chrompack Cp-Cyclodex β-236M, 135 °C, He 2.0 kg cm^2) of the corresponding carboxylic acid derived by the Jones oxidation of the product aldehyde. The absolute configuration of the *iso*-aldehyde was determined to be *R* for all runs. [b] The polymer ligand was prepared from a 3:87:10 mixture of **1b**, styrene, and divinylbenzenes (55% content). [c] Hexane was used as the solvent. [d] The reaction was carried out under CO (2.5 atm) and H$_2$ (2.5 atm) in a glass pressure-bottle. [e] The catalyst used in run 5 was reused.

(55% content) afforded the corresponding polymer-supported complex, PS-[Rh(acac)(**1b**)]. In the same procedure, PS-[Rh(acac)(**1c**)] and PS-[Rh(acac)(**1d**)] were synthesized. Asymmetric hydroformylation of styrene was examined with these PS-[Rh(acac)(ligand)] catalysts, and the results are summarized in Table 1, runs 9−11. Again, the activity and selectivity were comparable to the results with the corresponding homogeneous system.

Noteworthy is that the use of PS-[Rh(acac)(**1d**)] showed higher enantioselectivity than that with (PS-**1d**)−Rh(acac) (compare runs 8 and 11). The difference can be explained as follows. When the polymerization is carried out in the absence of Rh(I), ligand **1d** is frozen as a matrix of various conformations, some of which are not suitable to coordinate to Rh(I). This may result in the formation of a less stable Rh(I) complex, for example, with monodentate coordination. Existence of plural active species could have caused the loss of selectivity. On the other hand, the conformation of the ligand should be fixed to a suitable form for the bidentate coordination to Rh(I), when **1d** is complexed with Rh(I) before polymerization. In this case, the catalyst can work in a manner similar to a homogeneous catalyst. Such difference is observed only with **1d** in which both the phosphine site and the phosphite site are attached to the polymer. With **1b,c**, the ligands keep their flexibility in the polymer matrix because only one of the two binaphthyl groups is bound to the polymer chain.

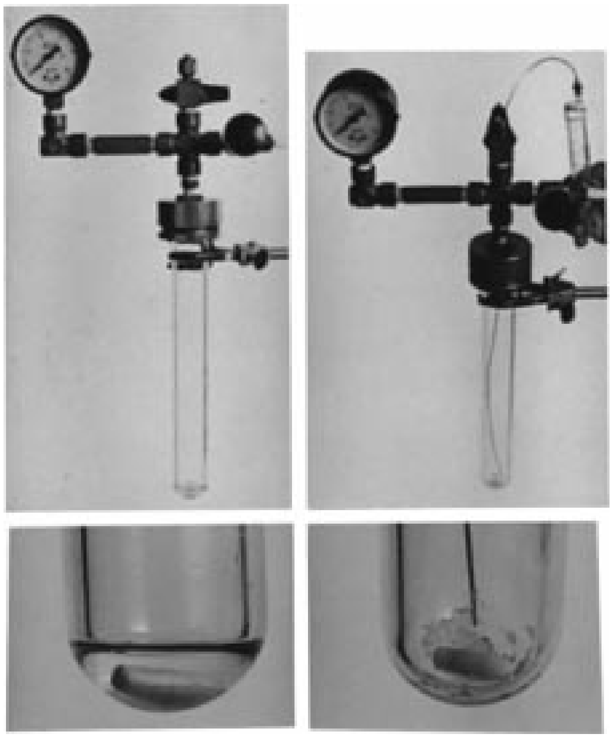


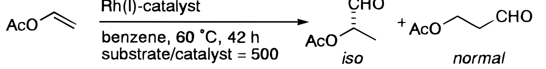
Figure 1. Left: The glass pressure-bottle when the asymmetric hydroformylation of styrene was completed using (PS-**1b**)−Rh(acac) (corresponds to Table 1, run 5). During the reaction, slow stirring was carried out with a magnetic stirring bar (shown as the white bar). The colorless supernatant fluid suggests that the Rh(I) catalyst stays in the yellow solid catalyst. Right: After removal of the product solution via a syringe in a stream of Ar. The yellow polymer was reused (Table 1, run 6).

Table 2. Asymmetric Hydroformylatyion of Vinyl Acetate Catalyzed by Polymer-Supported (*R*,*S*)-BINAPHOS[a,b]

run	catalyst	convn (%)	*i*-/*n*-	ee (%)
1	Rh(acac)(**1a**)	98	84:16	92
2	(PS-**1b**)−Rh(acac)	75	85:15	91
3	(PS-**1c**)−Rh(acac)	54	90:10	92
4	(PS-**1d**)−Rh(acac)	61	87:13	78
5	PS-[Rh(acac)(**1b**)]	67	87:13	92
6	PS-[Rh(acac)(**1c**)]	83	90:10	93
7	PS-[Rh(acac)(**1d**)]	78	90:10	89

[a] The reactions were carried out in a manner similar to that for styrene with the substrate/catalyst ratio of 500 and total pressure of 100 atm. The absolute configuration of the *iso*-aldehyde was *S* for all runs. [b] All runs were repeated at least twice to confirm the reproducibility. The *i*-/*n*- ratio and the ee were always reproducible, but the conversions in runs 2−6 contained errors of ±20%.

Asymmetric hydroformylation of vinyl acetate was also examined (eq 2). Total pressure of 100 atm is employed for this substrate because hydrogenated byproducts are produced under lower pressure. The results are summarized in Table 2. When the reaction was catalyzed by the polymer-supported catalysts, conversion of the reaction was variable (±20% range of error), but the *i*-/*n*- ratio and ee were sufficiently reproducible (±<5%) with the values of 85:15 to 90:10 and 89−93% ee(*S*) (runs 2, 3 and 5−7), similar to those attained in the homogeneous system (run 1). Again, slightly lower ee was observed when (PS-**1d**)−Rh(acac) was used as the catalyst (run 4).



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