Soluble Polymer-Supported Catalysts Containing Pendant Quaternary Onium Salt Residues for Regioselective Addition Reaction of Epoxy Compound with Active Ester

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ABSTRACT: Various soluble polymer-supported catalysts containing pendant quaternary onium salts were synthesized by the radical copolymerization of *p*-chloromethylated styrene with styrene followed by the addition reaction of the resulting copolymers with tributylamine or trialkylphosphines. The catalytic activity of the soluble polymer-supported quaternary onium salts on the regioselective addition reaction of phenyl glycidyl ether (PGE) with *S*-phenyl thioacetate (PTA) was evaluated from the rates of the reaction and yields of the product, 1-phenoxy-3-(phenylthio)-2-propyl acetate (PPA). The catalytic activity was strongly affected by the content of pendant quaternary onium salt in the polymer chains, by the structure of onium salt residues, and by the reaction solvents used. The polymer-supported catalyst having small amounts of pendant benzyltributylphosphonium chloride residue showed the highest catalytic activity in DMF. Furthermore, it was proved from the kinetic data that the rate of addition reaction of epoxy compound with active ester in homogeneous systems using soluble polymer-supported quaternary onium salt as a catalyst was proportional to the concentration of catalyst [Cat.] and the concentration of epoxy compound [PGE] as follows: $d[PPA]/dt = k_2[Cat.][PGE]$, where [PPA] is the concentration of the product and k_2 is the second-order rate constant. Furthermore, on the basis of these kinetic results, the reaction mechanism of epoxy compound with active ester catalyzed by the soluble polymer-supported quaternary onium salts can now be elucidated.

Introduction

It is well-known that quaternary ammonium salts bound to cross-linked polystyrene beads have so far been used as anion exchange resins for the purification of water and various ionic chemicals. Quaternary ammonium or phosphonium salts bound to cross-linked insoluble polystyrene or silica gel, which are ordinarily synthesized by the reaction between pendant chloromethyl groups in the polymers with tertiary amines or phosphines, were first utilized by Regen,[1] Montanari et al.,[2] and Brown et al.,[3] independently, as triphase transfer catalysts in the field of organic synthesis. Insoluble polymer-supported quaternary onium salts with certain counteranions such as cyanides[4] and chromates[5] were also applied as catalysts for benzoin condensation and as oxidizing reagents for alcohols, respectively. Insoluble polymer-supported crown ethers and cryptands have been used[6–9] as triphase transfer catalysts as have polymer-supported quaternary onium salts. On the other hand, the insoluble polymer-supported 4-(dimethylamino)pyridine[10–12] (DMAP) and 1,8-diazabicyclo[5.4.0]undec-7-ene[13] (DBU) have been widely employed as highly effective nucleophilic catalysts for acylation, alkylation, silylation, phosphorylation, and so on in synthetic organic chemistry. These insoluble polymer catalysts can be easily separated from the reaction vessel at the end of a reaction by filtration and can be reused for further runs. However, catalytic activities of the above polymer-supported catalysts are essentially lower than those of the corresponding low-molecular-weight catalysts.

We have reported recently that addition reactions of epoxy compounds with esters, thioesters,[14] acyl halides,[15] aryl halides,[16] aldehydes,[17] carbon dioxide,[18] and silyl halides[19] proceeded very smoothly when catalyzed by low-molecular-weight quaternary onium salts, crown ether complexes, DMAP, and DBU. Furthermore, it was also found that those reactions were effectively catalyzed by insoluble polymer-supported quaternary onium salts,[20] crown ether complexes,[21] and certain bases.[22] Insoluble polymer-supported catalysts with alkylene spacer chains separating them from the polystyrene backbone and quaternary onium salts[18,20b] or bases[22] show clearly higher catalytic activity than the corresponding low-molecular-weight compounds. However, the effect of the type of polymer chain, catalyst concentration of the polymer, content of the pendant onium salts in the polymer chains, structure of the onium salt residues, kind of reaction solvents, and so on cannot be clearly known in detail, because the reported reactions were carried out in a heterogeneous system.

In this paper, we wish to report on the synthesis of soluble polymer-supported quaternary onium salts and on the catalytic effects of the resulting polymers on the regioselective addition reaction of phenyl glycidyl ether (PGE) with *S*-phenyl thioacetate (PTA) in detail.

Experimental Section

Materials. PGE, styrene (ST), and reaction solvents were used after distillation on CaH_2. Azobis(isobutyronitrile) (AIBN) was recrystallized twice from benzene at 40 °C. *p*-Chloromethylated styrene (CMS) (donated by Seimi Chemical Co.,

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Table 1. Conditions and Results of Copolymerization of CMS and ST[a]

polym no.	CMS, mmol	ST, mmol	AIBN, mmol	solvent, mL	yield, %	Cl content, mg/g	CMS unit, mol %	η_{sp}/c,[b] dL/g
PCMS-1	200	200	4	80	64.5	137.9	50	0.12
PCMS-2	160	240	2	100	51.9	126.3	45	0.17
PCMS-3	120	280	4	100	58.3	101.4	35	0.11
PCMS-4	80	320	4	100	55.8	71.1	23	0.11
PCMS-5	60	340	4	100	57.8	62.0	20	0.11
PCMS-6	40	360	4	100	56.6	41.3	13	0.11
PCMS-7	40	760	8	200	56.3	28.8	9	0.12
PCMS-8	20	453	4	100	61.1	18.7	6	0.12

[a] The copolymerization was carried out in DMF at 60 °C for 5 h and then 80 °C for 3 h under nitrogen. [b] Measured at a concentration of 0.5 g/dL in DMF at 30 °C.

Chigasaki, Japan) was distilled twice under reduced pressure. Commercial acetyl chloride, thiophenol, tributylamine (TBA), triethylphosphine (TEP), tripropylphosphine (TPP), tributylphosphine (TBP), trihexylphosphine (THP), and trioctylphosphine (TOP) were used without further purification. PTA (bp 96–97 °C/7 mmHg) was prepared by the reaction of thiophenol with acetyl chloride as reported previously.[14b] Copolymer (PCMS) with a reacting chloromethyl group was synthesized by radical copolymerization of CMS with ST as follows (other results are summarized in Table 1): CMS [6.11 g (40 mmol)], 37.5 g (360 mmol) of ST, and 0.66 g (4 mmol) of AIBN were dissolved in toluene (100 mL), and the polymerization was carried out at 60 °C for 5 h and then 80 °C for 3 h under nitrogen. The polymer solution was poured into methanol, reprecipitated twice from THF into methanol, and then dried *in vacuo* at 50 °C. Yield of the recovered polymer (PCMS-6) was 24.7 g (57%). The reduced viscosity of the copolymer in DMF was 0.11 dL/g, measured at a concentration of 0.5 g/dL at 30 °C. The percent of CMS unit in the copolymer was 13%, which was determined from Cl analysis (41.3 mg/g).

Apparatus. Infrared (IR) spectra were measured on a JASCO Model IR-700 spectrometer. ^{1}H NMR spectra were recorded on a JEOL Model JNM EX-90 (90 MHz) in $CDCl_3$ with Me_4Si as an internal standard.

Synthesis of Soluble Polymer-Supported Catalyst Containing Quaternary Onium Salts. The typical procedure for the synthesis of the soluble polymer-supported catalyst having quaternary onium salt was as follows: PCMS-1 containing 50 mol % of CMS unit [2.57 g (10 mmol)] was dissolved in 15 mL of DMF, and 2.76 g (15 mmol) of TBA was added to the solution. The mixture was stirred at 80 °C for 48 h and then poured into diethyl ether. The obtained polymer-supported catalyst was purified by reprecipitating twice from methanol into diethyl ether and finally dried *in vacuo* at 50 °C. The yield of recovered polymer (catalyst **1**) was 3.46 g. The degree of introduction of the pendant quaternary onium salt residue in the copolymer was 45.0%, which was determined from elemental analysis of chlorine (80.6 mg/g). The reduced viscosity of the polymer in DMF was 0.65 dL/g, measured at 0.5 g/dL at 30 °C.

Regioselective Addition Reaction of PGE with PTA Using Soluble Polymer-Supported Catalyst. Polymer-supported catalyst **13** containing 12 mol % of benzyltributylphosphonium chloride residue [0.042 g (0.04 mmol)] was dissolved in 2 mL of DMF, and then 0.601 g (4 mmol) of PGE and 0.609 g (4 mmol) of PTA were added to the solution. The mixture was stirred at 90 °C for 8 h, and then diethyl ether was added to the mixture. The solution was washed several times with water to remove polymer-supported catalyst and DMF. The crude product thus obtained was purified by silica gel column chromatography using benzene as an eluent: isolated yield of 1-phenoxy-3-(phenylthio)-2-propyl acetate[14b] (PPA) was 0.809 g (67%). IR (neat) 1740 (C=O), 1235 (C–O–C, ester), 1050 cm^{-1} (C–O–C, ether); ^{1}H NMR ($CDCl_3$) δ 1.98 (s, 3 H, CH_3C), 3.28 (d, 2H, SCH_2), 4.14 (d, 2H, OCH_2O), 5.10–5.40 (m, 1H, CHO), 6.76–7.56 (m, 10H, aromatic protons).

Kinetic Measurement of the Reaction of PGE with PTA. Appropriate amounts of catalyst, PTA, reaction solvent, and *p*-dichlorobenzene (internal standard for GLC) were charged into the reaction flask and thermostatically kept at a fixed temperature with stirring under nitrogen. To the mixtures was added PGE at zero time. The reaction mixtures were periodically analyzed by the GLC method (Shimadzu Model GC-9AM gas chromatograph with a 3 mm × 2.6 m column packed with 3% Silicone OV-101 on Shimalite W) as reported previously.[20a]

Results and Discussion

Synthesis of Soluble Polymer-Supported Catalyst Containing Pendant Quaternary Onium Salt Residue. Radical copolymerization of CMS with ST was carried out at a certain feed ratio in DMF, and, as summarized in Table 1, reactive PCMS copolymers having appropriate amounts of pendant chloromethyl group were obtained with yields of about 52–64%.

Soluble polymer-supported catalysts (catalysts **1–7**) containing certain amounts of pendant benzyltributylammonium chloride residue were synthesized by the addition reaction of the reactive PCMSs with TBA in 1.5-fold excess. Catalysts (catalysts **8–15**) with similar amounts of pendant benzyltributylphosphonium chloride residue were also prepared by the addition reaction with TBP under the same reaction conditions. Soluble polymer-supported catalysts with 8–9 mol % of pendant benzyltriethylphosphonium chloride (catalyst **16**), benzyltripropylphosphonium chloride (catalyst **17**), benzyltrihexylphosphonium chloride (catalyst **18**), and benzyltrioctylphosphonium chloride (catalyst **19**) residues were also obtained by the reaction with TEP, TPP, THP, and TOP, respectively. As summarized in Table 2, most of the addition reactions of reactive polymer PCMSs with TBA or the above phosphines proceeded in good conversions to give the corresponding soluble polymer-supported catalysts (Scheme 1).

Furthermore, the reduced viscosity values of the resulting polymer-supported quaternary onium salts in DMF all increased compared with those of the starting reactive polymers. This shows that each polymer chain of the soluble polymer-supported catalyst was extended effectively in DMF solution by the ionic repulsion of the pendant onium salts. Accordingly, the solubility of typical polymer-supported catalysts was examined. As summarized in Table 3, each catalyst was quite soluble in aprotic high-polarity solvents such as DMSO, DMAc, and DMF. However, the solubility of these polymers varied slightly in other solvents. That is, the solubility of a polymer with large amounts of pendant onium salt was lower than that of a polymer with smaller amounts of pendant onium salt in low-polarity, lipophilic solvents such as toluene and anisole, whereas the solubility of the former polymer was better than that of the latter polymer in polar, hydrophilic solvents such as methanol and acetonitrile.

Catalytic Activity of Soluble Polymer-Supported Quaternary Onium Salt for Addition Reaction of

Table 2. Conditions and Results of Synthesis of Polymer-Supported Catalysts[a]

Cat. no.	PCMS (mmol)	amine or phosphine (mmol)	solvent, mL	yield, g	Cl content, mg/g	Q^+X^- unit, mol %	η_{sp}/c,[b] dL/g
1	PCMS-1 (10)	TBA (15)	15	3.5	83.6	45	0.65
2	PCMS-2 (10)	TBA (15)	15	4.1	80.6	35	1.39
3	PCMS-3 (10)	TBA (15)	15	4.7	67.8	30	0.58
4	PCMS-4 (10)	TBA (15)	20	6.0	54.6	17	0.46
5	PCMS-5 (10)	TBA (15)	15	5.2	48.9	15	0.81
6	PCMS-6 (10)	TBA (15)	20	9.3	33.7	13	0.31
7	PCMS-8 (10)	TBA (7.5)	20	8.9	17.1	6	0.25
8	PCMS-1 (10)	TBP (15)	15	3.8	78.7	48	0.41
9	PCMS-2 (10)	TBP (15)	15	4.1	75.5	42	0.63
10	PCMS-3 (10)	TBP (15)	15	4.4	69.1	28	0.32
11	PCMS-4 (10)	TBP (15)	15	5.3	52.9	20	0.29
12	PCMS-5 (10)	TBP (15)	15	5.7	48.5	16	0.26
13	PCMS-6 (10)	TBP (15)	20	10.1	34.1	12	0.22
14	PCMS-7 (5)[c]	TBP (7.5)	20	7.0	24.8	8	0.18
15	PCMS-8 (5)	TBP (7.5)	20	9.1	18.2	4	0.15
16	PCMS-7 (5)[c]	TEP (7.5)	20	5.7	26.4	8	0.19
17	PCMS-7 (8)[c]	TPP (12)	30	11.6	23.9	9	0.17
18	PCMS-7 (8)[c]	THP (12)	30	12.7	24.5	8	0.17
19	PCMS-7 (8)[c]	TOP (12)	30	12.5	23.9	9	0.14

[a] The reaction was carried out at 80 °C for 48 h. [b] Measured at a concentration of 0.5 g/dL in DMF at 30 °C. [c] The reaction was carried out for 96 h.

Scheme 1

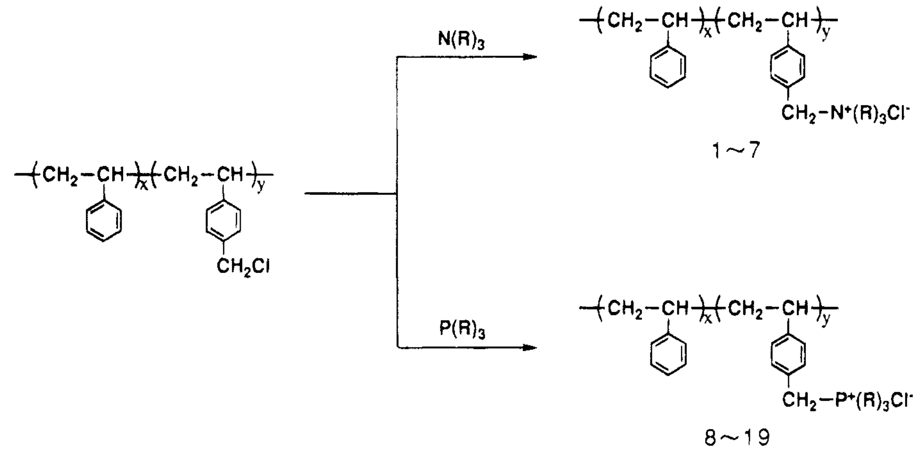


Table 3. Solubility of Typical Polymer-Supported Catalysts[a]

solvent	catalyst **8**	catalyst **13**	catalyst **14**
n-hexane	−	−	−
toluene	+ −	+ −	++
anisole	− −	+ −	+ −
diglyme	+ −	+ −	++
acetone	+ −	+	+
methanol	++	++	+
acetonitrile	++	++	+
DMF	++	++	++
DMAc	++	++	++
DMSO	++	++	++

[a] ++ = soluble at room temperature, + = soluble by heating, + − = partly soluble or swelling, − = insoluble.

Epoxy Compound with Active Ester. It has been reported[20a] that the addition reaction of PGE with PTA produced the regioselective adduct 1-phenoxy-3-(phenylthio)-2-propyl acetate (PPA) as the main product with small amounts of the hydrolysis product 1-phenoxy-3-(phenylthio)-2-propanol (PPP) as a byproduct when insoluble polymer-supported quaternary onium salts were used. No isomers were produced in the reaction.

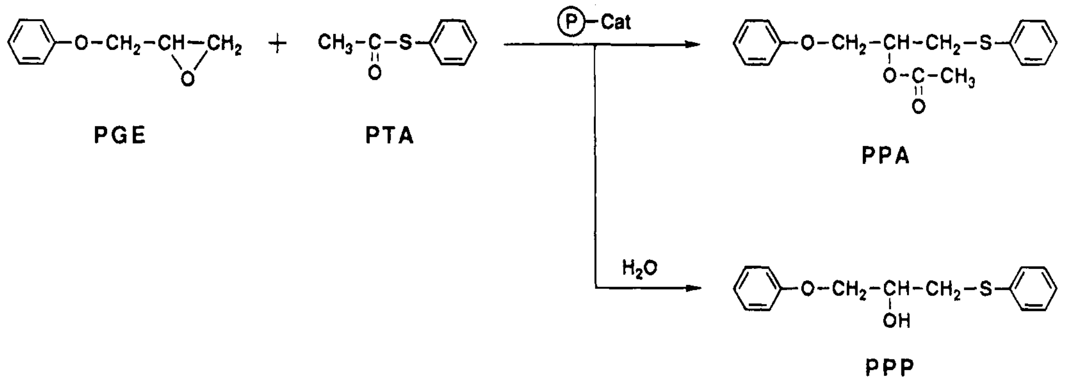
In the present case, the catalytic activities of certain new soluble polymer-supported catalysts (catalysts **1**−**19**) containing pendant ammonium or phosphonium salts were evaluated as to the yield of main product PPA and as to the observed pseudo-first-order rate constants.

The initial rate of PPA production increased with increasing reaction temperature when the reaction of PGE with PTA was carried out in DMF at 60−95 °C using 1 mol % of soluble polymer-supported catalyst **6**, which has 13 mol % of pendant benzyltributylammonium chloride residue in the polymer chain (Figure 1). Furthermore, as shown in Figure 2, the observed rate of the reaction obeyed first-order kinetics as did the same reaction when catalyzed by insoluble polymer-supported quaternary onium salts.[20a] As shown in Figure 1, however, the yields of PPA at 90 and 95 °C were lower than that of PPA at 80 °C when the reaction was carried out for 5 h.

When the reaction of PGE with PTA was carried out in DMF under the same reaction conditions using the same amount of soluble polymer-supported catalyst **13** containing 12 mol % of pendant benzyltributylphosphonium chloride residue, the initial rate of PPA production increased with increasing reaction temperature (Figure 3). The observed rate of this reaction also obeyed first-order kinetics. However, the yield of PPA at 95 °C was lower than that of PPA at 90 °C after 5 h.

These results suggest that the pendant benzyltributylammonium and benzyltributylphosphonium residues in the polymer chains were inactivated by Hofmann elimination[23] during the reaction, although the polymer-supported quaternary phosphonium salts had higher

Scheme 2



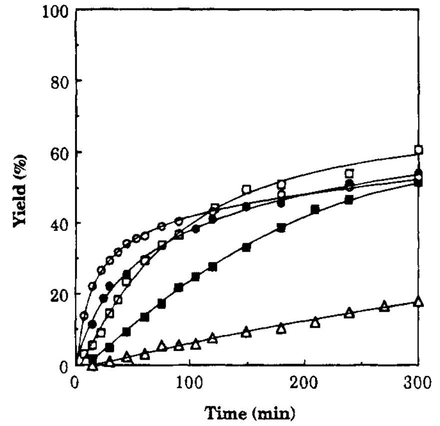


Figure 1. Graph of the percentage yields of main product PPA on the reaction of PGE (4 mmol) with PTA (4 mmol) in the presence of 1 mol % of catalyst **6** in DMF (2 mL): (△) at 60 °C; (■) at 70 °C; (□) at 80 °C; (●) at 90 °C; (○) at 95 °C.

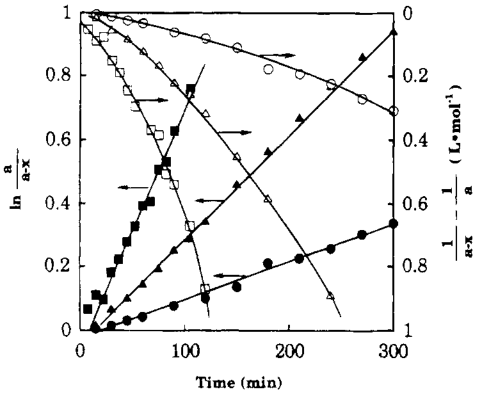


Figure 2. Rate of addition reaction of PGE (4 mmol) with PTA (4 mmol) by using catalyst **6** in DMF (2 mL): (●,○) at 60 °C; (▲,△) at 70 °C; (■,□) at 80 °C.

catalytic activity than the polymer-supported quaternary ammonium salts under the same reaction conditions.

The rates of reaction of PGE with PTA obey first-order kinetics at various temperatures, and Arrhenius plots based on the above-observed pseudo-first-order rate constants (k_1) vs reciprocal temperature are shown in Figure 4. The plots yield a straight line at 60–95 °C for the reaction catalyzed by **13**. However, whereas the plot gave a linear correlation at 60–70 °C, each plot at 80 and 90 °C was lower than the straight line made from the correlation between 60 and 70 °C when the reaction was carried out with catalyst **6**. The apparent activation energies of the reaction catalyzed by **6** and **13** were estimated from the above two straight lines as 125.9 and 89.0 kJ/mol, respectively.

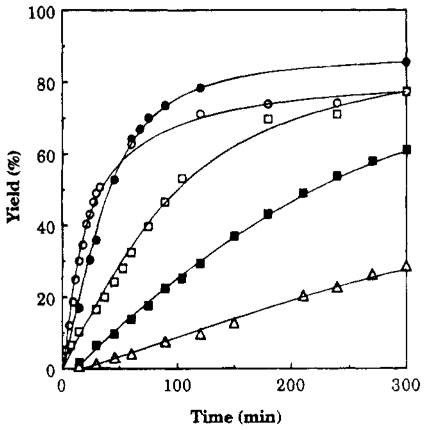


Figure 3. Graph of the percentage yields of main product PPA on the reaction of PGE (4 mmol) with PTA (4 mmol) in the presence of 1 mol % of catalyst **13** in DMF (2 mL): (△) at 60 °C; (■) at 70 °C; (□) at 80 °C; (●) at 90 °C; (○) at 95 °C.

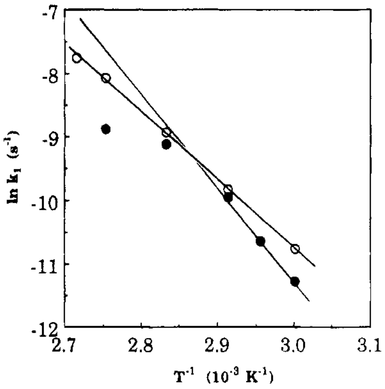


Figure 4. Arrhenius plots of the observed pseudo-first-order rate constant on the reaction of PGE with PTA by using catalysts **6** and **13**: (●) with catalyst **6**; (○) with catalyst **13**.

These results mean that the soluble polymer-supported catalyst having pendant quaternary phosphonium salt had good thermal stability even at 95 °C in the reaction. However, the soluble polymer-supported catalyst having pendant quaternary ammonium salt decomposed gradually from the initial stage of the reaction at the same high temperatures, and decomposition of the catalyst also occurred during the reaction even at low temperatures. That is, the initial rate constants (k_1) of the reaction catalyzed by **6** were mostly the same as those (k_1) of the reaction catalyzed by **13** (see Figure 4); however, the yields of main product PPA of the reaction catalyzed by **6** at 60 and 70 °C were lower than those of the PPA of the reaction catalyzed by **13** at the same temperatures for 5 h (see Figures 1 and 3).

Correlations between the observed pseudo-first-order rate constants and the content levels of pendant qua-

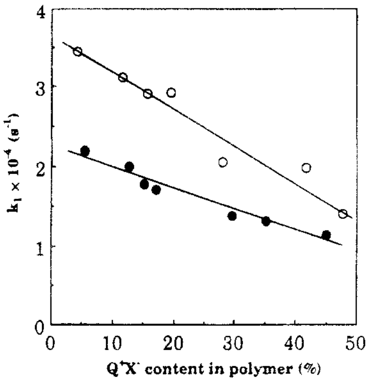


Figure 5. Correlation between the observed pseudo-first-order rate constant and the contents of pendant quaternary onium salts in the polymer chains on the reaction of PGE (4 mmol) with PTA (4 mmol) using 1 mol % of the soluble polymer-supported catalyst in DMF (2 mL) at 90 °C: (●) the polymer-supported catalysts having pendant benzyltributylammonium chloride; (○) the polymer-supported catalysts having pendant benzyltributylphosphonium chloride.

Table 4. Catalytic Activity of Soluble Polymer-Supported Quaternary Onium Salts on the Addition Reaction of PGE with PTA[a]

Cat. no.	Ⓟ-Q^+Cl^-	Q^+Cl^- unit in polymer chain, %	yield of adduct,[b] %		k_{obsd}, $\times 10^{-4}$ s^{-1}
			PPA	PPP	
1	$-N^+Bu_3Cl^-$	45	47	10	1.13
2	$-N^+Bu_3Cl^-$	35	40	8	1.31
3	$-N^+Bu_3Cl^-$	30	51	10	1.38
4	$-N^+Bu_3Cl^-$	17	53	11	1.71
5	$-N^+Bu_3Cl^-$	15	42	6	1.78
6	$-N^+Bu_3Cl^-$	13	59	9	2.00
7	$-N^+Bu_3Cl^-$	6	58	8	2.19
8	$-P^+Bu_3Cl^-$	48	76	12	1.40
9	$-P^+Bu_3Cl^-$	42	81	8	1.99
10	$-P^+Bu_3Cl^-$	28	78	11	2.06
11	$-P^+Bu_3Cl^-$	20	88	7	2.92
12	$-P^+Bu_3Cl^-$	16	80	13	2.91
13	$-P^+Bu_3Cl^-$	12	86	8	3.12
14	$-P^+Bu_3Cl^-$	9	88	10	3.43
15	$-P^+Bu_3Cl^-$	4	86	10	3.45
16	$-P^+Et_3Cl^-$	8	69	8	2.09
17	$-P^+Pr_3Cl^-$	9	85	8	2.39
18	$-P^+Hex_3Cl^-$	8	77	9	2.79
19	$-P^+Oct_3Cl^-$	9	65	1	0.92
20[c]	$-P^+Bu_3Cl^-$	10	10	5	0.17

[a] The reaction was carried out with 4 mmol of PGE and 4 mmol of PTA by using 0.04 mmol of catalyst in 2 mL of DMF at 90 °C for 5 h. [b] Determined by GLC analysis. [c] Reference 20b; the reaction was carried out using 1 mol % of insoluble cross-linked polystyrene-bound quaternary onium salt as a catalyst in chlorobenzene at 90 °C for 5 h.

ternary onium salts in the polymer chains were measured on the reaction of PGE with PTA using 1 mol % of the catalyst in DMF at 90 °C. As shown in Figure 5, the plots for the reactions catalyzed by the soluble polymer-supported quaternary ammonium or phosphonium chlorides gave the corresponding two straight lines, respectively. The observed first-order rate constants (k_1) and the yields of main product PPA and hydrolysis byproduct PPP for the reaction for 5 h are also summarized in Table 4.

These results show that the catalytic activity of soluble polymer containing pendant benzyltributylammonium or benzyltributylphosphonium salts increased with decreasing pendant onium salt residue. That is, the polymer chain, which is composed of polystyrene units that constitute the reaction medium, and the presence of an appropriate proportion of lipophilic domain becomes very important factors for the regioselective addition reaction of epoxy compound with active ester catalyzed by the soluble polymer-supported quaternary onium salts in aprotic polar solvent. In addition, it was also found that the soluble polymer-supported quaternary onium salt has a higher catalytic activity in the above reaction than does the corresponding insoluble polymer-supported quaternary onium salt (Table 4).

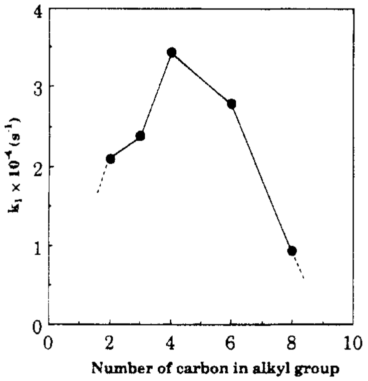


Figure 6. Correlation between the observed pseudo-first-order rate constant and the carbon number of the trialkyl groups on the pendant benzyltrialkylphosphonium chlorides on the reaction of PGE (4 mmol) with PTA (4 mmol) using 1 mol % of the soluble polymer-supported catalyst in DMF (2 mL) at 90 °C.

Correlation between the observed pseudo-first-order rate constants and the carbon numbers of the trialkyl groups on the pendant benzyltrialkylphosphonium salt is shown in Figure 6, where the reaction was accomplished with 1 mol % of soluble polymer-supported catalysts containing about 9 mol % of pendant onium salts in DMF at 90 °C. Interestingly, catalyst **14** showed the highest activity, and the activity of catalysts **16**, **17**, **18**, and **19** was depressed with either a decrease or an increase of the carbon number of the trialkyl groups on the phosphonium salts. The observed first-order rate constants (k_1) and the yields of main product PPA and hydrolysis byproduct PPP for the reaction for 5 h are given in Table 4.

The above results suggest that the catalytic activity of the soluble polymer-supported quaternary onium salts was significantly affected by the lipophilic interaction between the pendant onium salt residue in the polymer and the reactants and that catalyst **14** containing pendant benzyltributylphosphonium chloride residue was relatively more lipophilic than catalysts **16** and **17** containing pendant benzyltriethylphosphonium or benzyltripropylphosphonium chloride residues. On the other hand, increasing the alkyl chain length on the quaternary onium salts increased the lipophilicity of the catalyst; however, the introduction of relatively more bulky residues such as benzyltrihexylphosphonium or benzyltrioctylphosphonium chloride in catalysts **18** and **19** might have caused an increase in steric hindrance and decrease in catalytic activity.

The effect of the solvent used on the reaction of PGE with PTA was examined using catalysts **8** and **13** at 90 °C for 5 h, catalyst **8** having 48 mol % of the pendant benzyltributylphosphonium chloride residue in the polymer chain and catalyst **13** having 12 mol % of the pendant benzyltributylphosphonium chloride residue in the polymer chain. As summarized in Table 5, catalyst **13**, containing smaller amounts of the pendant onium salt residue, had a higher catalytic activity than did catalyst **8**, containing larger amounts of the pendant onium salt residue, in aprotic high-polarity solvents

Table 5. Solvent Effect on the Addition Reaction of PGE with PTA[a]

Cat. no.	solvent (dipole moment[b])	yield of adduct,[c] % PPA	PPP	k_{obsd}, $\times 10^{-4}$ s^{-1}
8	DMSO (4.30)	43	16	0.50
13	DMSO (4.30)	60	17	0.84
8	DMF (3.86)	67	11	0.96
13	DMF (3.86)	77	11	1.32
8	DMAc (3.72)	77	11	1.50
13	DMAc (3.72)	90	8	2.26
8	diglyme (1.97)	40	14	0.38
13	diglyme (1.97)	7	5	very slow
8	anisole (1.20)	29	7	0.37
13	anisole (1.20)	6	5	very slow
8	toluene (0.37)	26	6	0.26
13	toluene (0.37)	7	5	very slow

[a] The reaction was carried out with 4 mmol of PGE and 4 mmol of PTA by using 0.04 mmol of catalyst in 2 mL of DMF at 90 °C for 5 h. [b] In debye at 25 °C. [c] Determined by GLC.

such as DMSO, DMF, and DMAc. However, catalyst **8** showed a higher catalytic activity than catalyst **13** in ordinary organic solvents such as diglyme, anisole, and toluene. Furthermore, it was also found that the reaction proceeded more smoothly in the former solvents than in the latter solvents catalyzed by each polymer-supported onium salt, although a systematic correlation between the activity of the polymer-supported catalyst and dipole moment of the solvent could not be established from these data. In a previous paper, we reported,[20b] however, that insoluble polystyrene-supported catalysts having about 30 mol % of pendant quaternary onium salts have higher activity in toluene than in DMF.

These results mean that the solubility of the polymer-supported quaternary onium salts in reaction solvents was strongly related to the catalytic activity on the reaction of PGE with PTA. As shown in Table 3, catalysts **8** and **13** were quite soluble in the above aprotic high-polarity solvents; however, these polymers were not dissolved completely in ordinary organic solvents such as toluene, anisole, and diglyme. That is, catalysts **8** and **13** having pendant quaternary onium residues take a more expanded conformation in the aprotic high-polarity solvents, and thus catalyst **13**, which is relatively more lipophilic due to the smaller amounts of pendant onium salt residue, has a higher activity than does catalyst **8**, which is more hydrophilic. On the other hand, these two catalysts take a more contracted conformation in ordinary organic solvents, with most of the hydrophilic pendant onium salt residues being confined to the inside of the contracted polymer main chain. The activity of catalyst **13**, containing small amounts of the pendant quaternary onium salt residue, was thus dramatically reduced in ordinary organic solvents.

Kinetics of the Addition Reaction of Epoxy Compound with Active Ester Using Soluble Polymer-Supported Quaternary Onium Salt. To obtain detailed kinetic information on the addition reaction of epoxy compounds with active esters using polymer-supported catalysts, the reaction of PGE with PTA was carried out under various concentrations of catalyst **6** in DMF at 80 °C. As shown in Figure 7, the observed pseudo-first-order rate constants (k_1) of the reaction plotted against the catalyst concentrations show a straight line passing through the origin. This result means that the addition reaction of epoxy compounds with active esters does not proceed without a catalyst, and the reaction is proportional to the catalyst concentration.

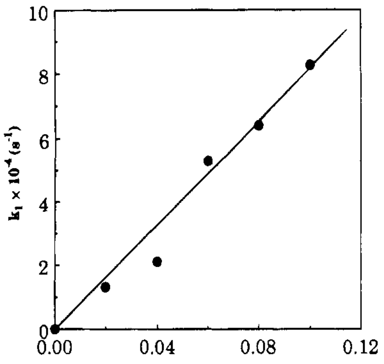


Figure 7. Correlation between the observed pseudo-first-order rate constant and the catalyst concentration on the reaction of PGE (4 mmol) with PTA (4 mmol) using catalyst **6** in DMF (2 mL) at 80 °C.

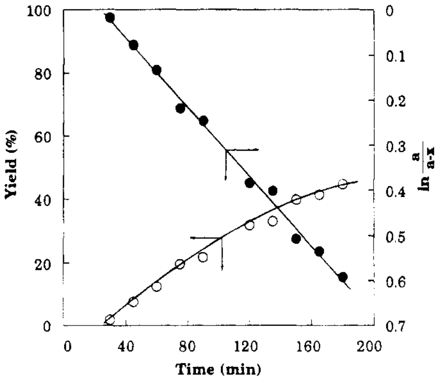


Figure 8. First-order dependence of the reaction in excess amounts of PTA (73.8 mmol) and PGE (7 mmol) using catalyst **13** (0.07 mmol) in DMF (9.1 mL) at 80 °C: $a = [\text{PGE}]_{\text{initial}}$, $x = [\text{PGE}]_{\text{decreased}}$.

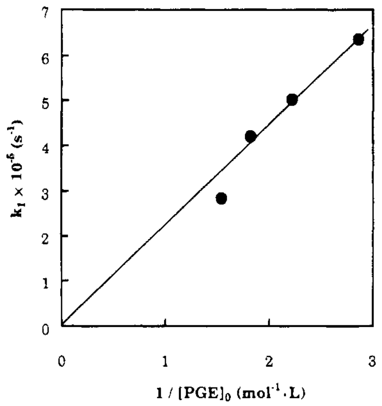
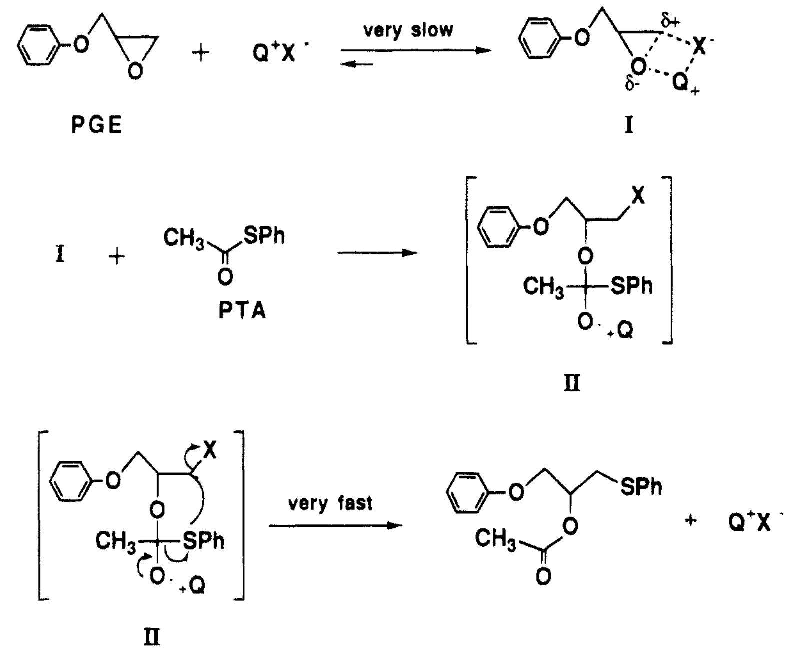


Figure 9. Correlation between the observed pseudo-first-order rate constant and the reciprocal epoxy concentration: carried out with PTA (73.8 mmol) and catalyst **13** (0.07 mmol) in DMF at 80 °C.

When the reaction of PGE with excess amounts of PTA was performed in DMF at 80 °C using 1 mol % of catalyst **13** to the PGE, as shown in Figure 8, the observed rate of reaction obeyed first-order kinetics and did not yield a straight line when plotted against the yield of reaction product PPA. That is, the rate of reaction correlated with the concentration of the epoxy compound. Furthermore, as shown in Figure 9, the observed pseudo-first-order rate constants (k_1) of the reaction plotted against the reciprocal of the initial epoxy concentration [PGE]$_0$ gives a straight line passing

Scheme 3



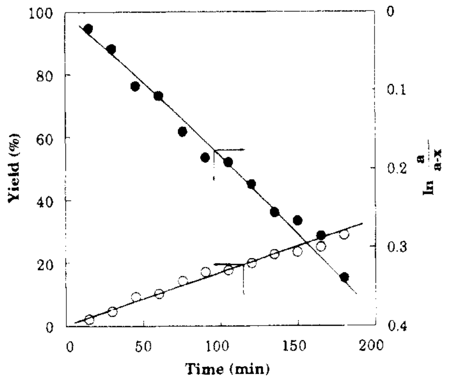


Figure 10. Zero-order dependence of the reaction in excess amounts of PGE (73.8 mmol) and PTA (7 mmol) using catalyst **13** (0.07 mmol) in DMF (9.1 mL) at 70 °C): a = $[\mathrm{PTA}]_{\mathrm{initial}}$, x = $[\mathrm{PTA}]_{\mathrm{decreased}}$.

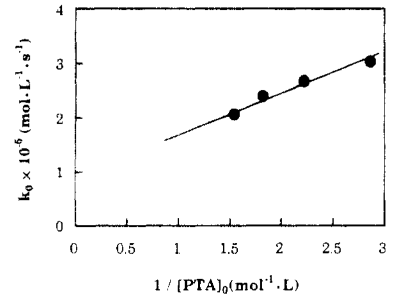


Figure 11. Correlation between the observed zero-order rate constant and the reciprocal ester concentration: carried out with PGE (73.8 mmol) and catalyst **13** (0.07 mmol) in DMF at 70 °C.

through the origin when the reaction is carried out under the same catalyst concentration.

When the reaction of large amounts of PGE with PTA was conducted in the presence of 1 mol % of catalyst **13** to PTA at 70 °C, the observed rate of reaction obeyed very clearly zero-order kinetics and did not give a straight line when plotted with first-order kinetics (Figure 10). As shown in Figure 11, however, the observed zero-order rate constants (k_0) of the reaction plotted against the reciprocal of the initial ester concentration $[\mathrm{PTA}]_0$ yielded a sloping straight line when the reaction took place under the same catalyst concentration. This result shows that the rate of addition reaction of epoxy compound with active ester may also be affected by the ester concentration, although in an earlier paper[20] on the addition reaction of epoxy compound with active ester catalyzed by insoluble polymer-supported quaternary onium salt in toluene such a correlation was not investigated.

From the kinetic data in Figures 7 and 9, it can be established that the rate of addition reaction of epoxy compound with active ester in a homogeneous system using soluble polymer-supported catalyst containing pendant quaternary onium salt as a catalyst is proportional to the product of concentration of catalyst [Cat.] and concentration of epoxy compound [PGE] as in the following equation:

$$d[\mathrm{PPA}]/dt = k_2[\mathrm{Cat.}][\mathrm{PGE}]$$

where k_2 is the second-order rate constant and [PPA] is the concentration of the product, 1-phenoxy-3-(phenylthio)-2-propyl acetate (PPA).

Therefore, as shown in Scheme 3, new, improved picture of the reaction mechanism for reaction of epoxy compound with active ester in a homogeneous system catalyzed by soluble polymer-supported onium salts can be proposed based on the above kinetic results and taking into account the results shown in Figure 11.

The catalyst, quaternary onium salt, attacks the epoxy compound to give intermediate I, which is a rate-determining step. The produced intermediate I reacts with the active ester to form unstable intermediate II, which then decomposes spontaneously to produce the product (PPA) and the polymer-supported quaternary onium salt (Q^+X^-). We recently proposed[24] a similar reaction mechanism based on kinetic data for the reaction of epoxy compounds with active esters catalyzed by insoluble polymer-supported tertiary amines.

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