Pergamon

Tetrahedron 55 (1999) 6311–6318

TETRAHEDRON

One-Pot Synthesis of Poly(cyclic ortho ester)s by the Reaction of Potassium Perfluoroalkanoates with Epibromohydrin Using Two-Step Catalysis of Quaternary Onium Salts

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Received 8 December 1998; accepted 25 February 1999

Abstract: One-pot synthesis of poly(cyclic ortho ester)s by the reaction of potassium perfluoroalkanoates with epibromohydrin (EBH) using quaternary onium salts is described. The reaction of potassium trifluoroacetate (KTFA) with EBH using quaternary onium salts such as tetrabutylphosphonium bromide (TBPB) produces the polymer with five-membered cyclic ortho ester structure in the backbone. This means that quaternary onium salts act as phase-transfer catalysts in the first step and polymerization catalysts in the second step during the reaction. © 1999 Elsevier Science Ltd. All rights reserved.

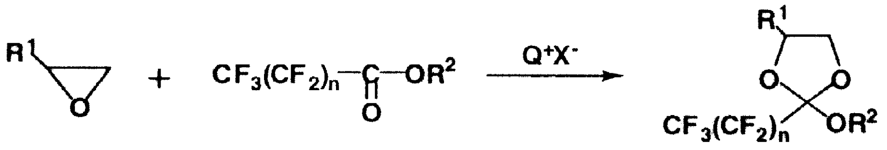
INTRODUCTION

Phase-transfer catalysis is a very convenient and useful method for synthetic organic chemistry and polymer synthesis. Our research group has studied in detail chemical modifications[1] of polymers such as poly(chloromethylstyrene) (PCMS) with potassium carboxylates using quaternary onium salts or crown ethers as phase-transfer catalysts (PTC). Moreover, photosensitive polymers[2] and photoresponsive polymers[3] for solar energy storage were successfully synthesized by the chemical modifications of PCMS using PTC.

Meanwhile, the authors found a new catalysis of quaternary onium salts or crown ether complexes on the addition reactions of cyclic ethers or sulfides with carboxylic acid derivatives[4] such as acyl chlorides and active carboxylic esters. For example, the addition reaction of oxiranes[5] or thiiranes[6] with *S*-phenyl thioacetate using the aforementioned catalysts proceeded smoothly and regioselectively to give the corresponding products. Addition reactions of oxiranes with active aromatic halides,[7] silyl chlorides,[8] phosphonic dichlorides,[9] and sulfonyl chlorides[10] also proceeded smoothly using the same catalysts under mild reaction conditions. An advantage of those reactions is the regioselective transformation of oxiranes to produce β-addition products. The regioselective reactions were applied to the synthesis of polymers with well-defined structures using addition reactions of bis(oxirane)s and diacyl chlorides,[11] dichlorosilanes,[8] phosphonic dichlorides[9], etc. An acyl transfer polymerization[12] of thiiranes was successfully achieved using carboxylic acid derivatives as initiators and quaternary onium salts or crown ether complexes as catalysts. A regioselective insertion of thiiranes into a poly(*S*-thioester) provided successfully new sequence-ordered polymers.[13]

We recently reported a unique cycloaddition reaction[14] of oxiranes with alkyl perfluoroalkanoate using the catalysts, which provided five-membered cyclic ortho esters.

PII: S0040-4020(99)00207-0

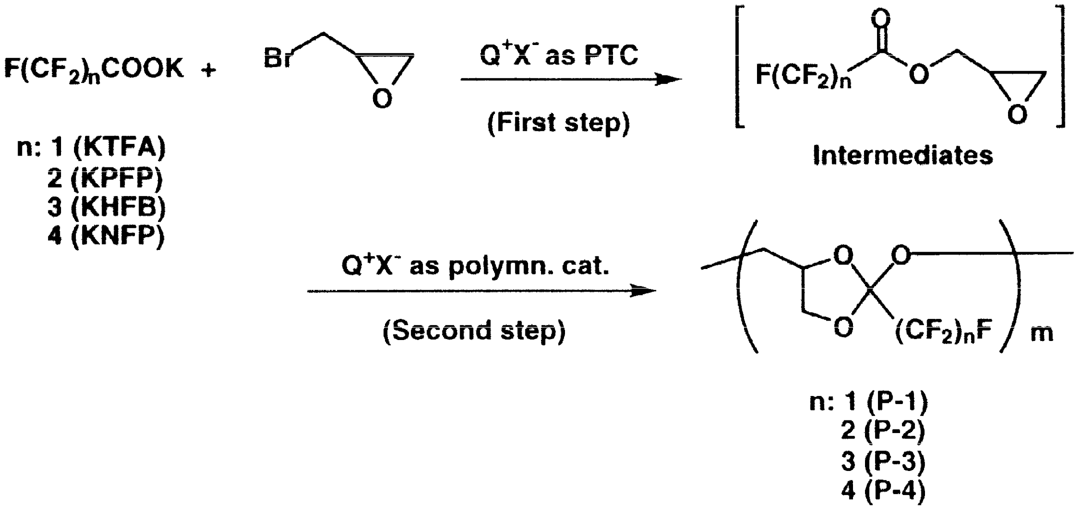


Scheme 1

It was found that although the reaction of oxiranes with alkyl carboxylates such as ethyl acetate or ethyl benzoate did not proceed at all, the reaction with alkyl perfluoroalkanoates proceeded very smoothly in the presence of quaternary onium salts. Furthermore, the cycloaddition reaction was successfully applied to the synthesis of poly(cyclic ortho ester)s[15] by the cycloaddition polymerization of bis(oxirane)s with bifunctional trifluorocarboxylates. It was also suggested that those cycloaddition reactions using conventional Lewis acids such as $BF_3 \cdot OEt_2$ did not proceed because of the acid-initiated ring-opening polymerization of the used oxiranes. Synthesis of ortho esters by Lewis acid catalyzed reactions of oxiranes[16] with certain carbonyl compounds is known, however, the reactions include the acid-initiated ring-opening polymerization of oxiranes as a side reaction. More recently, poly(cyclic ortho ester)s were synthesized selectively from glycidyl carboxylates using a bulky Lewis acid.[17] Thus, it should be emphasized that an advantage of the reactions using quaternary onium salts or crown ether complexes is the selective transformation of oxiranes under neutral conditions.

From these backgrounds, we designed a one-pot synthesis[18] of poly(cyclic ortho ester)s by the reaction of potassium perfluoroalkanoates with an oxirane on the basis of two kinds of catalyses of quaternary onium salts. In the reaction, glycidyl ester derivatives as intermediates would be produced by phase-transfer catalysis of those catalysts. Then, the cycloaddition polymerization of the formed glycidyl ester derivatives is catalyzed by quaternary onium salts to provide the corresponding poly(cyclic ortho ester)s.

In this paper, two-step catalysis of quaternary onium salts as phase-transfer catalysts and polymerization catalysts is described. New poly(cyclic ortho ester)s was synthesized by the one-pot reaction of potassium perfluoroalkanoates with epibromohydrin using quaternary onium salts. The characteristics of the one-pot synthesis were also investigated.



Scheme 2

RESULTS AND DISCUSSION

The reaction of KTFA with EBH was conducted using 8 mol% of tetrabutylammonium bromide (TBAB) as a catalyst in various solvents at 90 °C for 24 h (Table 1). In all cases, the reaction took place in heterogeneous systems, in which KTFA was insoluble. When the reaction was carried out in low-polar solvents such as anisole or chlorobenzene, the corresponding polymer was not obtained. This means that the first process, nucleophilic substitution reaction of KTFA with EBH to produce the corresponding intermediate (glycidyl trifluoroacetate), did not occur effectively, since the cycloaddition reaction of oxiranes with ethyl trifluoroacetate proceeded smoothly using TBAB in anisole. On the other hand, the reaction proceeded smoothly in *N*-methylpyrrolidone (NMP) to afford a polymer with number-average molecular weight (M_n) of about 9000 in 73 % yield, which was insoluble part in hexane. The reaction was efficiently enhanced in tetrahydrofuran (THF), or *N, N*-dimethylacetamide (DMAc) to produce the polymer with M_n of 11000. It was found that the polymer with high molecular weight was obtained from the reaction in polar solvents, in which the nucleophilic substitution reaction of KTFA with EBH proceeded smoothly by using TBAB as a PTC.

The structure of the resulting polymer (P-1) was identified using IR and ^{1}H NMR spectroscopy. The IR spectrum showed characteristic peaks at 2962 cm^{-1} due to C-H stretching, at 1280 cm^{-1} due to C-F stretching, and at 1184 and 1116 cm^{-1} due to the C-O-C stretching. In addition, no peaks due to carbonyl groups and oxirane ring of EBH were observed in the expected regions. As shown in Figure 1, ^{1}H NMR spectral data were identified with reference to the spectral data of a poly(cyclic ortho ester) previously reported by Hall.[19] It was proved that the targeted polymer with five-membered cyclic ortho ester in the main chain was obtained by the one-pot reaction of KTFA with EBH.

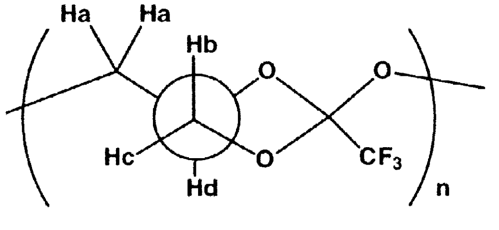
Table 1. Solvent Effect on the reaction of KTFA with EBH using TBAB[a]

Solvent	Yield, %[b]	M_n[c]	M_w / M_n[c]
Anisole	0	---	---
Chlorobenzene	0	---	---
THF	77	11600	1.44
NMP	73	8600	1.27
DMAc	64	11000	1.31
DMSO	40	11000	1.58

[a] The reaction was carried out with KTFA (3 mmol) and EBH (3 mmol) using TBAB (8 mol%) in solvent (1 mL) at 90 °C for 24 h.

[b] Insoluble parts in n-hexane.

[c] Estimated by GPC based on polystyrene standards.



^{1}H NMR data (δ)
3.62-3.94 (m, 2 H, Ha)
3.94-4.09 (m, 1 H, Hb)
4.09-4.30 (m, 1 H, Hc)
4.30-4.81 (m, 1 H, Hd)

Figure 1.

The effect of the catalysts on the reaction of KTFA with EBH was examined (Table 2). When the reaction was carried out without catalysts in NMP at 90 °C for 24 h, the polymer with M_n of 6700 was obtained in 56 % yield. It seems that the substitution reaction of KTFA with EBH proceeded gradually in NMP to form glycidyl trifluoroacetate as the intermediate eliminating KBr in the first step, and then the produced KBr catalyzed the following cycloaddition polymerization of the intermediate. Although isolation of the intermediate was attempted, a mixture of the intermediate and polymer was obtained. The reaction using 18-crown-6 (18-C-6) or 15-crown-5 (15-C-5) provided the polymer with M_n of about 10000. In polyaddition reaction, catalytic activity can be estimated generally by the molecular weight of the resulting polymers. Thus, the increase of the molecular weight might be ascribed to extraction of solid KTFA in the NMP solution by 18-C-6 to accelerate the substitution reaction of CF_3COO^- with EBH (first step). After the substitution reaction, 18-C-6 incorporates eliminated KBr to form 18-C-6/KBr complex, which catalyzed the following cycloaddition polymerization of the intermediate (second step). In the case of 15-C-5, a complex of KBr and double 15-C-5 would be produced. Quaternary onium salts such as tetrabutylammonium chloride (TBAC) and tetrabutylphosphonium bromide (TBPB) also enhanced the reaction, in particular, the reaction using TBAC provided the polymer with the highest molecular weight (M_n : 12000). This means that TBAC enhanced efficiently the substitution reaction in the first step as PTC in the heterogeneous reaction system, then catalyzed the following cycloaddition polymerization.

Table 2. Effect of Catalysts on the Reaction of KTFA or KPFP with EBH in NMP[a]

Perfluoroalkanoates	Catalyst	Yield, %[b]	M_n[c]	M_w / M_n[c]
KTFA	None	56	6700	1.37
	TBAC	60	11900	1.32
	TBAB	73	8600	1.27
	TBPC	43	10500	1.29
	TBPB	63	11300	1.30
	15-C-5	54	10400	1.29
	18-C-6	59	10100	1.32
KPFP	None	50	5900	1.24
	TBAC	50	6200	1.24
	TBAB	45	6200	1.24
	TBAI	42	4900	1.25
	TBPB	60	6000	1.26
	15-C-5	56	5900	1.22
	18-C-6	48	5500	1.24

[a] The reaction was carried out with KTFA or KPFP (3 mmol) and EBH (3 mmol) using catalysts (8 mol%) in NMP (1 mL) at 90 °C for 24 h.

[b] Insoluble parts in n-hexane.

[c] Estimated by GPC based on polystyrene standards.

Table 3. One-Pot Synthesis of Poly(cyclic ortho ester)s by the Reaction of Potassium Perfluoroalkanoates and EBH without Catalysts [a]

Perfluoroalkanoates	Yield, % [b]	M_n [c]	M_w / M_n [c]
KTFA	56	6700	1.37
KPFP	49	7800	1.93
KHFB	73	2000	1.36
KNFP	43	1500	3.13

[a] The reaction was carried out with KTFA (3 mmol) and EBH (3 mmol) in NMP (1 mL) at 90 °C for 24 h.

[b] Insoluble parts in n-hexane.

[c] Estimated by GPC based on polystyrene standards.

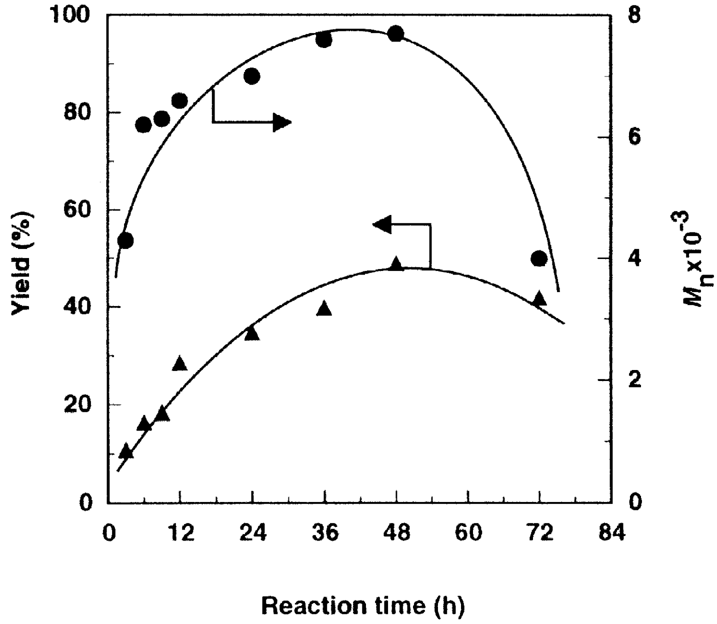


Figure 2. Time-Course of the Reaction of KPFP with EBH without Catalysts at 90 ^{o}C.

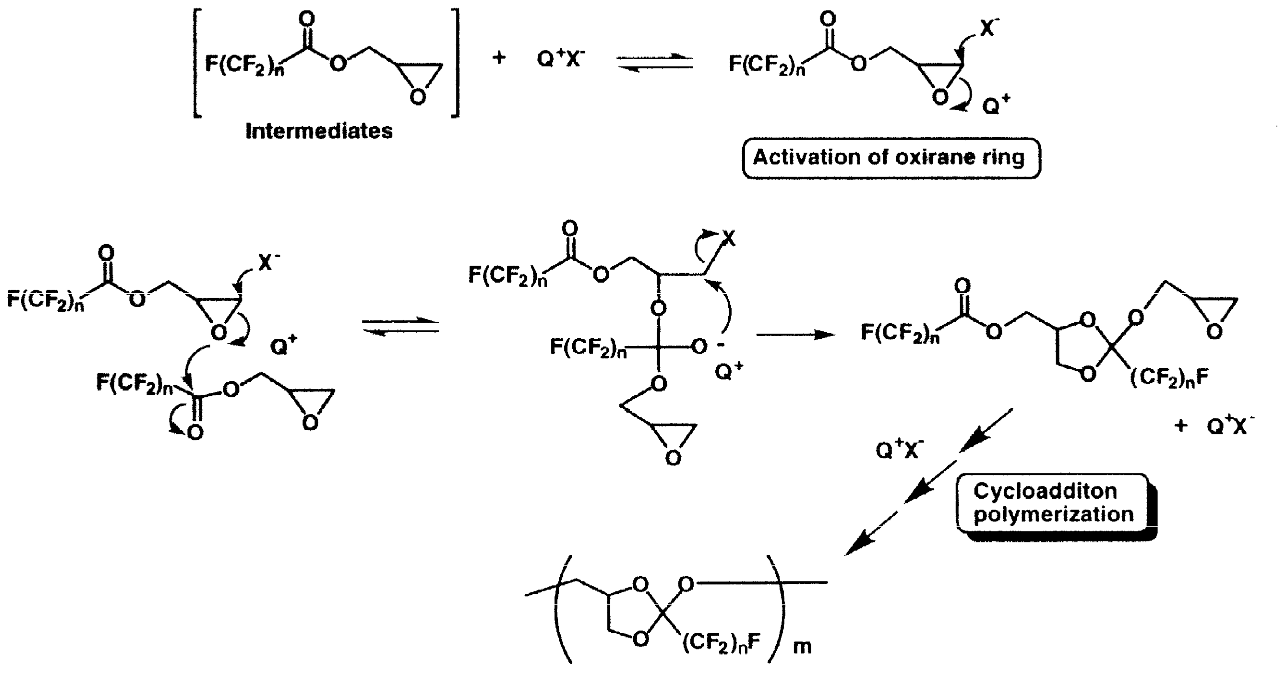
The reaction of potassium pentafluoropropanoate (KPFP) with EBH was also carried out without catalysts under the same conditions to obtain the corresponding polymer with M_n of 6000. When the reaction was conducted using quaternary onium salts such as TBAB, TBPB, or crown ethers, M_ns of the resulting polymers were about 6000 (Table 2). Thus, the catalytic effect was not observed in the reaction of

KPFP with EBH in NMP. This suggests that the substitution reaction of the extracted $CF_3CF_2COO^-$ by the used catalysts with EBH proceeded very slowly. Because the nucleophilicity of $CF_3CF_2COO^-$ is relatively low compared to CF_3COO^- due to the electron withdrawing effect of CF_3CF_2 group.

Figure 2. shows the time-course of the reaction of KPFP with EBH without catalysts. The polymer yield and molecular weight increased gradually with the reaction time, and reached to 50 % yield and M_n of ca. 8000 for 48 h, respectively. This means that the reaction proceeded in a step growth polymerization, that is, cycloaddition polymerization. After 48 h, the yield and the molecular weight of the obtained polymer decreased. It seems that the produced cyclic ortho ester group in the polymer decomposed gradually to decrease its molecular weight.

In the case of the reaction of EBH with potassium heptafluorobutanoate (KHFB) or potassium nonafluoropentanoate (KNFP) without catalysts under the similar conditions, the corresponding polymers with M_ns of 2000 and 1500 were obtained, respectively (Table 3). This means that the molecular weights of the obtained poly(cyclic ortho ester)s decreased with increasing the length of the perfluoroalkyl chains. A reason of the low molecular weights of the resulting polymers is low nucleophilicity of the corresponding perfluoroalkanoate anions to EBH in the first step. In addition, it seems that the cycloaddition reaction of the corresponding intermediates from the potassium perfluoroalkanoates did not proceed smoothly because of the steric hindrance of the long perfluoroalkyl chains of the used potassium perfluoroalkanoates.

A reaction mechanism for the cycloaddition polymerization of the produced intermediates is proposed as shown in Scheme 3. Oxirane ring of the intermediate will be activated by halides (X^-) of quaternary onium salts, then react with carbonyl group of the another intermediate to produce a tetrahedral intermediate. In the intermediate, oxy-anion attack intramolecular β-carbon to replace the X recovering Q^+X^-, and a cyclic ortho ester derivative was provided. Then, cycloaddition reaction of the produced cyclic ortho ester derivatives would proceed in a step growth polymerization to give a poly(cyclic ortho ester).



Scheme 3

EXPERIMENTAL

Measurements

Infrared (IR) spectra were measured on a JASCO Model IR-700 spectrometer. ^1H NMR spectra were recorded on JEOL Models JNM EX-90 (90 MHz) or JNM FX-200 (200 Hz) instruments. The molecular weights were estimated by gel permeation chromatography (GPC) with the use of TOSOH Model HLC-8020 GPC system with TSK-gel columns (2 x GMH_{XL} and 2 x $G2000H_{XL}$, eluent: DMF, calibrated with narrow molecular weight polystyrene standards).

Materials

Potassium perfluoroalkanoates were prepared in a conventional method: Potassium trifluoroacetate (KTFA) was prepared with KOH in methanol followed by evaporating methanol to yield solid products. The obtained products were washed with small amount of methanol and dried under reduced pressure to obtain KTFA as white powders. Potassium pentafluoropropanoate (KPFP), potassium heptafluorobutanoate (KHFB), and potassium nonanefluoropentanoate (KNFP) were also prepared in the same way. Tetrabutylammonium bromide (TBAB, Tokyo Kasei Kogyo Co., Ltd.) was purified by recrystallization four times with dried ethyl acetate. Other quaternary onium salts and crown ethers were used as received. Anisole, chlorobenzene, *N,N*-dimethylacetamide (DMAc), NMP, and dimethylsulfoxide (DMSO) were distilled over CaH_2. Tetrahydrofuran (THF) was distilled over sodium wires. Epibromohydrin (EBH) and other reagents were used as received.

One-pot reaction of KTFA with EBH

A typical procedure is as follows; TBAB (0.0774 g, 0.24 mmol) was placed in an ampoule tube under dry atmosphere (moisture <10 %), and dried under reduced pressure at 70 °C for 5 h. KTFA (0.4564 g, 3 mmol) and EBH (0.4109 g, 3 mmol), and NMP (1 mL) were added into the ampoule tube under the dry atmosphere, then the tube was sealed followed by heating at 90 °C for 24 h. The reaction mixture was diluted with chloroform, washed five times with small amount of water, then dried with $MgSO_4$. After filtration of $MgSO_4$, chloroform was evaporated, and then poured into n-hexane. The resulting polymer was purified by reprecipitation with chloroform and n-hexane, then dried under reduced pressure to obtain a polymer (P-1). Yield: 0371 g (73 %). M_n : 8600, M_w/M_n : 1.27. IR (neat): 3284 ($\nu_{O\text{-}H}$), 2962 ($\nu_{C\text{-}H}$), 1280 ($\nu_{C\text{-}F}$), 1184, 1116 cm^{-1} ($\nu_{C\text{-}O\text{-}C}$). ^1H NMR (90 MHz, $CDCl_3$, TMS) δ 3.62 – 3.94 (m, 1 H), 3.94 – 4.0 (m, 1 H), 4.09 – 4.30 (m, 1 H), 4.30 – 4.81 (m, 2 H).

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