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3-Alkoxyphthalides as Nonhomopolymerizable, Highly Reactive Comonomers for ABC Pseudo-Periodic Terpolymers and Degradable Polymers via Cationic Co- and Terpolymerizations with Oxiranes and/or Vinyl Ethers

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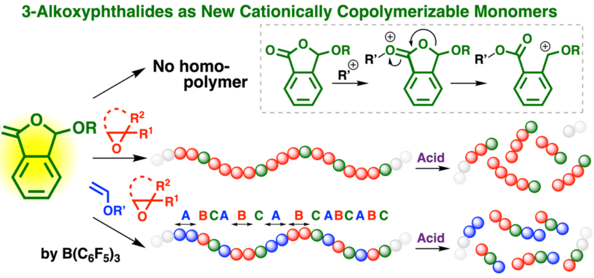


Abstract

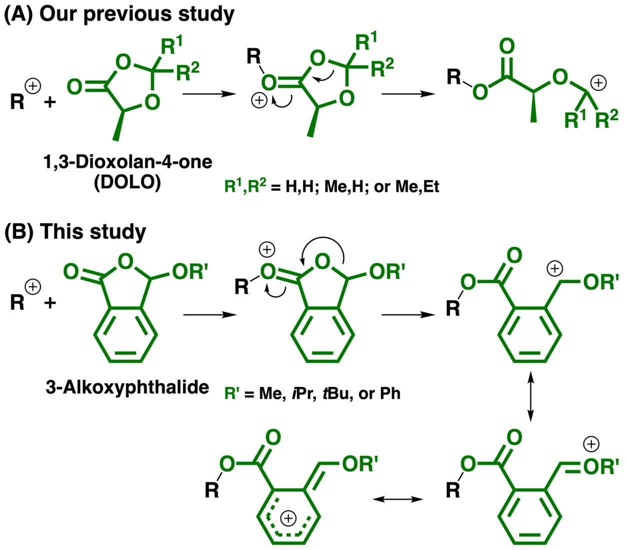
3-Alkoxyphthalides (ROPTs) are promising candidate monomers that react with a cationic species at the carbonyl group and subsequently undergo ring-opening to generate a carbocation adjacent to both aryl and alkoxy groups (oxocarbenium ion). In this study, cationic polymerizations of ROPTs bearing methoxy, isopropoxy, *tert*-butoxy, or phenoxy groups were investigated with a particular focus on the copolymerizations with oxiranes. Cationic homopolymerization of ROPTs did not occur under any of the examined conditions. In contrast, cationic copolymerizations of ROPT with oxiranes, such as 4-vinyl-1-cyclohexene-1,2-epoxide (VCHO), proceeded smoothly via very frequent crossover reactions. The copolymers could be degraded under acidic conditions due to the cleavage of the acetal moieties generated by the crossover reactions from ROPT to VCHO. Cationic copolymerizations of ROPT with most of the examined vinyl ethers (VEs) and styrene derivatives did not proceed, likely due to inefficient crossover reactions from the vinyl monomers to ROPT. However, cationic terpolymerizations of VE, oxirane, and ROPT successfully proceeded via highly

selective crossover reactions, resulting in ABC-type pseudo-periodic terpolymers under optimized conditions.

Introduction

Cationic ring-opening polymerization (ROP) is a highly promising strategy to produce polymers with functional groups, such as ether, ester, amino, and siloxy groups, in the main chain from various cyclic monomers.[1–7] The propagation reaction in cationic ROP by the active chain end mechanism generally consists of the reaction of a propagating species, such as an oxonium ion, with the reactive group of a monomer through the ring-opening reaction of the propagating species. In the design of new cyclic monomers for cationic ROP, we need to consider various factors, including ring strain, reactive groups, and generated propagating species. In particular, the release of ring strain is an important driving force of ROP due to the small enthalpic contribution of new bond formation in a propagating reaction, unlike vinyl polymerization, because, in many cases, the same functional group in a monomer is regenerated in a polymer chain after a propagating reaction in ROP. Cyclic compounds, such as tetrahydropyran, 1,4-dioxane, and 1,3-dioxane, do not undergo cationic homopolymerization due to very small ring strain. However, cationic copolymerizations with other monomers are often effective for incorporating such nonhomopolymerizable cyclic compounds into polymer chains.[8–13]

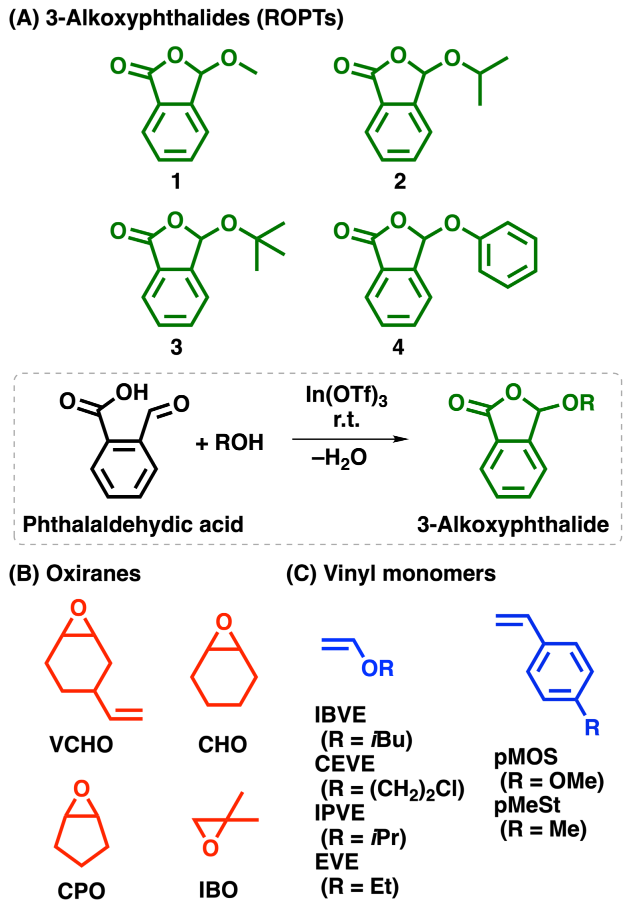
Cyclic hemiacetal esters are of great interest as cyclic monomers for cationic ROP. A cyclic hemiacetal ester potentially reacts with a cationic species through the reaction of the carbonyl group and subsequent ring-opening to generate an alkoxy group-adjacent carbocation (oxocarbenium ion). This cation is stabilized by electron donation from the alkoxy group via the resonance effect, which is advantageous for efficient cation generation. Hillmyer and coworkers reported that a six-membered cyclic hemiacetal ester undergoes cationic homopolymerization with a protic acid as a catalyst.[14] A seven-membered cyclic hemiacetal ester[15] and bicyclic monomers containing a five-membered hemiacetal ester moiety[16] also exhibit homopolymerizability. However, five-membered cyclic hemiacetal esters (1,3-dioxolan-4-ones, DOLOs; Scheme 1A)[17–19] were cationically nonhomopolymerizable, as demonstrated in our study,[20] potentially due to very small ring strain. In contrast, cationic copolymerization of DOLO was feasible when combined with appropriate oxiranes. Ester and acetal moieties are formed via a crossover reaction between oxirane and DOLO in the copolymerization, which is in contrast to the absence of DOLO homopolymerization that requires hemiacetal ester formation in the main chain. In addition, cationic terpolymerization of vinyl ether (VE), oxirane, and DOLO proceeded via the crossover reaction from the DOLO-derived cation (Scheme 1A) to VE.



Scheme 1. Reactions of a Cation with (A) DOLO or (B) ROPT.

Based on the above background, we focused on 3-alkoxyphthalides (ROPTs)[21–23] as a new cyclic hemiacetal ester monomer. As shown in Scheme 1B, ROPT potentially reacts with a cationic species to generate a carbocation adjacent to both aryl and alkoxy groups (oxocarbenium ion). Therefore, this cation is more stable than the DOLO-derived carbocation adjacent to only an alkoxy group (Scheme 1A) and is expected to be generated more efficiently. Moreover, ROPTs with various alkoxy groups are obtained by the reactions of phthalaldehydic acid and various alcohols. However, to the best of our knowledge, there have been no examples of cationic ROP of ROPTs.

In this study, we aimed to examine the cationic polymerization of ROPTs. Methoxy- (**1**), isopropoxy- (**2**), *tert*-butoxy- (**3**), and phenoxy-containing (**4**) ROPTs were synthesized from phthalaldehydic acid and their corresponding alcohols (Scheme 2A). These ROPTs did not undergo cationic homopolymerizations. However, copolymerizations with oxiranes successfully proceeded to yield degradable polymers with acetal and ester moieties in the main chain. Moreover, cationic terpolymerization of VEs, oxiranes and ROPTs occurred via highly selective crossover reactions in the direction of VE→oxirane, oxirane→ROPT, and ROPT→VE, resulting in ABC-type pseudo-periodic terpolymers under optimized conditions.



Scheme 2. (A) ROPTs Used in This Study. (B) Oxiranes and (C) Vinyl Monomers Used for the Co- and Terpolymerizations with ROPTs

Experimental Section

See the Supporting Information for the Materials, Polymerization procedures, Characterization, and Acid hydrolysis subsections.

Synthesis of ROPTs. ROPTs **1**, **2**, **3**, and **4** were synthesized by the acetalization of phthalaldehydic acid (TCI; >98.0%) with methanol (Nacalai Tesque; >99.0%), 2-propanol (Nacalai Tesque; >99.0%), *tert*-butyl alcohol (Nacalai Tesque; >98.0%), and phenol (Nacalai Tesque; >98.0%), respectively. $In(OTf)_3$ (Sigma–Aldrich or Strem; 99%) was used as a catalyst unlike the past examples (Scheme 2A).[21–23] After the reaction for a day (**1**) or three days (**2**, **3**, and **4**), the reactions were quenched with Et_3N (Nacalai Tesque; >98.0%), extracted with dichloromethane, and then washed with water (**1**, **2**, and **3**) or aqueous sodium hydroxide solution and then water (**4**) followed by brine. The organic layer was dried over sodium sulfate, and the solvents were evaporated under reduced pressure. The residual solid was recrystallized twice from *n*-hexane/dichloromethane to yield a ROPT monomer. Each is described below:

3-Methoxyphthalide (1): Synthesized from phthalaldehydic acid (20 g) and methanol (300 mL) using In(OTf)$_3$ (0.37 g). Colorless solid. Yield: 22%. ^{1}H NMR (CDCl$_3$): δ 7.90 (Ar, 1H), 7.71 (Ar, 1H), 7.61 (Ar, 1H), 7.58 (Ar, 1H), 6.31 (s, 1H), 3.63 (s, 3H).^{13}C NMR (CDCl$_3$): δ 168.6, 144.7, 134.4, 130.9, 127.2, 125.5, 123.4, 103.1, 56.8. MS (ESI) *m/z* $[M + Na]^+$, calcd: 187.0366, found: 187.0369.

3-Isopropoxyphthalide (2): Synthesized from phthalaldehydic acid (20 g) and 2-propanol (300 mL) using In(OTf)$_3$ (0.37 g). Colorless solid. Yield: 22%. ^{1}H NMR (CDCl$_3$): δ 7.88 (Ar, 1H), 7.70 (Ar, 1H), 7.58 (Ar, 1H), 7.55 (Ar, 1H), 6.42 (s, 1H), 4.24 (sep, 6.0 Hz, 1H), 1.36 (d, 6.0 Hz, 3H), 1.33 (d, 6.0 Hz, 3H). ^{13}C NMR (CDCl$_3$): δ 168.9, 145.5, 134.3, 130.7, 127.2, 125.4, 123.3, 101.4, 73.7, 23.3, 22.1. MS (ESI) *m/z* $[M + Na]^+$, calcd: 215.0679, found: 215.0682.

3-*tert*-Butoxyphthalide (3): Synthesized from phthalaldehydic acid (20 g) and *tert*-butyl alcohol (400 mL) using In(OTf)$_3$ (0.37 g). Colorless solid. Yield: 29%. ^{1}H NMR (CDCl$_3$): δ 7.81 (Ar, 1H), 7.68 (Ar, 1H), 7.56 (Ar, 1H), 7.48 (Ar, 1H), 6.55 (s, 1H), 1.45 (s, 9H). ^{13}C NMR (CDCl$_3$): δ 169.2, 146.4, 134.3, 130.5, 127.2, 125.3, 123.2, 97.9, 77.8, 28.6. MS (ESI) *m/z* $[M + Na]^+$, calcd: 229.0835, found: 229.0837.

3-Phenoxyphthalide (4): Synthesized from phthalaldehydic acid (21 g) and phenol (100 mL) using In(OTf)$_3$ (0.37 g). Colorless solid. Yield: 7%. ^{1}H NMR (CDCl$_3$): δ 7.94 (Ar, 1H), 7.78 (Ar, 1H), 7.71 (Ar, 1H), 7.66 (Ar, 1H), 7.38 (PhO, 2H), 7.24 (PhO, 2H), 7.14 (PhO, 1H). ^{13}C NMR (CDCl$_3$): δ 168.3, 156.7, 144.6, 134.8, 131.3, 129.9, 126.9, 125.7, 123.9, 123.8, 117.2, 99.8. MS (ESI) *m/z* $[M + Na]^+$, calcd: 249.0522, found: 249.0526.

Results and Discussion

Cationic Homopolymerization of ROPTs

Cationic homopolymerization of **1**, **2**, or **3** was conducted using $B(C_6F_5)_3$, $GaCl_3$, or BF_3OEt_2 as a Lewis acid catalyst in dichloromethane at –78 or 0 °C at monomer concentrations of 0.75 or 1.5 M (Table 1). However, polymerizations did not proceed at all under any conditions. The inertness of ROPTs in homopolymerization is similar to that of DOLOs.[20]

Table 1. Cationic Homopolymerization of ROPTs under Various Conditions [a]

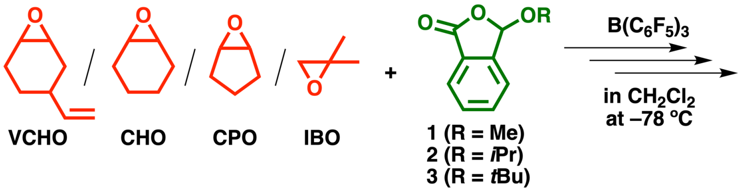
entry	catalyst		temp (°C)	ROPT (M)		time	ROPT conv (%)[b]
1	$B(C_6F_5)_3$	3.0 mM	–78	**1**	0.75	24 h	0
2	$B(C_6F_5)_3$	3.0 mM	0	**1**	0.75	168 h	0
3	$GaCl_3$	10 mM	–78	**1**	1.50	140 h	0
4	BF_3OEt_2	10 mM	–78	**1**	1.50	140 h	0
5	$B(C_6F_5)_3$	3.0 mM	–78	**2**	0.75	23 h	0
6	$B(C_6F_5)_3$	3.0 mM	–78	**3**	0.75	23 h	0

[a] In dichloromethane. [b] Determined by ^1H NMR.

Cationic Copolymerization of Oxiranes and ROPTs

To facilitate cationic polymerization of ROPTs, oxiranes were used as comonomers (Scheme 2B, Table 2), which resulted in successful copolymerizations via frequent crossover reactions. As a representative example, the cationic copolymerization of 4-vinyl-1-cyclohexene-1,2-epoxide (VCHO) and **1** is explained in detail. Copolymerization was conducted using $B(C_6F_5)_3$ as a catalyst in dichloromethane at –78 °C. A cationogen was not used; hence, the polymerization was likely initiated by a proton generated via the reaction of adventitious water with $B(C_6F_5)_3$ and/or the direct interaction between the catalyst and VCHO or ROPT.[24] The monomer conversion of VCHO and **1** reached 93% and 37%, respectively, in 2 min, resulting in a polymer product with an M_n of 9.4 × 10^3 (entry 1 in Table 2, Figure 1A; a sharp peak in the low-molecular-weight (low-MW) of the molecular weight distribution (MWD) curve is likely assigned to cyclic oligomers (see Figure S1 for electron spray ionization mass spectrometry (ESI-MS) analysis)). The ^{1}H NMR spectrum of the product (Figure 2A) had a peak at 6.4 ppm (peak 10), which was assigned to an acetal moiety derived from the crossover reaction from **1** to VCHO. A methine proton adjacent to an ester group derived from the crossover from VCHO to **1** exhibited a peak at around 5 ppm (peak 8), although the peak overlapped with a peak of olefin protons (peaks 6 and 7). The assignments of these peaks were confirmed by ^{13}C and 2D (^{1}H–^{1}H COSY, ^{1}H–^{13}C HSQC, and ^{1}H–^{13}C HMBC) NMR analyses (Figures S2–S5). The average numbers of VCHO and **1** units per block were estimated to be 2.3 and 1.0, respectively, from the integral ratios of the ^{1}H NMR spectrum (Figure 2A), indicating that the copolymerization successfully proceeded via very frequent crossover reactions. In addition, the monomer reactivity ratios[25,26] of VCHO and **1** were determined to be 2.3 (VCHO) and approximately 0 (**1**) (Figure 3), which were consistent with both the occurrence of frequent crossover reactions and the nonhomopolymerizability of **1**. Notably, **1** underwent more frequent crossover reactions than DOLOs in the copolymerization with VCHO, as discussed below. In addition, the result shown in Figure 3 indicates that the proportion of **1** in copolymers can be regulated by changing the feed ratio of the monomers.

Table 2. Cationic Copolymerization of ROPTs with Oxiranes at –78 °C[a]



entry	oxirane	ROPT	time	oxirane conv (%)	ROPT conv (%)	M_n × 10^{-3} [b]	M_w/M_n [b]	average unit number per block[c]	
								oxirane	ROPT
1	VCHO	**1**	2 min	93	37	9.4[d]	3.81[d]	2.3	1.0
2		**2**	10 min	65	23	4.9[d]	1.63[d]	2.6	1.0
3		**3**	30 min	82	29	9.0	2.72	2.5	1.0

4	CHO	**1**	2 min	88	23	9.2	3.24	3.5	1.0
5		**2**	2 min	89	27	6.9	2.09	3.4	1.0
6		**3**	5 min	88	28	6.3	2.12	3.1	1.0
7	CPO	**1**	20 h	11	1	0.6	1.40	–	–
8		**2**	19 h	18	4	2.3	1.29	4.3	1.0
9		**3**	22 h	26	6	3.4	1.31	4.5	1.0
10	IBO	**1**	23 h	36	6	0.6	1.70	–	–
11		**2**	23 h	45	9	0.8	1.51	–	–
12		**3**	23 h	58	7	0.4	1.37	–	–

[a] $[\text{Oxirane}]_0 = 0.75$ M, $[\text{ROPT}]_0 = 0.75$ M, $[B(C_6F_5)_3]_0 = 3.0$ mM, in dichloromethane at –78 ºC. [b] By GPC (polystyrene calibration). [c] Calculated by ^{1}H NMR. After purification by preparative GPC (except for entry 2) or reprecipitation in methanol (entry 2). [d] M_n and M_w/M_n were calculated from the polymer peak (the low-MW oligomer peak was not used for calculation).

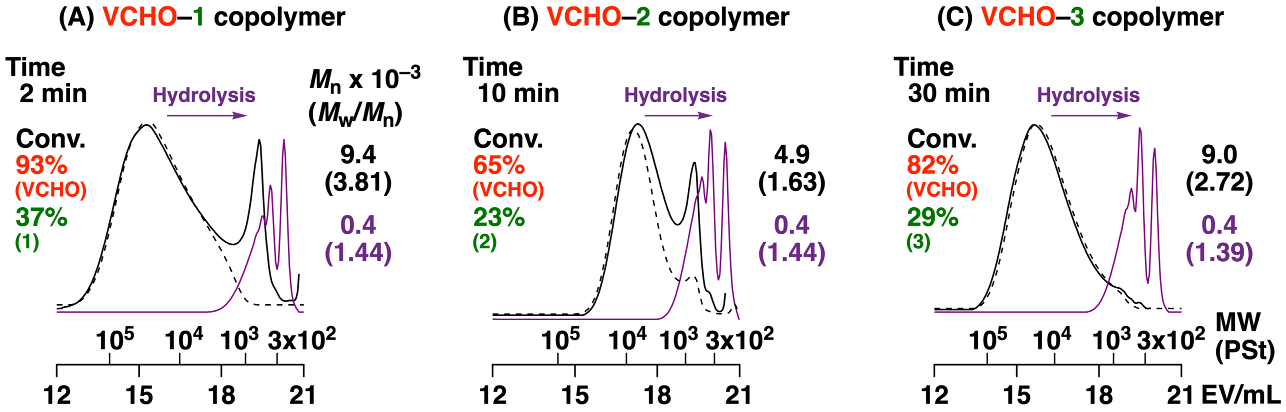


Figure 1. MWD curves of the (A) VCHO–**1** (entry 1 in Table 2), (B) VCHO–**2** (entry 2), and (C) VCHO–**3** (entry 3) copolymers (black; solid: the original products, dashed: after purification by preparative GPC (A and C) or reprecipitation in methanol (B)) and their hydrolysis products (purple; hydrolysis after purification by preparative GPC). See Table 2 for the polymerization conditions.

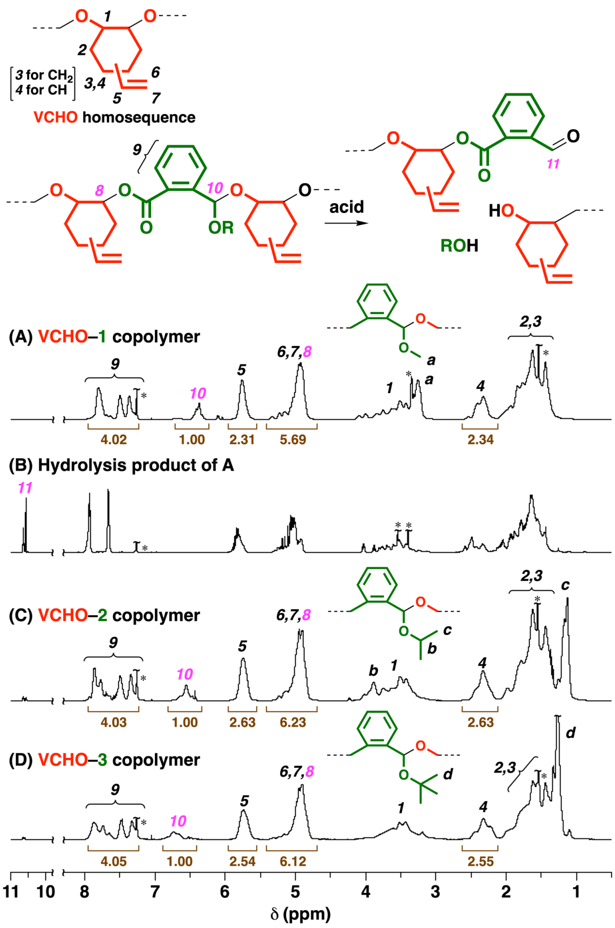


Figure 2. ^{1}H NMR spectra of (A) the VCHO–**1** copolymer (entry 1 in Table 2; Figure 1A), (B) its hydrolysis product (purple curve in Figure 1A), (C) the VCHO–**2** copolymer (entry 2 in Table 2; Figure 1B), and (D) the VCHO–**3** copolymer (entry 3 in Table 2; Figure 1C). After purification by preparative GPC (expect for (B)). Values shown in brown are integral ratios. * Water, $CHCl_3$, methanol, or 1,2-dimethoxyethane.

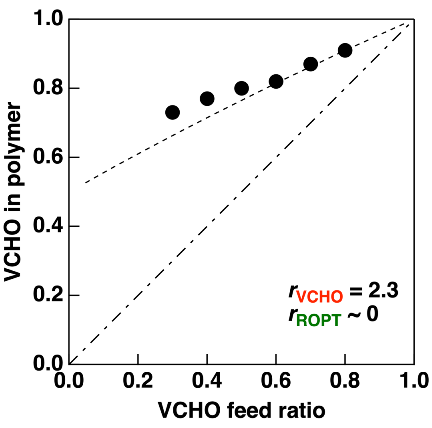


Figure 3. Copolymer compositions in the copolymerization of VCHO and **1** ($[VCHO]_0 + [\mathbf{1}]_0 = 1.0$ M, $[B(C_6F_5)_3]_0 = 1.0$ mM, in dichloromethane at –78 ºC). Polymerization data shown in Table S1 were used. The monomer reactivity ratios were determined by the Kelen–Tüdõs method[25,26] (see also Figure S6). The dashed-dotted line is an azeotropic line. The dotted line was drawn using the r values ($r_{\mathrm{VCHO}} = 2.3$ and the $r_{\mathrm{ROPT}} = 0.0$).

The VCHO–**1** copolymer could be hydrolyzed under acidic conditions via the cleavage of the acetal moieties in the main chain. The peak of the acetal moieties at 6.4 ppm (peak 10) in the ^{1}H NMR spectrum of the copolymer (Figure 2A) disappeared after acid hydrolysis (Figure 2B). Instead, a peak attributed to an aldehyde moiety, which was derived from acetal degradation, appeared at 10.6 ppm. Moreover, a polymer peak completely disappeared in GPC analysis, and instead, a hydrolysis product with an M_n of 0.4×10^3 was obtained (Figure 1A, purple). The very low MW value of the hydrolysis product was also consistent with the small average number of VCHO/**1** units per block (2.3/1.0) derived from very frequent crossover reactions.

Similar copolymerization results were obtained when **2** or **3**, which is the isopropoxy or *tert*-butoxy counterparts of **1**, respectively, was used instead of **1** in the copolymerization with VCHO. In both cases, copolymerizations proceeded to yield polymers with M_n values of thousands (entries 2 and 3 in Table 2; Figure 1B and 1C). The average number of VCHO/**2** or **3** per block was estimated to be 2.6/1.0 and 2.5/1.0, respectively, via ^{1}H NMR analysis (Figure 2C and 2D). In addition, products with MWs similar to those derived from **1** were obtained by acid hydrolysis of the copolymers (Figure 1B and 1C, purple).

Copolymerizations of ROPTs and other oxiranes were also examined. CHO was effective in the copolymerization with **1**, **2**, or **3**, resulting in copolymers with an average number of CHO/**1**, **2**, or **3** units per block of 3.5/1.0, 3.4/1.0 or 3.1/1.0, respectively (entries 4–6 in Table 1; Figures S7 and S8). Copolymers were also obtained when CPO was used with **2** or **3,** although the MWs were lower than those of VCHO and CHO (entries 8 and 9; Figures S9 and S10). An oligomer with an M_n of 0.6×10^3 was obtained from CPO and **1** (entry 7). Moreover, the use of IBO resulted in oligomers with M_n values less than 10^3 (entries 10–12; Figures S11 and S12). The copolymerization at –40 ºC (the other conditions were similar to those for entry 10 in Table 2) proceeded faster than that at –78 ºC (IBO conversion of 73% in 1 h), although the product was an oligomer with an M_n of 0.4 × 10^3. The ineffective copolymerization with IBO is different from the copolymer formation from IBO and DOLOs. The reason of the ineffectiveness is unclear presently. However, as demonstrated below, high-MW polymers were obtained in the terpolymerizations of VE, IBO and ROPT, indicating that the crossover reaction from the ROPT-derived cation to an IBO monomer is inefficient in the copolymerization.

Copolymerizations of oxiranes and **4**, a phenoxy-containing ROPT, could not be examined under the same conditions as those for **1**, **2**, and **3** because **4** was insoluble in dichloromethane at –78 °C. Therefore, the copolymerizations of oxiranes and **4** were conducted at 0 °C. **4** was soluble at this temperature. As a result, a copolymer with an M_n of 8.0 × 10^3 was obtained in the copolymerization with VCHO (entry 1 in Table 3; Figure S13). The average number of VCHO/**4** units per block was 2.0/1.0, which was similar to the **1** counterpart obtained under the same conditions (entry 2). However, the M_n value of the VCHO–**4** copolymer was clearly higher than that of the VCHO–**1** copolymer. The difference was potentially derived from the stability of the acetal structures in the main chain. More specifically, an acetal with a phenoxy group is more stable than the alkoxy counterpart;[27] hence, the **1**-derived acetal was not efficiently generated and/or partly degraded during copolymerization at this temperature. CHO was also effective in the copolymerization with **4** at 0 °C (entry 3), while the reactions with CPO or IBO resulted in oligomer products (entries 4 and 5).

Table 3. Cationic Copolymerization of 4 or 1 with Oxiranes at 0 ºC[a]

entry	oxirane	ROPT	time	oxirane conv (%)	ROPT conv (%)	$M_\mathrm{n} \times 10^{-3\ b}$	$M_\mathrm{w}/M_\mathrm{n}$[b]	average unit number per block[c] oxirane	ROPT
1	VCHO	**4**	2 min	92	50	8.0[d]	2.79[d]	2.0	1.0
2	VCHO	**1**	10 s	78	35	2.3[d]	1.81[d]	1.9	1.0
3	CHO	**4**	10 s	90	31	9.1	3.83	2.8	1.0
4	CPO	**4**	24 h	99	32	0.4[d]	1.65[d]	–	–

5	IBO	**4**	23.5 h	25	0	0.5[d]	1.16[d]	–	–

[a] [Oxirane]$_0$ = 0.60 M, [ROPT]$_0$ = 0.60 M, [B(C_6F_5)$_3$]$_0$ = 3.0 mM, in dichloromethane at 0 ºC. [b] By GPC (polystyrene calibration). [c] Calculated by ^{1}H NMR. After purification by preparative GPC. [d] M_n and M_w/M_n values were calculated from the polymer peak (the low-MW oligomer peak was not used for calculation).

Cationic Copolymerization of the Vinyl Monomers and ROPTs

Copolymerizations of ROPTs with VEs or styrene derivatives (Scheme 2C) were examined; however, ROPTs were not consumed at all in most cases (entries 1–6 and 9–13 in Table 4). Even when polymers were obtained, ^{1}H NMR analysis showed that the products were not copolymers but homopolymers of vinyl monomers. Remarkably, copolymerizations of CEVE and **2** or **3** proceeded to yield polymers (entries 7 and 8 in Table 4; Figure 4). ^{1}H NMR analysis indicated copolymer formation via crossover reactions (Figure S14). In addition, the copolymers were hydrolyzed into very low-MW products under acidic conditions due to the cleavage of the hemiacetal moieties derived from crossover from CEVE to ROPTs (Figure 4, purple).

Table 4. Cationic Copolymerization of ROPTs with Vinyl Monomers [a]

entry	vinyl monomer	ROPT	time	vinyl monomer conv (%)	ROPT conv (%)	$M_n \times 10^{-3}$ [b]	M_w/M_n [b]	average unit number per block[c]	
								vinyl	ROPT
1	IBVE	**1**	1 min	0	0	—	—	—	—
2		**2**	68 h	100	0	23	2.14	—	—
3[d]		**2**	68 h	100	0	9.1	1.94	—	—
4		**3**	20 h	100	0	33	2.17	—	—
5	CEVE	**1**	117 h	0	0	—	—	—	—
6[e]		**1**	23 h	0	0	—	—	—	—
7		**2**	68 h	39	11	42[h]	2.09[h]	3.0	1.0
8		**3**	24 h	100	13	19	1.90	6.7	1.0
9	pMOS	**1**	22 h	18	0	148	2.04	—	—
10		**3**	72 h	11	0	24	2.99	—	—
11[f]	pMeSt	**1**	24 h	0	0	—	—	—	—
12		**3**	72 h	1	0	—	—	—	—
13[g]		**3**	71.5 h	25	0	6.8	1.66	—	—

[a] [Vinyl monomer]$_0$ = 0.75 M (except for entry 3), [ROPT]$_0$ = 0.75 M, [B(C_6F_5)$_3$]$_0$ = 3.0 mM (except for entry 6), in dichloromethane at –78 ºC (except for entries 11 and 13). IBVE: isobutyl VE, CEVE: 2-chloroethyl VE, pMOS: *p*-methoxystyrene, pMeSt: *p*-methylstyrene. [b] By GPC (polystyrene calibration). [c] Calculated by ^{1}H NMR. After purification by preparative GPC. [d] [Vinyl monomer]$_0$ = 0.20 M, [e] [B(C_6F_5)$_3$]$_0$ = 6.0 mM at 0 ºC. [f] At –40 ºC. [g] At 0 ºC. [h] M_n and M_w/M_n values were calculated

from the polymer peak (the low-MW oligomer peak was not used for calculation).

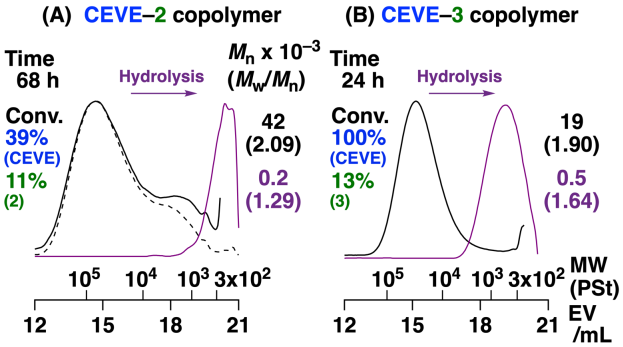
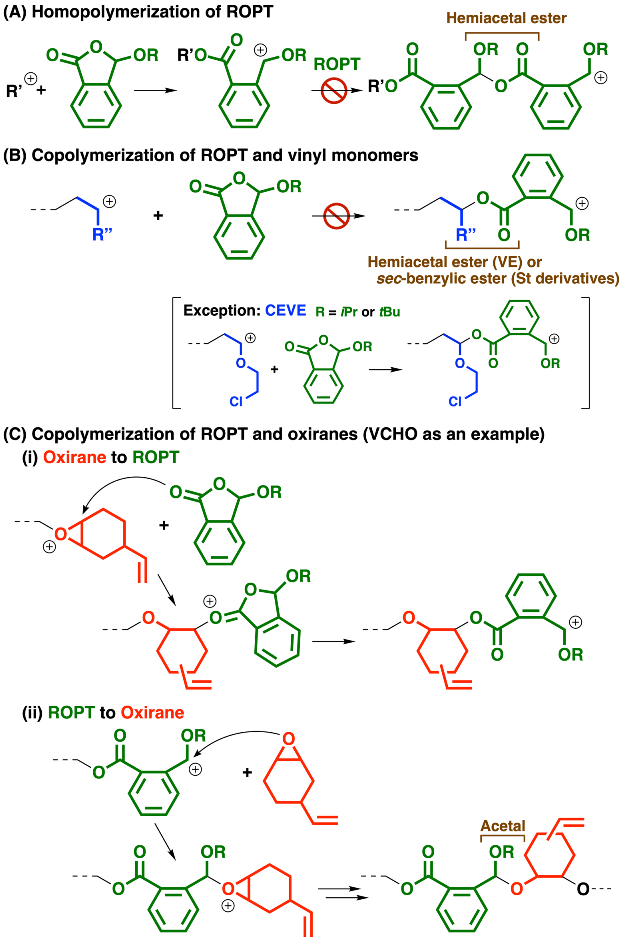


Figure 4. MWD curves of (A) the CEVE–**2** (entry 7 in Table 4) and (B) CEVE–**3** (entry 8) copolymers (black, solid: the original products; dashed: after purification by preparative GPC) and their hydrolysis products (purple; hydrolysis after purification by preparative GPC). See Table 4 for the polymerization conditions.

Polymerization Mechanisms

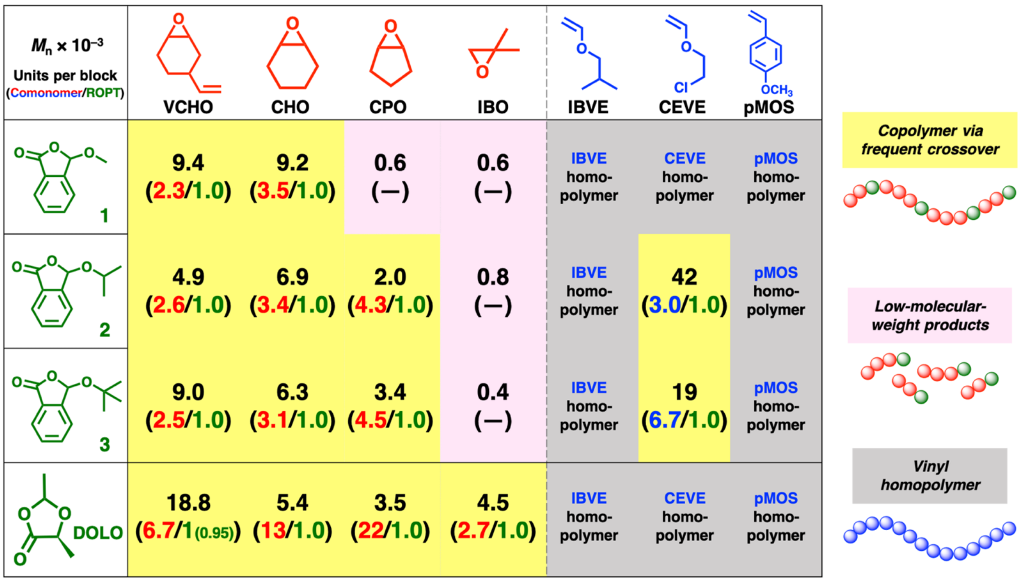
Polymerization mechanisms are discussed with a focus on propagating cations, structures resulting from propagation reactions, and alkoxy groups of ROPTs. Homopolymerization of ROPTs did not proceed under any of the examined conditions, which was likely due to both the small ring strain of the five-membered cyclic hemiacetal ester structure and the relatively low stability of a hemiacetal ester structure that was potentially formed by homopropagation of ROPTs (Scheme 3A), similar to the case of DOLOs.[20] Moreover, the instability of a hemiacetal ester structure, which was also formed via the crossover reaction from VE to ROPT, caused the inertness of the copolymerizations of VEs and ROPTs (Scheme 3B). A *sec*-benzyl ester structure was difficult to generate in copolymerizations with styrene derivatives. However, the copolymerizations of CEVE with **2** or **3** effectively occurred. CEVE was a less reactive monomer than other VEs,[28] such as IBVE, due to the electron-withdrawing effect of the 2-chloroethyl side chain. A cation from a less reactive monomer exhibited higher activity, which potentially contributed to overcoming the inefficient hemiacetal ester formation via the crossover from VE to ROPT and thus resulted in copolymer formation.



Scheme 3. Homopropagation and Crossover Reactions of ROPTs (Counteranions Are Omitted).

Unlike the ineffective homopolymerization and copolymerizations with vinyl monomers, copolymerizations with oxiranes efficiently proceeded via frequent crossover reactions. The crossover reactions between VCHO and ROPT are shown as an example in Scheme 3C. The crossover reaction from a VCHO-derived oxonium ion occurs through the nucleophilic reaction of the ROPT carbonyl group with the carbon atom adjacent to the cationically charged oxygen atom (Scheme 3C(i)). Subsequently, a ring-opening reaction occurs to generate a ROPT-derived cation. This cation is stabilized by conjugation with both aryl and alkoxy groups (Scheme 1B). The ROPT-derived cation does not react with an ROPT monomer due to the nonhomopolymerizability of ROPT, whereas it reacts with VCHO (Scheme 3C(ii)). The structures derived from these crossover reactions are ester and acetal, which are easier to generate than a hemiacetal ester and responsible for efficient copolymerizations, unlike the ineffective homopolymerization and copolymerizations with VEs.

The difference in the alkoxy groups of ROPTs did not significantly affect the polymerization behavior (Figure 5). For example, the average number of VCHO/ROPT units per block was comparable among **1**, **2**, and **3**. The three ROPTs generated a methoxy, isopropoxy, or *tert*-butoxy group-adjacent carbocation (oxocarbenium ion) by ring-opening. The comparable results indicate that the reactivity of the cations negligibly affected the copolymerization reactions. This was interesting because VEs with a primary, secondary, or tertiary alkoxy group exhibited very different reactivities.[29] Similar reactivities of **1**, **2**, and **3** in copolymerizations likely stem from similar nucleophilicities of the carbonyl group irrespective of the alkoxy groups. The nucleophilicity of ROPTs mainly governed the copolymerization reactions, while the cations generated by ring-opening underwent smooth crossover reactions with an oxirane monomer.



M_n × 10^{-3} Units per block (Comonomer/ROPT)	VCHO	CHO	CPO	IBO	IBVE	CEVE	pMOS
1	9.4 (2.3/1.0)	9.2 (3.5/1.0)	0.6 (–)	0.6 (–)	IBVE homopolymer	CEVE homopolymer	pMOS homopolymer
2	4.9 (2.6/1.0)	6.9 (3.4/1.0)	2.0 (4.3/1.0)	0.8 (–)	IBVE homopolymer	42 (3.0/1.0)	pMOS homopolymer
3	9.0 (2.5/1.0)	6.3 (3.1/1.0)	3.4 (4.5/1.0)	0.4 (–)	IBVE homopolymer	19 (6.7/1.0)	pMOS homopolymer
DOLO	18.8 (6.7/1$_{(0.95)}$)	5.4 (13/1.0)	3.5 (22/1.0)	4.5 (2.7/1.0)	IBVE homopolymer	CEVE homopolymer	pMOS homopolymer

Figure 5. Summary of the products obtained in the copolymerization of oxiranes or vinyl monomers

with ROPTs or DOLO (2,5-dimethyl-1,3-dioxolan-4-one). Polymerizations were conducted under the same conditions as those for Table 2. Upper number: the M_n values of the products. Lower number: average number of comonomer/ROPT or DOLO units per block. The data of DOLO with VCHO or IBO were reported in reference 20. The data of DOLO with CHO or CPO are unpublished.

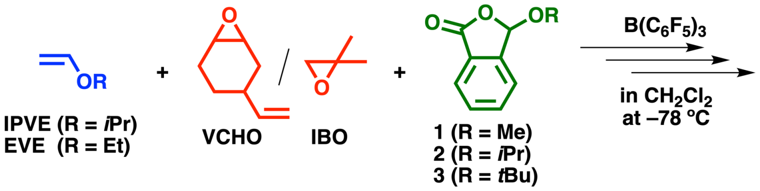
When compared with DOLOs,[20] ROPTs exhibited a higher tendency for crossover reactions. The results of the copolymerizations of a DOLO (2,5-dimethyl-1,3-dioxolan-4-one; R^1 = Me and R^2 = H in Scheme 1A) are also summarized in the bottom line in Figure 5. The average number of oxirane units per block was always higher in the copolymerizations with DOLO than in those with ROPTs. ROPT reacted more efficiently with the oxirane-derived oxonium ions than DOLO, potentially due to the more efficient generation of a cation via nucleophilic attack and ring-opening. Specifically, the ROPT-derived carbocation was adjacent to both aryl and alkoxy groups, which was responsible for the higher stability of this cation than the DOLO-derived carbocation adjacent to only an alkoxy group (Scheme 1). An aryl group was also adjacent to the carbonyl group; hence, the nucleophilicity of ROPTs could also be affected by the aryl group.

Cationic Terpolymerization of VE, Oxirane, and ROPT

The inertness of the copolymerizations of VEs and ROPTs is most likely caused by inefficient crossover reactions from VE to ROPT. However, the ROPT-derived, aryl- and alkoxy-adjacent carbocation (oxocarbenium ion) has a structure similar to that of the VE-derived, alkoxy-adjacent carbocation (oxocarbenium ion) and can potentially react with a VE monomer. To overcome the inefficiency of the crossover reaction from VE to ROPT, cationic terpolymerization of VE, oxirane, and ROPT was investigated. A similar strategy was effective for the terpolymerization of VE, oxirane, and ketone or DOLO in our previous studies.[20,30]

Cationic terpolymerization of IPVE, VCHO, and **1** was examined under the same conditions as those for the copolymerizations of oxiranes and ROPTs, although the concentrations of oxiranes were lower than those of VE and ROPT to facilitate the crossover reactions. IPVE exhibits higher reactivity than IBVE and CEVE, which were used above. The polymerization proceeded smoothly with consumption of the three monomers to yield a polymer with an M_n of 18 × 10^3 (entry 1 in Table 5; Figure 6A). The ^{1}H NMR spectrum of the product (Figure 7A; see Figure S15 for the ^{13}C NMR spectrum) had a shoulder at the higher-field side of a peak at 4.6–5.3 ppm (peak 14), which was assigned to an acetal moiety derived from the crossover reaction from IPVE to VCHO. Interestingly, a peak was negligibly observed at 6.4 ppm (<1% of ROPT units), different from the spectrum of the VCHO–**1** copolymer (peak 10); this result indicated that the crossover reaction from **1** to VCHO was negligible in the terpolymerization. More specifically, the VCHO-derived oxonium ion reacted with **1,** and subsequently, the **1**-derived cation reacted with IPVE exclusively instead of VCHO. The peaks derived from the VCHO–**1**–IPVE crossover reactions (peaks 8 and 15) overlapped with other peaks (4.6–5.3 ppm). Very similar results were obtained when **2** or **3** was used instead of **1** (entries 2 and 3 in Table 5; Figures S16 and S17).

Table 5. Cationic terpolymerization of VE, Oxirane and ROPT[a]



	monomer				conv (%)					average unit number per block[c]		
entry	VE	oxirane	ROPT	time	VE	oxirane	ROPT	M_n × 10^{-3} [b]	M_w/M_n [b]	VE	oxirane	ROPT
1	IPVE	VCHO	**1**	30 min	79	94	18	18	1.88	4.7	1.3	1.0
2			**2**	15 min	47	56	12	25	2.17	4.4	1.2	1.0
3			**3**	30 min	82	92	21	36	2.11	4.5	1.2	1.0
4	IPVE	IBO	**1**	17.5 h	90	44	25	13	2.53	3.5	1.2	1.0
5			**2**	3 h	72	41	23	18	2.25	3.7	1.3	1.0
6			**3**	2 h	66	45	20	25	2.21	3.7	1.4	1.0
7	EVE	VCHO	**1**	5 min	15	73	13	16	2.22	1.2	1.4	1.0

8			**2**	1 h	17	73	15	16	2.29	1.3	1.2	1.0
9			**3**	1 h	23	88	19	24	1.94	1.4	1.2	1.0
10	EVE	IBO	**1**	20.5 h	24	69	24	7.5	2.15	1.2	1.5	1.0
11			**2**	71 h	52	83	41	12	2.78	1.3	1.2	1.0
12[d]			**3**	22 h	25	50	20	6.9	1.92	1.3	1.4	1.0

[a] $[\mathrm{VE}]_0 = 0.80$ M, $[\mathrm{oxirane}]_0 = 0.20$ (VCHO) or 0.44 (IBO) M, $[\mathrm{ROPT}]_0 = 0.80$ M, $[\mathrm{B(C_6F_5)_3}]_0 = 1.0$ mM (except for entry 12), in dichloromethane at –78 ºC. [b] By GPC (polystyrene calibration). [c] Calculated by ^{1}H NMR. After purification by preparative GPC. [d] $[\mathrm{B(C_6F_5)_3}]_0 = 2.0$ mM.

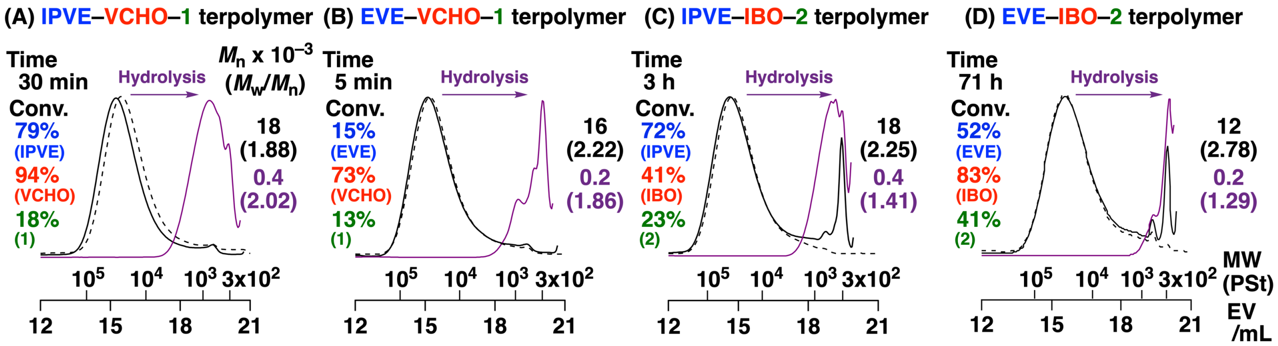


Figure 6. MWD curves of (A) the IPVE–VCHO–**1** (entry 1 in Table 5), (B) EVE–VCHO–**1** (entry 7), (C) IPVE–IBO–**2** (entry 5), and (D) EVE–IBO–**2** (entry 11) terpolymers (black: the original products; dashed: after purification by preparative GPC) and their hydrolysis products (purple; hydrolysis after purification by preparative GPC). See Table 5 for the polymerization conditions.

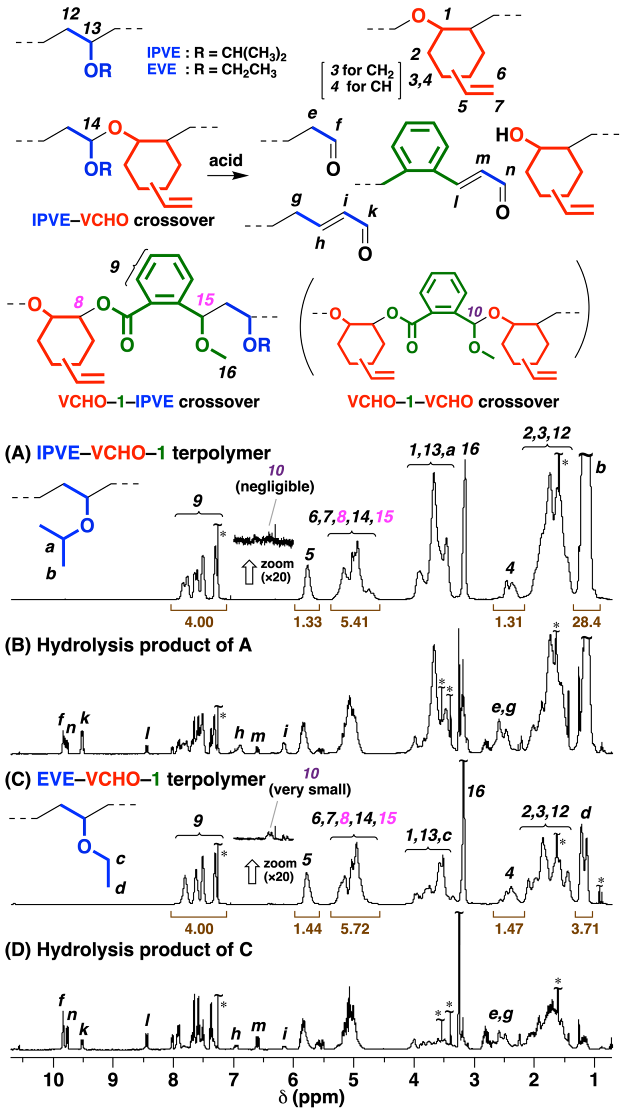
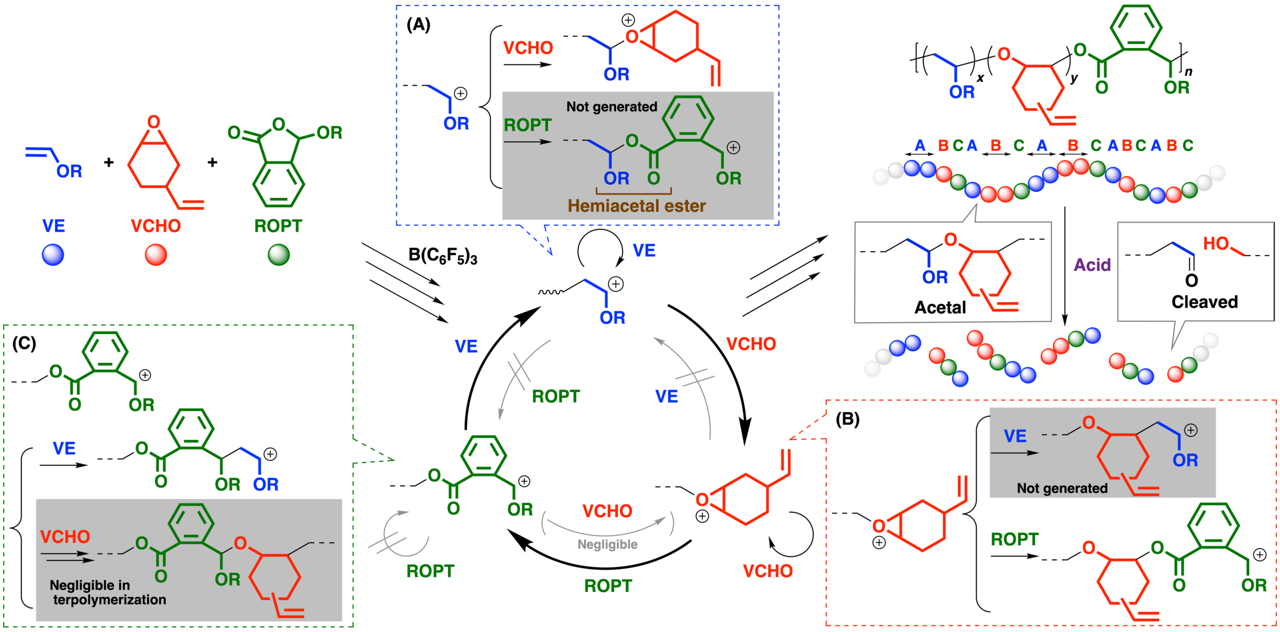


Figure 7. ^{1}H NMR spectra of (A) the IPVE–VCHO–**1** terpolymer (entry 1 in Table 5; Figure 6A), (B) its hydrolysis product (Figure 6A, purple), (C) the EVE–VCHO–**1** terpolymer (entry 7 in Table 5; Figure 6B), and (D) its hydrolysis product (Figure 6B, purple). After purification by preparative GPC for (A) and (C). Values shown in brown are integral ratios. * Water, $CHCl_3$, hexane, etc.

The terpolymerization result indicated that the propagation reactions occurred via selective crossover reactions in the direction of IPVE→VCHO, VCHO→**1**, and **1**→IPVE (Scheme 4). The IPVE-derived cation reacted with VCHO, while it did not react with **1**, as expected from the ineffective copolymerization of VEs and **1** (Scheme 4A). The VCHO-derived oxonium ion reacted with **1**, whereas the reaction with IPVE did not occur due to negligible generation of a carbocation by ring-opening of the oxonium ion (Scheme 4B).[24,30] Notably, the **1**-derived cation negligibly reacted with VCHO (Scheme 4C), which was different from the copolymerization of VCHO and **1** (entry 1 in Table 2; Figure 1A). The crossover reaction from **1** to IPVE was more likely to occur compared to that to VCHO in the terpolymerization because the aryl-adjacent acetal structure derived from the crossover reaction from **1** to VCHO was less efficiently generated than the *sec*-benzylic ether structure derived from the crossover reaction to IPVE. Moreover, an aryl-adjacent acetal was more reactive in acid hydrolysis than the alkyl-adjacent acetal,[27] which indicated a lower stability of the former than that of the latter. In addition, in the terpolymerization of IPVE, VCHO, and DOLO (2-ethyl-2,5-dimethyl-1,3-dioxolan-4-one; R^1 = Me, R^2 = Et in Scheme 1A), the DOLO-derived cation reacted with IPVE and VCHO at ratios of approximately 80% and 20%, respectively,[20,31]; this result was in contrast to the exclusive crossover reaction from the **1**-derived cation to IPVE. The average number of IPVE/VCHO/**1** per block was estimated to be 4.7/1.3/1.0 (entry 1 in Table 5) from the integral ratios of the ^{1}H NMR spectrum. A similar number was also obtained in the terpolymers from **2** or **3** (entries 2 and 3). In addition, the terpolymers were degraded under acidic conditions via the cleavage of the acetal moieties, resulting in low-MW products (Figure 6A, purple; Figure 7B; Figure S18 for ESI-MS analysis; Figure S16).



Scheme 4. Reaction Mechanism of Terpolymerization.

Highly selective crossover reactions in one direction occurred in the terpolymerization; hence, the suppression of homopropagation reactions of VE and VCHO potentially leads to ABC-type periodic sequence. To achieve this, EVE, which is less reactive than IPVE, was used in the terpolymerizations. Terpolymerizations with **1**, **2**, or **3** proceeded smoothly to yield polymers with M_n values higher than 10^4 (entries 7–9 in Table 5; Figures 6B, 7B, S19, and S20). The crossover reaction from ROPT to VCHO was inefficient despite the lower reactivity of EVE than IPVE (peak 10 in Figure 7B; approximately 1% of ROPT units). As expected, the homopropagation of VE was effectively suppressed, resulting in an average number of EVE/VCHO/**1**, **2**, or **3** units per block of 1.2/1.4/1.0, 1.3/1.2/1.0, or 1.4/1.2/1.0, respectively. The results suggest that ABC pseudo-periodic terpolymers were obtained. The very low-MW products obtained by acid hydrolysis (Figures 6B and S19, purple; Figure 7D) were also consistent with the occurrence of very frequent crossover reactions in the terpolymerizations.

The use of IBO instead of VCHO was also suitable for terpolymerization, unlike the oligomer formation in the copolymerizations of IBO and ROPTs (entries 10–12 in Table 2). Terpolymerizations of IPVE, IBO, and ROPTs (**1**, **2**, or **3**) yielded polymers with M_n values higher than 10^4 (entries 4–6 in Table 5; Figures 6C and S21–S23). The IBO-derived oxonium ion could undergo ring-opening to generate a tertiary carbocation; hence, the crossover reaction from IBO to VE occurred.[24] However, ^{1}H NMR analysis (Figure S22A) showed that the amount of the IBO-to-IPVE crossover-derived structure was approximately 3% of **1** units. The amount of the **1**-to-IBO crossover-derived structure was also very minimal (approximately 1% of **1** units). Moreover, the use of EVE instead of IPVE was effective for the suppression of VE homopropagation (entries 10–12 in Table 5; Figures 6D, S24, and S25) and resulted in ABC pseudo-periodic terpolymers, as in the case of the VCHO counterpart. The amounts of IBO-to-EVE and **1**-to-IBO crossover-derived structures were approximately 4% and 4%, respectively, of **1** units. The efficient crossover reactions from ROPT to VE most likely contributed to terpolymer formation, unlike the oligomer formation in the copolymerizations.

Thermal Properties of the Obtained Polymers

The thermal properties of the obtained polymers were investigated via DSC and TGA. The side group of ROPTs affected the T_g values of the copolymers. Copolymers from **1** or **3**, which are the alkoxy group-containing ROPTs, exhibited lower T_gs (20 °C for **1** and 27 °C for **3**; entries 1 and 2 in Table 6) than that of a VCHO homopolymer (50 °C; entry 4). In contrast, the copolymer obtained from **4**, containing a phenoxy group, exhibited a higher T_g (80 °C, entry 3). The EVE–VCHO–**3** terpolymer had a lower T_g (14 ºC; entry 5) than the corresponding VCHO–**3** copolymer (entry 2). The decrease in the amount of the VCHO-derived alicyclic structures is responsible for the low T_g. In addition, the EVE–IBO–**1** terpolymer had a low T_g of –17 ºC (entry 6). TGA analysis indicated that the copolymers began to degrade at approximately 300 °C, which was approximately 50 °C lower than the VCHO homopolymer (Figure S27).

Table 6. T_g values of the obtained polymers [a]

entry	polymer	average unit number per block[b]			$M_n \times 10^{-3}$ [c]	M_w/M_n[c]	T_g (°C)
		VE	oxirane	ROPT			
1	VCHO–**1** copolymer	–	2.6	1.0	7.6	2.33	20
2	VCHO–**3** copolymer	–	2.5	1.0	7.2	3.02	27
3	VCHO–**4** copolymer	–	2.0	1.0	14	1.84	80
4	VCHO homopolymer	–	–	–	45	1.95	50
5	EVE–VCHO–**3** terpolymer	1.4	1.2	1.0	13	1.81	14
6	EVE–IBO–**1** terpolymer	1.2	1.5	1.0	7.0	2.13	–17

[a] Determined by DSC. The heating and cooling rates were 10 °C min^{-1}. The T_g values were determined by the second heating scan (see Figure S26). After purification by preparative GPC. Entry 1: obtained under the same conditions as those for entry 1 in Table 2. Entry 2: entry 3 in Table 2. Entry 3: entry 1 in Table 3. Entry 4: $[VCHO]_0 = 0.26$ M, $[B(C_6F_5)_3]_0 = 1.0$ mM, in dichloromethane at –78 °C. Entry 5: entry 9 in Table 5. Entry 6: entry 10 in Table 5. [b] Calculated by the ^{1}H NMR. After purification by preparative GPC. [c] Determined by GPC (polystyrene calibration). GPC analysis was conducted after purification by preparative GPC.

Conclusion

In conclusion, ROPTs were demonstrated to function as comonomers that are highly efficient in cationic copolymerizations with oxiranes and terpolymerizations with VEs and oxiranes. Copolymerizations of appropriate oxiranes and ROPTs proceeded smoothly to yield copolymers with acetal and ester moieties in the main chain. The copolymers exhibited acid degradability due to the cleavage of the acetal moieties. Unlike oxiranes, vinyl monomers did not undergo cationic copolymerization with ROPTs in most cases. Remarkably, copolymerizations of CEVE and **2** or **3** yielded copolymers with hemiacetal ester moieties in the main chain. In addition, cationic terpolymerizations of VE, oxirane, and ROPT successfully proceeded via selective crossover reactions in the direction of VE→oxirane, oxirane→ROPT and ROPT→VE, resulting in ABC pseudo-periodic terpolymers under optimized conditions. The reactivity of the propagating species and the stability of the resulting structures caused the selective crossover reactions. Our results from this study could greatly contribute to the construction of a design strategy for cationically polymerizable cyclic monomers. Moreover, we are currently investigating the potential of ROPTs for sequence-controlled polymerization with the use of nonhomopolymerizable comonomers, which will be reported in the future.

Associated Content

Supporting Information

Experimental section, polymerization data, and NMR and ESI-MS spectra of polymerization products.

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Notes

The authors declare no competing financial interest.

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31. Data shown in Figures S15 and S16A in reference 20. $[\mathrm{IPVE}]_0$ = 0.80 M, $[\mathrm{VCHO}]_0$ = 0.20 M, [2-ethyl-2,5-dimethyl-1,3-dioxolan-4-one]$_0$ = 1.2 M, $[\mathrm{B(C_6F_5)_3}]_0$ = 1.0 mM, in dichloromethane at –78 ºC.