Synthesis of Networked Polyesters by Cationic Ring-Opening Copolymerization of Lactones with Oxetane Derivatives

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1. Introduction

Aliphatic polyesters prepared by ring opening polymerization (ROP) of lactones have received much attention because of their biodegradability and biocompatibility. In this study, we describe the ring-opening copolymerization of lactones with oxetanes having hydroxyl group by cationic initiator. The copolymerization of ε-caprolactone (1) with 3-ethyl-3-(hydroxymethyl)oxetane (2b) (equimolar feed ratio) by scandium trifluoromethanesulfonate was carried out in bulk at 60-120 °C for 6 h. In the polymerization at 60 °C, it was found that the resulting polymer was the corresponding copolymer with hydroxyl groups from NMR measurements and was soluble in DMSO and DMF. At 120 °C, the obtained networked copolymer was insoluble in solvents, although respective homopolymerization gave soluble polymers. In addition, it was found that the thermal stability was drastically improved by copolymerization with only addition ca. 6% of 2b to 1. These results might suggest that 2b served as a crosslinkable monomer for ring-opening copolymerization.
the corresponding polyesters with high molecular weight. For instance, tin (II) 2-ethylhexanoate [Sn(Oct)2] is also known to be efficient initiator in ROP of lactones and related heterocyclic compounds.\(^2\) In addition, the Sn(Oct)\(_2\) catalyst is easy to handle, and soluble in common organic solvents. Aluminum isopropoxide [Al(O\(^3\)Pr)\(_3\)] is the most versatile initiator for the controlled polymerization of lactones.\(^3\) However, careful purification of initiator, monomer and solvent is necessary for achieving controlled ROP because the catalyst is not stable toward moisture. Recently, cationic ROP of lactones has been extensively studied. Okada et al. reported controlling the number-average molecular weight (M\(_n\)) and molecular weight distribution (M\(_w\)/M\(_n\)) in a lactone polymerization initiated by an alcohol in conjunction with scandium trifluoromethanesulfonate [Sc(OT\(_3\))] as a cationic initiator.\(^4\) Lanthanide triflates such as Sc(OT\(_3\)) offer the advantages of their stability toward the hydrolysis and that they have a strong Lewis acid character. Our group reported the controlled ROP of lactones with \(\text{-BuOH/HCl\cdot Et}_2\text{O}\) as an initiator system.\(^5\) No harmful metallic compounds is required in this polymerization. In spite of these advantages, approach from cationic initiators lead to not high molecular weight polyesters because of side reactions. Hence, the application of materials is limited. Since the networked polymers generally have many significant practical advantages compared to linear polymers, such as rather high mechanical strength and chemical and/or thermally stability, synthesis of the networked polyesters may be one of feasible methods to overcome limitation toward application.\(^6\) Synthesis of the networked polyesters by using lactones as a monomer has been reported so far. Networked polyesters have been prepared by copolymerization of \(\varepsilon\)-caprolactone (1) with a tetrafunctional monomer.\(^7\) Copolymerization of diepoxide with \(\gamma\)-butyrolactone catalyzed by ytterbium triflate afforded the corresponding insoluble polymer.\(^8\) Not only epoxides but also oxetane derivatives are known to polymerize cationically.\(^9\) Prud’home et al. recently reported the copolymerization of 3,3-bis(chloromethyl)oxetane and \(\varepsilon\)-caprolactone to afford the corresponding copolymer.\(^10\) In this paper, we describe the synthesis of the networked polyesters based on the strategy of ring-opening copolymerization of lactones with oxetane derivatives using Sc(OT\(_3\)) as a cationic initiator.

2. Experimental Section

Materials. \(2\text{b}\) and \(2\text{c}\) were kindly donated by TOAGOSEI CO., LTD. Other reagents were commercially available.

Cationic Copolymerization. A typical run was as follows (run 7 in Table 1.). A mixture of 1 (3.0 mmol, 0.34 g), \(2\text{b}\) (3.0 mmol, 0.35 g), and Sc(OT\(_3\)) (1.0 mg) was heated at 60 °C for 6 h and then opened.

NMR analysis. \(^{13}\)C NMR of poly(1-co-2a) (run 2 in Table 1.) (CDCl\(_3\)): \(\delta\) 173.5 (-C(=O)OC-), \(\delta\) 77.3 (-CH\(_2\)(CH\(_3\))\(_3\)C\(_2\)H\(_2\)O-), \(\delta\) 69.0-71.2 (the joint or terminal units), \(\delta\) 64.1 (-CH\(_2\)OC(O)-), \(\delta\) 62.5 (-CH\(_2\)CH\(_2\)OH), \(\delta\) 34.4-36.5 (-CH\(_2\)C(CH\(_3\))\(_3\)CH\(_2\)O-), \(\delta\) 34.1 (-C(O)CH\(_2\)O-), \(\delta\) 32.3 (the joint or terminal units), \(\delta\) 29.2 (the joint or terminal units), \(\delta\) 28.3 (-CH\(_2\)CH\(_2\)OC(O)-), \(\delta\) 25.5 (-C(O)CH\(_2\)CH\(_2\)CH\(_2\)O-), \(\delta\) 24.5 (-C(O)CH\(_2\)CH\(_2\)O-), and \(\delta\) 21.7 (-CH\(_2\)C(CH\(_3\))\(_3\)CH\(_2\)O-).

Measurements. \(^1\)H and \(^{13}\)C NMR spectra were recorded on varian 500 spectro meters, using tetramethylsilane (TMS) as an internal standard in CDCl\(_3\) and DMSO-\(d_6\). FT-IR spectra were obtained with a Shimadzu IR-8020 spectrometer. Number-average molecular weight (M\(_n\)) and molecular weight distribution (M\(_w\)/M\(_n\)) were estimated by size-exclusion chromatography (SEC) using a Tosoh HPLC HLC-8020 system equipped with four consecutive polystyrene gel columns [TSK-gels (bead size); aM (13 \(\mu\)m), a4000H (10 \(\mu\)m),...
a3000H (7 μm), and a2500H (7 μm)] and refractive index at 40 °C. The system was operated at a flow rate of 1.0 mL/min, using THF or N, N-dimethylformamide (DMF, 5.0 mM lithium bromide, and 5.0 mM phosphoric acid solution) as an eluent. Polystyrene standards were employed for calibration.

3. Results and Discussion

In this study, oxetane derivatives 3,3-dimethyloxetane (2a), 3-ethyl-3-(hydroxymethyl)oxetane (2b), 1,4-[(3-ethyl-3-(phenoxymethyl)methoxy)methyl]oxetane (2c) were used as comonomer (Scheme 1). At first, the monomer were tested for the homopolymerization. The resulting poly 1 and poly 2a were soluble in THF and CHCl₃. It is well known that the cationic ROP of 2b afforded a hyperbranched hydroxyl-functional polyether. Even using Sc(OTf)₃ as a cationic initiator, the similar structure was obtained. Poly 2b is soluble in DMF and DMSO. Table 1. shows the results of Sc(OTf)₃-catalyzed homo and copolymerization of 1 and/or 2 in bulk. Runs 2-4 in Table 1. show the results of copolymerizations of 1 with 2a in bulk at 60 °C for 6 h. Various copolymer samples were prepared by changing the amount of 2a in the feed. There was a decrease in the yield of the polymer obtained on increasing the 2a content in the feed. Molecular weight of the polymer was determined by size exclusion chromatograph (SEC). There was a decrease in the molecular weight of the polymers with an increase in feed ratios of the 2a. These polymerization behavior may indicate that chain transfer or chain termination be favored for 2a than 1.

Table 1. Cationic Ring-Opening Copolymerization of 1 with 2 by using Sc(OTf)₃ at bulk for 6 h

<table>
<thead>
<tr>
<th>Run</th>
<th>Feed ratio 1:2 (ratio)</th>
<th>Temp (°C)</th>
<th>Yield (%)</th>
<th>Mn (Mw/Mn)</th>
<th>Tg (°C)</th>
<th>Tm (°C)</th>
<th>Td (°C)</th>
<th>Td (°C)</th>
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<tbody>
<tr>
<td>1</td>
<td>1:-- (100:0)</td>
<td>60</td>
<td>&gt; 95 a)</td>
<td>5800 (1.5 b)</td>
<td>-60 b)</td>
<td>65 b)</td>
<td>244</td>
<td>264</td>
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<tr>
<td>2</td>
<td>1:2a (75:25)</td>
<td>60</td>
<td>82 a)</td>
<td>3900 (1.4 b)</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>3</td>
<td>1:2a (50:50)</td>
<td>60</td>
<td>37 a)</td>
<td>1600 (1.5 b)</td>
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<td></td>
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</tr>
<tr>
<td>4</td>
<td>1:2a (25:75)</td>
<td>60</td>
<td>19 a)</td>
<td>1100 (1.5 b)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>5</td>
<td>-2a (0:100)</td>
<td>60</td>
<td>-- c)</td>
<td>410 (2.4 b)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1:2b (25:75)</td>
<td>60</td>
<td>31 b)</td>
<td>1000 (1.5 i)</td>
<td></td>
<td></td>
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<tr>
<td>7</td>
<td>1:2b (50:50)</td>
<td>60</td>
<td>22 b)</td>
<td>910 (1.3 i)</td>
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<tr>
<td>8 b</td>
<td>1:2b (25:75)</td>
<td>60</td>
<td>22 b)</td>
<td>1100 (1.7 i)</td>
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<tr>
<td>9</td>
<td>1:2b (50:50)</td>
<td>120</td>
<td>66 b)</td>
<td>networked polymer</td>
<td>-50</td>
<td>--</td>
<td>200</td>
<td>238</td>
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<tr>
<td>10</td>
<td>1:2b (94:6)</td>
<td>120</td>
<td>97 a)</td>
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<td>120</td>
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<td>--</td>
<td>200</td>
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<td>12</td>
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<td>80 a)</td>
<td>networked polymer</td>
<td>--</td>
<td>32</td>
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a) Conditions: monomer 2.0 mmol, initiator 5.0 mg. b) Conditions: monomer 6.0 mmol, initiator 1.0 mg. c) Conditions: monomer 16 mmol, initiator 5.0 mg. d) n-hexane-insoluble part. e) Not determined. f) Water-insoluble parts were separated by centrifugation. g) Chloroform insoluble part. h) Determined by SEC based on polystyrene standards eluted by THF. i) Determined by SEC based on polystyrene standards. Eluent: LiBr (5.0 mM) and phosphoric acid (5.0 mM) solution in DMF. j) Determined by differential scanning calorimetry. All the samples were used without further treatment. k) Determined by thermogravimetric analysis under a N₂ atmosphere. All the samples were used without further treatment. l) Reference 12.
Microstructure of the obtained polymers was done using one- and two-dimensional NMR spectroscopic techniques. The peaks in the $^1$H NMR spectra of the resulting polymer were assigned on the basis of the homopolymers of 1 and 2a. Poly 1 signals were obtained at $\delta$4.07 (-CH$_2$OC(O)-), $\delta$2.32 (-C(O)CH$_2$-), $\delta$1.66 (-CH$_2$CH$_2$OC(O)-)+-C(O)CH$_2$CH$_2$-, and $\delta$1.40 (-C(O)CH$_2$CH$_2$CH$_2$-) whereas poly 2a signals were present at $\delta$3.15 (-CH$_2$C(CH$_3$)$_2$CH$_2$0-), and $\delta$0.92 (-CH$_2$C(CH$_3$)$_2$CH$_2$O-). Fig. 1 indicates the $^1$H-$^1$H COSY (correlation spectroscopy) NMR spectrum of the resulting polymer. Three correlation peaks are observed correlating the d methylene protons of the 1 units with e, g, and j methylene protons of the 1 units. The formation of the trifluoroacetate ester derivative at hydroxyl chain terminal of the 1 and 2a units resulted in the change of chemical shifts of the j and k proton peaks. These peaks j and k could therefore be reasonably assigned to the j and k methylene protons of the terminal units of 1 and 2a. Then, the g methylene protons of the 1 units adjacent to a 2a unit should show the presence of the chemical links between 1-2a units. In the $^{13}$C NMR of the polymer sample (data not shown), one set of six strong carbon signals at $\delta$ 173.5 (-C(=O)OC-), $\delta$ 64.1 (-CH$_2$OC(O)-), $\delta$ 34.1 (-C(O)CH$_2$-), $\delta$ 28.3 (-CH$_2$CH$_2$OC(O)-), $\delta$ 25.5 (-C(O)CH$_2$CH$_2$-), and $\delta$ 24.5 (-C(O)CH$_2$CH$_2$-) was identical with that of poly 1 and was assigned to the 1 units of the obtained polymer, and the signals from 2a were obtained at $\delta$ 77.3 (-CH$_2$C(CH$_3$)$_2$CH$_2$O-), $\delta$ 34.4-36.5 (-CH$_2$C(CH$_3$)$_2$CH$_2$O-), and $\delta$ 21.7 (-CH$_2$C(CH$_3$)$_2$CH$_2$O-). The peak assigned at $\delta$ 77.3 was investigated by DEPT (distortionless enhancement by polarization transfer) method. On the basis of the $^1$H-$^{13}$C HMOC ($^1$H-detected multiple
quantum coherence) NMR spectrum shown in Fig. 2, among the peaks in the region of $\delta 68-72$, one peak could be easily assigned to the methylene carbon because there is a correlation peak corresponded the methylene protons of the 1 units. The other peaks are related to the methyl protons of the 2a units judging from $^1$H-$^{13}$C HMBC ($^1$H-detected multiple-bond heteronuclear multiple quantum coherence) NMR spectrum (data not shown). Therefore, the other peaks could be assigned to the methylene carbon of the 2a units, showing the presence of the chemical links between 2a-1 units and that of terminal units of 2a. Also, the peaks are related to the peaks in the region of $\delta 68-72$, judging from $^1$H-$^{13}$C HMQC NMR spectrum shown in Fig. 2. Hence, the peaks should correspond the methylene protons of the 2a units adjacent to a 1 unit. From the microstructure analysis as discussed above, it was found that the 1 unit and the 2a unit are connected in the obtained polymer.

In the case of copolymerizations of 1 with 2b (equimolar feed ratio) in bulk at 60 °C for 6 h (runs 6-8 in Table 1.) (Scheme 2), after work-up procedures, the $^1$H NMR analysis confirmed the quantitative consumption of 1 and 2b. The crude polymer was soluble in DMF and DMSO and was precipitated into water to isolate the pure polymer. The structure of the resulting polymers was confirmed by $^{13}$C NMR and $^1$H NMR spectroscopy. The polymer sample for NMR measurement was treated with trifluoroacetic anhydride in order to get better resolution. Fig. 3 shows $^{13}$C NMR spectrum of the resulting polymer with an expanded region of quaternary carbon absorption of oxetane derivatives. Assignment of the signals are based on the data for the homopolymers of 1 and 2b. Since the corresponding chemical shift in the poly 2b is equal to 42.6, the signal (at $\delta 42.6$) may be attributed to 2b-2b homolinkage. The overlapping signals in the $\delta 42.0$ region are observed. These signals increased with an increase in feed ratios of 1. No peaks derived from poly 1 were observed in the expanded region. From $^1$H NMR measurements, it was found that monomer ratios in copolymers are very close to feed ratios. The peaks at hydroxyl groups were observed by $^1$H NMR in solution of DMSO-$d_6$ in comparison with poly 2b. There were two characteristic peaks: a singlet peaks at $\delta 4.25$ and $\delta 4.16$ probably due to protons of the hydroxyl groups. These results indicate that the resulting polymer was not a mixture of homopolymer but the corresponding copolymer with hydroxyl groups, judging from the results of the solubility and $^1$H NMR spectrum of the resulting polymer. Because of the signal overlapping, it is difficult to
determine whether the resulting polymer has a hyperbranched structure. Further, in the same copolymerizations with various monomer ratios, similar polymers were obtained. Most of the molecular weight of the resulting polymer was in the range of a thousand. SEC profile of the resulting polymer was symmetrical and unimodal. The molecular weight of the resulting polymer may be not appropriate data as measured a linear polymer since there is the possibility of hyperbranched polymer.

Next, copolymerization of 1 with 2b at 120 °C afforded the insoluble polymer which did not dissolve in CHCl₃, THF, DMF, and DMSO (runs 9 and 10 in Table 1.) (Scheme 2). Further, in the same copolymerization with various monomer rations, similar insoluble polymers was obtained. In the case of copolymerization of 1 with 2a, the resulting polymer dissolve in CHCl₃ and THF (runs 2-4 in Table 1.). Therefore, these results indicate that hydroxyl groups of the resulting polymers participate in networked reaction. The structure of resulting insoluble polymers was confirmed by IR measurement (Fig. 4). For preparation of IR samples, treatment of Soxhlet extractor were carried out to remove the soluble byproducts were extracted with CHCl₃. Infrared absorptions due to hydroxyl, methylene, ester, and ether groups are observed at ca. 3400, 2936, 1734, 1105 cm⁻¹, respectively. These results strongly suggest that the resulting insoluble polymer has the copolymerized structure of 1 with 2b. In addition, the copolymerization 1 with 2c afforded the corresponding insoluble polymer (run 12 in Table 1.).

The thermal properties of the resulting networked polymer are also summarized in Table 1. In the case of copolymerization of 1 with 2b at equimolar feed ratio, the glass transition temperatures (Tg) of the resulting polymer was higher than that of poly 1 (run 9 in Table 1.). The melting temperature (Tm) of the resulting polymer was not observed. The weight loss decomposition temperatures of compounds were much lower than that of poly 1. In the copolymerization with only addition of ca. 6% of 2b to 1, the resulting polymer had a lower Tm compared with poly 1 (run 10 in Table 1.). Tg of the resulting polymer could not be observed in a DSC scan. We are now considering another approach for the measurement. The 10% weight loss decomposition temperature was much higher than poly 1. It was found that the thermal stability was drastically improved by copolymerization with only addition ca. 6% of 2b to 1. Also, the thermal stability of the polymer prepared by 1 and 2c shows higher the 10% weight loss decomposition temperatures than that of poly 1 (run 12 in Table 1.).

There are two mechanisms in cationic ring-opening polymerization. One is the activated monomer (AM) mechanism, which is based on the hydrolysis of monomers and has been proposed for the polymerization of cyclic monomers such as lactones, cyclic ethers, and acetals. The other one is known as an active chain end (ACE) mechanism and is derived from the chain propagation reaction of a monomer nucleophilic site with a tertiary oxonium ion at the end of a polymer chain. These two mechanisms coexist, and macromolecules are built in each way, which complicates the reaction. In the course of the copolymerization of 1 with 2b, the concentration of hydroxyl groups in monomer decreases because of monomer consumption, whereas the concentration of hydroxyl groups in polymer increases. After the nearly complete consumption of 2b, etherification between hydroxyl groups should occur as the coupling of macromolecules formed at the
first stage by ROP, leading to the networked polymer. Takasu reported that the direct polycondensation of a dicarboxylic acid with diols catalyzed by Sc(OTf)$_3$ was carried out at bulk to synthesize poly-(alkylene succinate). It was revealed that Sc(OTf)$_3$ catalyzes not only the esterification but also etherification as a side reaction, which depends on the chain length of the diols. As a model reaction, etherification between 1-octanol was carried out at 120 °C for 3 h in bulk under reduced pressure (150 mmHg) in the presence of Sc(OTf)$_3$. Analysis of the $^1$H NMR spectrum of the resulting compound showed the formation of ether linkage. These results supported Sc(OTf)$_3$ catalyze etherification between hydroxyl groups.

In summary, it was confirmed that 1 was readily copolymerized with 2a, 2b, or 2c by Sc(OTf)$_3$ to afford the corresponding copolymer or networked polymer. An oxetane with hydroxyl methyl group acts as a bifunctional comonomer containing a polymerizable group and a crosslinking moiety. These results might suggest that 2b served as a crosslinkable monomer for ring-opening copolymerization. The physico-chemical properties and biodegradabilities of the corresponding networked polymer will be published elsewhere.

Acknowledgment:
We acknowledge the gift of oxetane derivatives 2b, 2c from TOAGOSEI CO., LTD.

References