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ARTICLE

# Ring-Opening Polymerization of L-Lactide and ε-Caprolactone Utilizing Biocompatible Zinc Catalysts. Random Copolymerization of L-Lactide and ε-Caprolactone

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ABSTRACT: Polylactide and polycaprolactone were synthesized utilizing biocompatible zinc complexes as initiators at ambient temperature in "controlled"/"living" polymerization processes. The zinc complex containing a Schiff base ligand derived from the natural amino acid phenylalanine was found to catalyze the ring-opening polymerization of L-lactide and ε-caprolactone in the melt at 110 °C to afford a series of random copolymers. These copolymers were shown to possess monomer contents which correlated well with their composition in the monomer feed. The thermal properties of the various copolymers ($T_g$, $T_c$, and $T_m$) as determined by differential scanning calorimetry were found to depend strongly on the copolymers' composition. For example, the $T_g$s were shown to vary linearly with the molar % lactide in the copolymer over a temperature range of −67 to 60 °C.

## Introduction

Polylactide, poly(ε-caprolactone), and their copolymers are among the most widely used polymeric materials in medical and pharmaceutical applications due to their physical properties and nontoxicity to humans. Biodegradable sutures, artificial skin, resorbable prostheses, and controlled drug release[1−3] are examples of the applications of these polymeric materials, since these copolymers can be metabolized and remove from the body via normal metabolic pathways.[3−6] It has been shown that polylactides from *rac*-lactide have shorter half-life (a few weeks) *in vivo* than that of polycaprolactone (one year);[7,8] in addition, the permeability to drugs of polycaprolactone is higher than polylactide.[3] The permeability to drugs and biodegradability[1,9,10] of copolymers of these two monomers can be fine-tuned by the copolymer composition, monomer sequencing, and polymer's molecular weight.[11] Therefore, a number of reports have been focused on producing both random[7,12−18] and block[2,17,19−25] copolymers from lactide and ε-caprolactone to provide copolymers with desirable properties.

While a large variety of metal complexes successfully catalyzes the ring-opening polymerization (ROP) of lactide and ε-caprolactone, it is desirable to use biocompatible metals since polylactides, ε-caprolactone, and their copolymers are widely utilized in biomedical applications. We have recently reported the effective use of zinc complexes derived from natural amino acids (Scheme 1) for the ROP of lactides that produces heterotactic polylactide with $P_r$ value up to 0.89.[26] Since ε-caprolactone is expected to undergo the ring-opening polymerization in the same manner as lactide, we have investigated these zinc complexes for the ROP of ε-caprolactone. Our results show that these zinc complexes are active catalysts for the ring-opening polymerization of ε-caprolactone. Included in these studies is the production of copolymers from L-lactide and ε-caprolactone as well as the effect of the monomer composition on the thermal properties of produced polymers.

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## Experimental Section

**Methods and Materials.** All manipulations were carried out using a double manifold Schlenk vacuum line under an argon atmosphere or an argon-filled glovebox unless otherwise stated. Toluene was freshly distilled from sodium/benzophenone before use. Methanol and dichloromethane were purified by an MBraun Manual Solvent Purification System packed with Alcoa F200 activated alumina desiccant. Pentane was freshly distilled from $CaH_2$. Deuterated chloroform and deuterated benzene from Cambridge Isotope Laboratories Inc. were stored in the glovebox and used as received. L-Lactide and *rac*-lactide were gifts from PURAC America Inc. These lactides were recrystallized from toluene, dried under vacuum at 40 °C overnight, and stored in the glovebox. ε-Caprolactone was distilled under vacuum from $CaH_2$ and strored on 4A molecular sieves in the glovebox. The zinc complexes **1a** and **1b** were synthesized according to our previously reported procedure.[26]

**Measurements.** $^1$H NMR spectra were recorded on Unity+ 300 MHz and VXR 300 MHz superconducting NMR spectrometers. Molecular weight determinations were carried out with a Viscotek Modular GPC apparatus equipped with ViscoGEL I-series columns (H + L) and Model 270 dual detector comprised of refractive index and light scattering detectors. DSC measurements were performed with a Polymer DSC by Mettler Toledo. The samples were scanned from −100 to 200 °C under a nitrogen atmosphere. The glass transition temperature ($T_g$), the crystallization temperature ($T_c$), and the melting temperature ($T_m$) of polymers were determined from the second heating at heating rate of 5 °C/min. For these DSC measurements, samples were first heated to 200 °C at a rate of 10 °C/min and cooled to 20 °C for two cycles. The samples were then cooled to −100 °C by liquid nitrogen, followed by heating to 200 °C at a heating rate of 5 °C/min to determine their thermal properties ($T_g$, $T_c$, and $T_m$).

**Lactide Polymerization Procedure.** In a typical experiment (Table 1, entry 1), in a glovebox, a Schlenk flask was charged with a solution of complex **1a** (8.58 mg, 13.87 μmol) in $CHCl_3$ (2 mL) equipped with a magnetic stirring bar. To this solution was added *rac*-lactide (100 mg, 0.69 mmol, 50 equiv). The mixture was stirred at room temperature for 60 min. After a small

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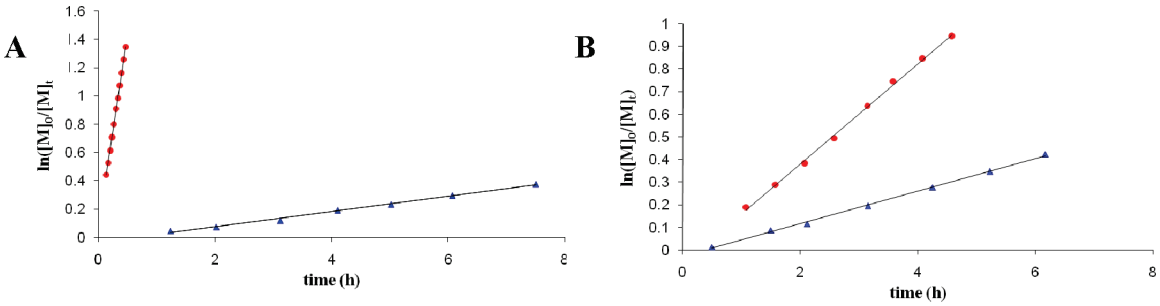


**Figure 1.** Plots of $\ln([M]_0/[M]_t$ vs time for ROP of L-lactide (red solid circles) or $\varepsilon$-caprolactone (blue solid triangles) catalyzed by the specified zinc complex at ambient temperature. Each reaction was performed in $C_6D_6$ at ambient temperature. Monomer and catalyst concentrations were held constant at 0.34 and 0.0069 M, respectively. (A) Complex **1a**: the rate constants were determined by the slope of the plots and were found to be $0.110 \pm 0.005\ M^{-1}\ s^{-1}$ with $R^2 = 0.999$ for ROP of L-lactide and $(2.17 \pm 0.10) \times 10^{-3}\ M^{-1}\ s^{-1}$ with $R^2 = 0.994$ for ROP of $\varepsilon$-caprolactone. (B) Complex **1b**: the rate constants were determined by the slope of the plots and were found to be $(8.90 \pm 0.12) \times 10^{-3}\ M^{-1}\ s^{-1}$with $R^2 = 0.998$ for ROP of L-lactide and $(2.90 \pm 0.10) \times 10^{-3}\ M^{-1}\ s^{-1}$with $R^2 = 0.998$ for ROP of $\varepsilon$-caprolactone.

**Scheme 1**

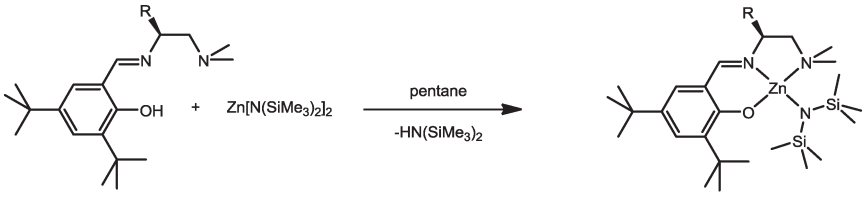


**Table 1. Rate Constants for the ROP of L-Lactide or $\varepsilon$-Caprolactone in the Presence of Zinc Complexes**[a]

| entry | M | $k_{\text{L-lactide}}\ (M^{-1}\ s^{-1})$ | $k_{\varepsilon\text{-capro}}\ (M^{-1}\ s^{-1})$ | $k_{\text{L-lactide}}/k_{\varepsilon\text{-capro}}$ |
|---|---|---|---|---|
| 1 | **1a** | $0.110 \pm 0.005$ | $(2.17 \pm 0.10) \times 10^{-3}$ | 51 |
| 2 | **1b** | $(8.90 \pm 0.12) \times 10^{-3}$ | $(2.90 \pm 0.10) \times 10^{-3}$ | 3 |

[a] Each reaction was performed in $C_6D_6$ at ambient temperature. Monomer and catalyst concentrations were held constant at 0.34 and 0.0069 M, respectively. The rate constants were determined from the slope of the plots of $\ln([LA]_0/[LA]_t)$ vs time divided by [catalyst].

**Table 2. Polylactides Produced from the ROP of *rac*-Lactide in Chloroform at Ambient Temperature**

| | | | $M_n$ | | | |
|---|---|---|---|---|---|---|
| entry | M/I | conversion (%)[a] | theoretical[b] | GPC | $0.58M_{n,GPC}$[c] | PDI |
| 1 | 50 | 97 | 6 990 | 8 630 | 5 000 | 1.08 |
| 2 | 300 | 96 | 41 509 | 96 191 | 55 790 | 1.05 |
| 3 | 700 | 96 | 96 855 | 181 730 | 105 400 | 1.08 |
| 4 | 1000 | 96 | 138 782 | 285 108 | 165 360 | 1.05 |
| 5 | 2000 | 96 | 279 612 | 530 141 | 307 480 | 1.07 |

[a] Obtained from $^1$H NMR spectroscopy. For entry 1 the reaction times was 2 h, all other reactions were carried out for 24 h. [b] Theoretical $M_n$ = (M/I) × (% conversion) × (mol wt of lactide). [c] $M_n$ values corrected by the equation $M_n = 0.58M_{n,GPC}$.[36,37]

sample of the crude solution was removed with a syringe to be characterized by $^1$H NMR spectroscopy, the product was isolated and purified by precipitation from dichloromethane by the addition of 5% hydrochloric acid in methanol. The polymer was collected and dried under vacuum to constant weight.

**Caprolactone Polymerization Procedure.** In a typical experiment (Table 2, entry 1), in a glovebox, a glass ampule equipped with a magnetic stirring bar was charged with complex **1a** (23.80 mg, 38.48 $\mu$mol) and $\varepsilon$-caprolactone (219.65 mg, 1.92 mmol, 50 equiv). The ampule was sealed under vacuum. The reaction mixture was stirred at 110 °C for 60 min. After the reaction mixture was allowed to cool to room temperature, 1 mL of $CDCl_3$ was added to the reaction mixture, and the reaction mixture was analyzed by $^1$H NMR spectroscopy. The product was isolated and purified by precipitation from dichloromethane by the addition of 5% hydrochloric acid in methanol. The polymer was collected and dried under vacuum to constant weight.

**Copolymerization of L-Lactide and $\varepsilon$-Caprolactone.** In a typical experiment (Table 4, entry 2), in a glovebox, a glass ampule equipped with a magnetic stirring bar was charged with complex **1a** (8.58 mg, 13.87 $\mu$mol), $\varepsilon$-caprolactone (285.06 mg, 2.49 mmol, 180 equiv), and L-lactide (40 mg, 0.27 mmol, 20 equiv). The ampule was sealed under vacuum. The reaction mixture was stirred at 110 °C for 30 min. After the reaction mixture was allowed to cool to room temperature, 1 mL of $CDCl_3$ was added, and the solution was analyzed by $^1$H NMR spectroscopy. The product was isolated and purified by precipitation from dichloromethane by the addition of 5% hydrochloric acid in methanol. The polymer was collected and dried under vacuum to constant weight.

**Kinetic Studies.** Polymerizations of L-lactide and $\varepsilon$-caprolactone using complexes **1a** and **1b** were monitored by $^1$H NMR spectroscopy. L-Lactide or $\varepsilon$-caprolactone and the corresponding zinc complex were dissolved in $C_6D_6$, and the % conversion was investigated from the integration of polymer and monomer signals. The chemical shifts of polylactide are 5.01 (q, H) and 1.32 (d, $CH_3$), and the chemical shifts of lactide monomer are 3.79 (q, H) and 1.16 (d, $CH_3$). The chemical shifts of polycaprolactone are 3.94 (2*H*, t, $-O-CH_2-CH_2-$), 2.09 (2*H*, t, $-CH_2-CH_2-C{=}O$), 1.47 (2*H*, m, $-CH_2-$), and 1.13 (4*H*, m, $-CH_2-$). The chemincal shifts of $\varepsilon$-caprolactone are 3.46 (2*H*, t, $-O-CH_2-CH_2-$), 2.09 (2*H*, t, $-CH_2-CH_2-C{=}O$), 1.12 (2*H*, m, $-CH_2-$), and 0.98 (4*H*, m, $-CH_2-$).

## Results and Discussion

**Polymerization of L-Lactide and $\varepsilon$-Caprolactone.** As mentioned earlier, the zinc complexes indicated in Scheme 1 were shown to be very effective catalysts for the controlled ring-opening polymerization (ROP) of lactides. Since lactides and lactones undergo similar ROP processes via a coordination–insertion mechanism,[27−35] it is of interest to examine the efficiency of these zinc derivatives to catalyze the ROP of $\varepsilon$-caprolactone. First, we determined the catalytic activity of complexes **1a** and **1b** for the ROP of L-lactide and $\varepsilon$-caprolactone

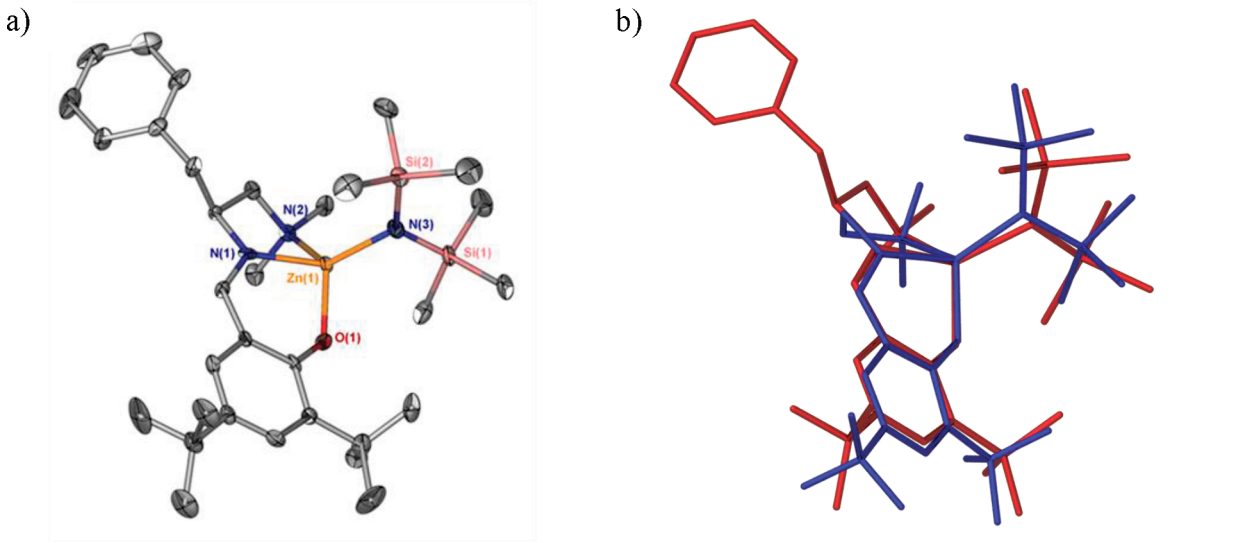


**Figure 2.** (a) X-ray crystal structure of complex **1a**. (b) Stick drawings of complexes **1a** (red) and **1b** (blue) obtained for X-ray determined structures.[26]

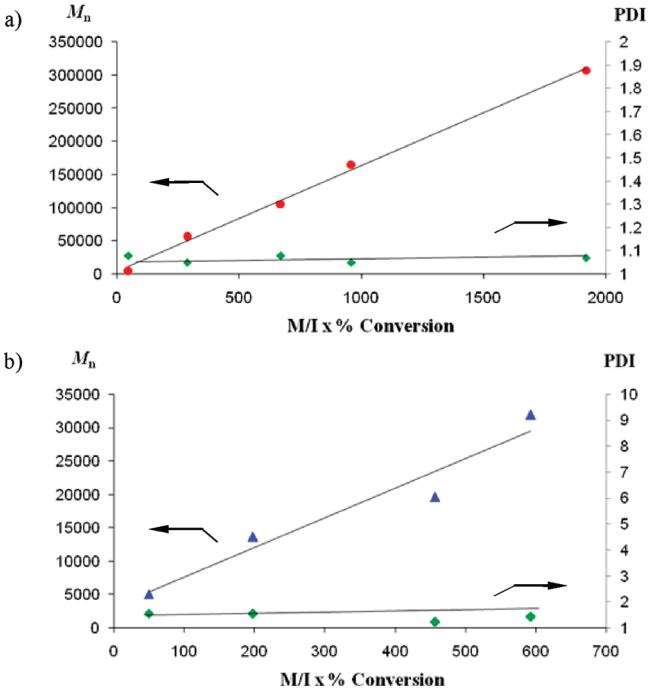


**Figure 3.** (a) Linear relationship observed between $M_n$ and monomer/initiator ratio of polylactide from *rac*-lactide catalyzed by complex **1a** at ambient temperature in $CHCl_3$. (b) Linear relationship observed between $M_n$ and monomer/initiator ratio of polycaprolactone from ε-caprolactone in bulk at 110 °C.

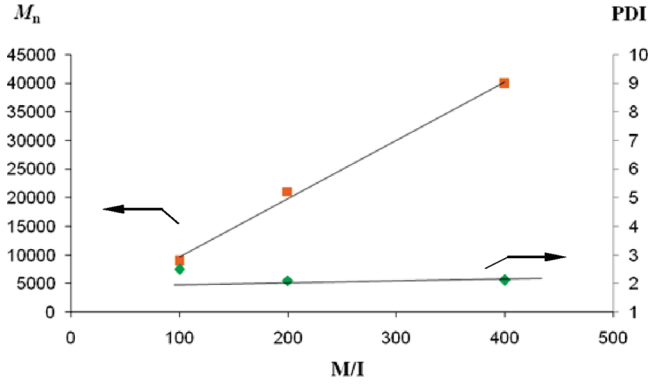


**Figure 4.** Linear relationship observed between $M_n$ and monomer/initiator ratio of copolymer from L-lactide and ε-caprolactone catalyzed by complex **1a** in the melt at 110 °C.

under identical reaction conditions. This was achieved by monitoring the polymerization reactions in $C_6D_6$ at ambient temperature by $^1H$ NMR spectroscopy. Both complexes were found to be active catalysts for the ROP of L-lactide and ε-caprolactone, providing polymers with the expected molecular weights and with low polydispersity indices. The polymerization processes were shown to be first-order in monomer concentrations as depicted in Figure 1, affording the rate constants summarized in Table 1. A zinc analogue complex containing a N,N,O ligand where the nitrogen atom is saturated was found to catalyze the ROP of lactide at 25 °C ~20 times faster than complex **1a**, 2.2 $M^{-1}$ $s^{-1}$ vs 0.11 $M^{-1}$ $s^{-1}$.[34]

As is evident from Figure 1 as well as Table 1, complex **1a** catalyzes the polymerization of L-lactide significantly faster than complex **1b**, with the ratio of $k_{obsd}$ values determined to be 12.4 at ambient temperature. This behavior has previously been noted for a slightly different set of reaction conditions and was ascribed to sterically bulky substituents on the Schiff base ligands being rate enhancing.[26] However, as depicted in Figure 2 for overlapping stick structures for the two catalysts as defined by X-ray crystallography, in the solid state the steric impact of the benzyl group appears to be minimal. Hence, the rate enhancement observed may at least in part be due to the electron-donating effect of the benzyl substituent. By way of contrast, the rate constants for the ROP of ε-caprolactone catalyzed by the two zinc complexes were quite similar at 2.17 × $10^{-3}$ and 2.90 × $10^{-3}$ $M^{-1}$ $s^{-1}$ at ambient temperature. This difference in rates of polymerization of the two monomers may reflect the difference in Lewis basicity of lactides vs caprolactone. Even if the Lewis basicities are similar, lactides have two carboxyl groups for potential coordination at the metal center. Another consideration is that the alkoxide resulting from the ring-opening of a caprolactone monomer is a primary alkoxide which should bind to zinc more strongly than the secondary alkoxide afforded from ring-opening lactide, thereby resulting in a slower polymerization process.

The preparation of polymer samples of polylactide and polycaprolactone as a function of the monomer-to-initiator ratio was carried out using complex **1a** as catalyst. The ROP of *rac*-lactide was performed in chloroform at ambient

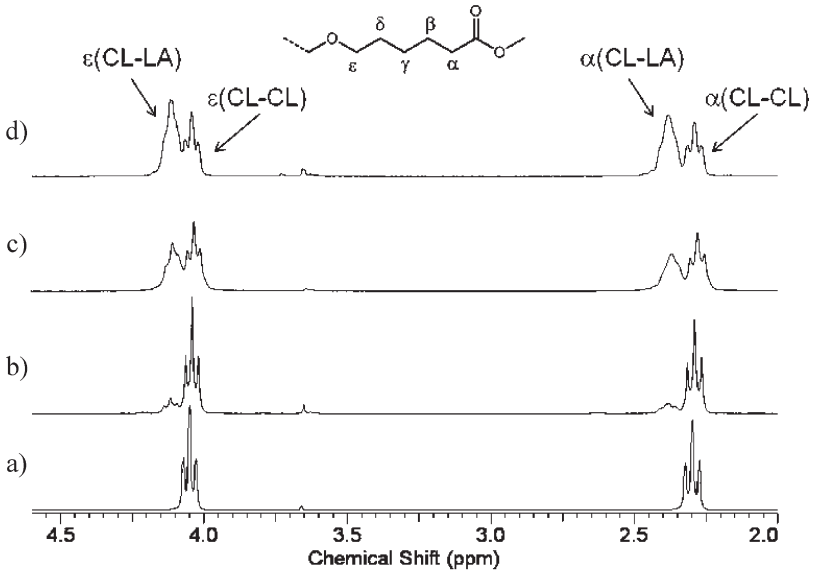


**Figure 5.** $^1$H NMR spectra of the copolymer in $CDCl_3$ at ambient temperature showing the ε- and α-methylene ranges in the copolymers of entry 1 (a), entry 2 (b), entry 3 (c), and entry 4 (d) from Table 4.

**Table 3. Polycaprolactone Produced from the ROP of ε-Caprolactone in the Melt at 110 °C**

| | | | | $M_n$ | | |
|---|---|---|---|---|---|---|
| entry | M/I × monomer conversion | M/I | conversion (%)[a] | theoretical[b] | GPC | PDI |
| 1 | 50 | 50 | 100 | 5 707 | 5 115 | 1.56 |
| 2 | 198 | 200 | 99 | 22 828 | 13 632 | 1.55 |
| 4 | 460 | 2000 | 23 | 45 656 | 19 613 | 1.23 |
| 5 | 595 | 700 | 85 | 67 114 | 31 887 | 1.43 |

[a] Obtained from $^1$H NMR spectroscopy. The reaction times was 60 min. [b] Theoretical $M_n$ = (M/I) × (% conversion) × (mol wt of ε-caprolactone).

temperature, whereas the ring-opening polymerization of caprolactone was carried out in the melt at 110 °C. The resulting polymers were isolated and purified by precipitation from $CH_2Cl_2$ with 5% HCl in methanol followed by drying *in vacuo*. Gel permeation chromatography (dual RI and light scattering detectors) using polystyrene as a standard was used to determine the molecular weights and polydispersities of the purified polymers in THF. These experiments revealed that complex **1a** behaved in a well-controlled manner producing polylactide with narrow PDIs (1.05−1.08) at ambient temperature as shown in Table 2. Furthermore, the polymerization process displayed a linear correlation between $M_n$ and the monomer/initiator ratio as illustrated in Figure 3a. A pseudoliving character for the ROP of ε-caprolactone is seen in the linear relationship between $M_n$ and the monomer/initiator ratio (Table 3 and Figure 3b); however, the polydispersity indices are rather broad (1.23−1.56). In addition, the molecular weights of the polycaprolactones were not in agreement with their expected theoretical values. These findings suggest the existence of transesterification occurring during the polymerization process (*vide infra*).

**Copolymerization of L-Lactide and ε-Caprolactone.** The random copolymerization of L-lactide and ε-caprolactone was carried out in the melt at 110 °C using complex **1a** as the catalyst. In order to gain insight into the copolymerization process of these cyclic esters in the presence of this catalytic system, a series of reactions were performed at various molar ratio of L-lactide and ε-caprolactone. These copolymerization were undertaken in sealed ampules stirred at 110 °C for 30 min. The resulting copolymers were purified by precipitation from dichloromethane by the addition of 5% hydrochloric acid in methanol. The copolymers were characterized by $^1$H and $^{13}$C NMR spectroscopy, gel permeation chromatography, and differential scanning calorimetry. The results of these random copolymerization reactions are summarized in Table 4.

The percentage of each monomer incorporated into polymer chains was analyzed by $^1$H NMR spectroscopy in $CDCl_3$. The methylene signal of polycaprolactone (−COO−$CH_2$−) is observed around 4.00 ppm, and the methine signal of polylactide (−COO−C*H*$CH_3$) appears around 5.20 ppm. Experimental observations revealed that the percent of lactide and ε-caprolactone units in the polymer chains corresponded well with the monomer feed ratios. In all the cases, the percent conversion of lactide was 98−99%, while the percent conversion of ε-caprolactone ranged from 82 to 99% (Table 4). This result correlates with the reactivity of complex **1a** which displayed a higher reactivity toward the ROP of L-lactide as discussed earlier. Two additional copolymerization reactions were performed for the 50:50 feed ratio of lactide:CL for shorter reaction times of 8 and 16 min. These runs resulted in 79 and 94% conversions of lactide and 75 and 80% conversions of CL with the percentages of lactide in the copolymers of 51 and 54%, respectively. Hence, these results are not very different from entry 5 which resulted in a copolymer composed of 55% lactide. The dependence of the molecular weights of the copolymers on monomer/initiator ratios was investigated by performing a series of experiments as listed in Table 5. The experimental results revealed that there is a linear correlation of $M_n$ and monomer/initiator ratio (Figure 4). All molecular weights of the produced copolymers were lower than their theoretical values, and the polydispersity indices were broad compared to those of their homopolymers.

As illustrated in Table 4 and Figure 5, increasing the percentage of L-lactide in the feed from 0 to 100% resulted in the formation of ε-caprolactone and lactide linkages, with the $^1$H NMR signals for the CL-LA heterodiads resonances increasing. That is, as seen in Figure 5a−d, the intensities of the resonances assigned to ε(CL-LA) and α(CL-LA) are increased as the mole ratio of the lactide in the monomer feed increases, indicative of a higher propensity for random copolymerization behavior. In addition, the copolymer's microstructure was assessed by $^{13}$C NMR spectroscopy in

**Table 4. Copolymerization of L-Lactide and ε-Caprolactone with Complex 1a[a]**

| | | % conversion | | | $M_n$ | | |
|---|---|---|---|---|---|---|---|
| entry | L-lactide:ε-CL in the feed (mmol); M/I = 200 | lactide | CL | % lactide in the polymer | theoretical[b] | GPC | PDI |
| 1 | 0:100 | | 100 | 0 | 22 828 | 13 632 | 1.55 |
| 2 | 10:90 | 98 | 82 | 15 | 19 729 | 9 253 | 1.26 |
| 3 | 30:70 | 98 | 98 | 30 | 24 148 | 21 341 | 1.46 |
| 4 | 50:50 | 99 | 84 | 55 | 23 887 | 16 330 | 1.70 |
| 5 | 70:30 | 98 | 86 | 77 | 26 067 | 21 062 | 2.12 |
| 6 | 90:10 | 99 | 99 | 95 | 28 227 | N/A[c] | N/A[c] |
| 7 | 100:0 | 99 | | 100 | 28 828 | N/A[c] | N/A[c] |

[a] Each reaction was performed in the melt at 110 °C using complex **1a** 30 min; (L-lactide + ε-caprolactone): complex **1a** = 200. [b] Theoretical $M_n$ = [(M/I) × (% conversion of L-lactide) × (mol wt of L-lactide)] + [(M/I) × (% conversion of ε-caprolactone) × (mol wt of ε-caprolactone)]. [c] Molecular weight was not measured because of polymer's insolubility in THF due to its high crystallinity.

**Table 5. Molecular Weight of Copolymer Depending on M/I[a]**

| | | % conversion[b] | | | $M_n$ | | |
|---|---|---|---|---|---|---|---|
| entry | M/I (lactide:CL = 70:30) | lactide | CL | % lactide in the polymer[b] | theoretical[c] | GPC | PDI |
| 1 | 100 | 99 | 87 | 73 | 10 933 | 8 923 | 2.50 |
| 2 | 200 | 98 | 86 | 77 | 22 828 | 21 062 | 2.12 |
| 3 | 400 | 98 | 54 | 84 | 47 754 | 39 879 | 2.10 |
| 4 | 800 | 99 | 40 | 90 | 91 669 | N/A[d] | N/A[d] |
| 5 | 1600 | 73 | 20 | 95 | 127 191 | N/A[d] | N/A[d] |

[a] Each reaction was performed in the melt at 110 °C using complex **1a** for 30 min. [b] Obtained from $^1$H NMR spectroscopy. [c] Theoretical $M_n$ = [(M/I) × (% conversion of L-lactide) × (mol. wt. of L-lactide)] + [(M/I) × (% conversion of ε-caprolactone) × (mol wt of ε-caprolactone). [d] Molecular weight was not measured because of polymer's insolubility in THF due to its high crystallinity.

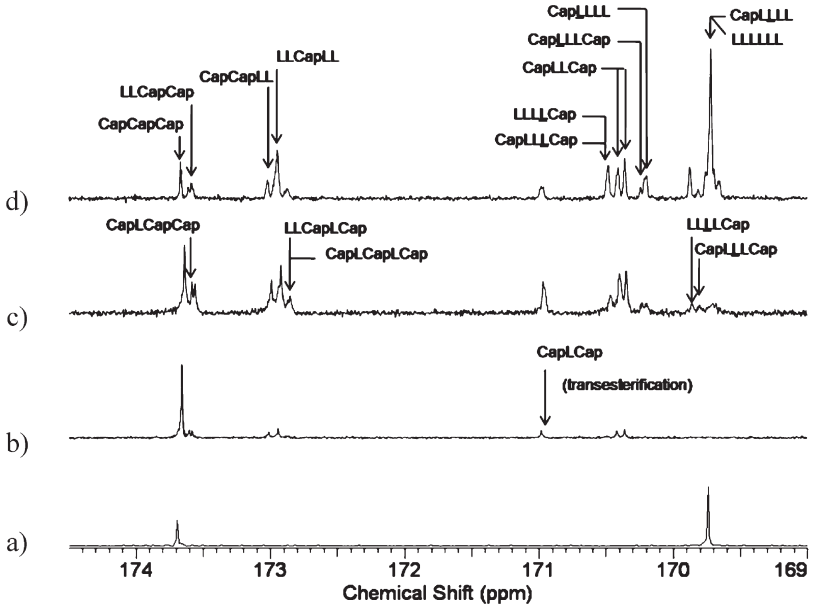


**Figure 6.** $^{13}$C NMR spectra of the copolymer in $CDCl_3$ at ambient temperature of the mixture of polylactide and polycaprolactone (a), entry 2 (b), entry 3 (c), and entry 4 (d) from Table 4.

the carbonyl region of the spectra. Figure 6 displays the $^{13}$C NMR spectrum (a) of a mixture of polylactide and polycaprolactone, with spectra for the random copolymers with increasing lactide compositions in (b) (15%), (c) (30%), and (d) (50%). The $^{13}$C NMR carbonyl sequences were assigned according to the reported literature.[38,39] A $^{13}$C NMR resonance at 170.9 ppm corresponds to the carbonyl group of a CapLCap linkage, indicative of transeserification occurring during the copolymerization process.

**DSC Studies.** The thermal properties of the polymers prepared in this study were measured by differential scanning calorimetry. The thermal parameters are listed in Table 6 for polylactide, polycaprolactone, and their copolymers. DSC thermograms of the copolymers of varying composition are provided in Figure 7. As anticipated, the thermal properties for the copolymers are very dependent on the composition of the monomers incorporated in the polymer chains. That is, the $T_g$ of the copolymers increased from −67 °C (pure polycaprolactone) to 60 °C (pure polylactide) as the percent of lactide units in the copolymer increased (Figure 8). The values calculated from Fox law fit reasonably well with the obtained values listed in Table 6. The same trend was observed for $T_m$, as the crystalline units (lactide) increased the $T_m$ increased as noted in entries 6−10 in Table 6. By way of contrast, the $T_c$'s of the copolymers decreased with increasing lactide content (entries 7−10).

## Conclusions

Herein we have reported biocompatible zinc complexes which are effective catalysts for the ring-opening polymerization of L-lactide and ε-caprolactone. The most active catalyst utilized in

**Table 6. Thermal Properties of Copolymers of Polylactide and Polycaprolactone**

| entry | % lactide in the copolymers[a] | $T_g$ (°C) | $T_g$[b] (°C) | $T_c$ (°C) | $T_{m1}$ (°C) |
|---|---|---|---|---|---|
| 1 | 0 | −67 | −67 | −62 | 57 |
| 2 | 15 | −60 | −47 | −55 | 49 |
| 3 | 30 | −31 | −40 | n.d. | 49 |
| 4 | 55 | 9 | −24 | n.d. | n.d. |
| 5 | 73 | 22 | 12 | n.d. | n.d. |
| 6 | 77 | 35 | 19 | n.d. | 164 |
| 7 | 84 | 42 | 30 | 116 | 166 |
| 8 | 90 | 52 | 41 | 105 | 171 |
| 9 | 95 | 55 | 50 | 98 | 175 |
| 10 | 100 | 60 | 60 | 88 | 179 |

[a] Determined by $^1$H NMR spectroscopy on purified copolymers. The glass transition temperature ($T_g$), the crystallization temperature ($T_c$), and the melting temperature ($T_m$) of copolymers were determined from the second heating at heating rate of 5 °C/min. [b] Theoretical values calculated by Fox equation according to the literature reported.[12]

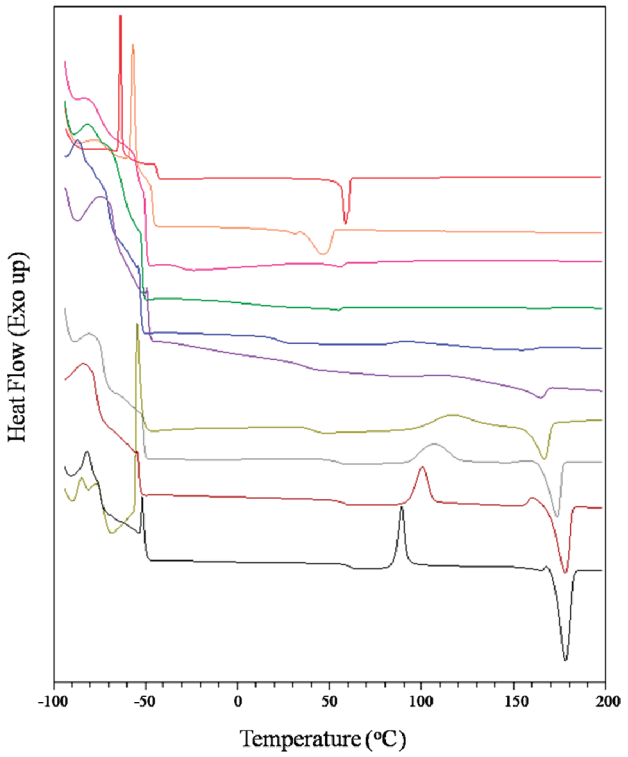


**Figure 7.** DSC curves (second heating run) of polymers from Table 5, entries 1−10 from top to bottom.

detailed studies contained a Schiff base ligand derived from the natural amino acid phenylalanine. Although homopolymerization rates in the presence of this initiator of lactide and caprolactone differ significantly in benzene at ambient temperature, the polyester resulting from the copolymerization of equimolar quantity of lactide and caprolactone has a close content of both monomers. That is, copolymerization of L-lactide and caprolactone in the presence of this catalyst in the melt at 110 °C afforded random copolymers of content consistent with the monomer mixture in the feed. This suggests that caprolactone significantly inhibits the reactivity of lactide leading to a matched reactivity of the two monomers during the copolymerization process. Nevertheless, reactions run under these conditions showed evidence of some transesterification occurring during the copolymerization process. Differential scanning calorimetry revealed the thermal properties of the copolymers to be highly dependent upon the monomer compositions. For example, the $T_g$ is adjustable in a linear fashion between −67 and 60 °C by controlling the relative

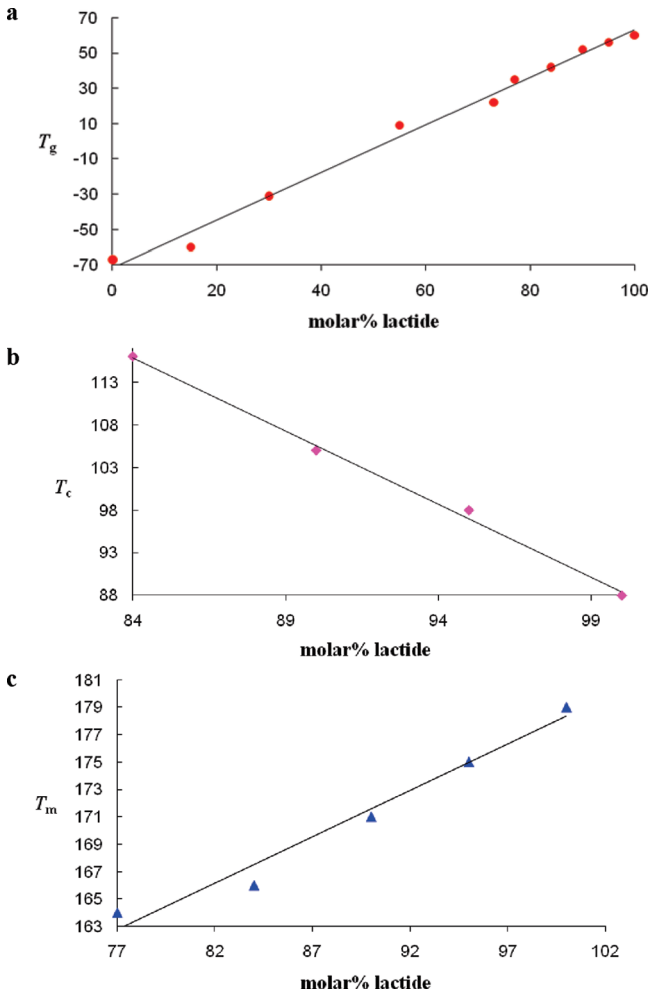


**Figure 8.** Plots of the dependence of $T_g$ (a), $T_c$ (b), and $T_m$ (c) of copolymers on the molar % lactide in copolymers.

proportions of lactide and caprolactone content. Similar trends were observed in the measured $T_c$ and $T_m$ parameters as a function of monomer ratio in the copolymers.

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