

# Synthesis and Characterization of Poly( $\epsilon$ -caprolactone)–Poly(L-lactide) Diblock Copolymers with an Organic Amino Calcium Catalyst

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**ABSTRACT:** The quasiliving characteristics of the ring-opening polymerization of  $\epsilon$ -caprolactone (CL) catalyzed by an organic amino calcium were demonstrated. Taking advantage of this feature, we synthesized a series of poly( $\epsilon$ -caprolactone) (PCL)–poly(L-lactide) (PLA) diblock copolymers with the sequential addition of the monomers CL and L-lactide. The block structure was confirmed by <sup>1</sup>H-NMR, <sup>13</sup>C-NMR, and gel permeation chromatography analysis. The crystalline structure of the copolymers was investigated by

differential scanning calorimetry and wide-angle X-ray diffraction analysis. When the molecular weight of the PLA block was high enough, phase separation took place in the block copolymer to form PCL and PLA domains, respectively. © 2006 Wiley Periodicals, Inc. *J Appl Polym Sci* 102: 2654–2660, 2006

**Key words:** biodegradable; biopolymers; block copolymers; catalysts; living polymerization

## INTRODUCTION

In a previous article,<sup>1</sup> we reported the ring-opening polymerization of  $\epsilon$ -caprolactone (CL) and L-lactide (LA) with an organic amino calcium catalyst and elucidated the structure and polymerization mechanism of the catalysts. The catalysts exhibited high activity, and the ring-opening polymerization displayed a quasiliving character, which could be used to control the molecular weight of the polyesters and to prepare block copolyesters.

Poly(L-lactide) (PLA) has been widely used for medical purposes, such as bone fixation and surgical sutures, because of its good bioresorbability and biocompatibility.<sup>2</sup> However, its application is limited by its brittleness. This weakness might be improved by blending PLA with lower glass-transition temperature polymers, such as biodegradable poly( $\epsilon$ -caprolactone) (PCL).<sup>3</sup> Unfortunately, the miscibility of PLA and PCL is very poor due to their widely different physicochemical properties.<sup>4</sup> If we use a PCL–PLA block copolymer as a compatibilizer for both components, the mis-

cibility might be improved, and the mechanical properties should be enhanced.<sup>5,6</sup>

There are two main approaches to the preparation of a PCL–PLA block copolymer: (1) the sequential addition of LA to living PCL initiated by aluminum isopropoxide Al(O<sup>*i*</sup>Pr)<sub>3</sub><sup>7</sup> or by sequential addition of CL to yttrium trifluoroacetate Y(CF<sub>3</sub>COO)<sub>3</sub> catalyzed PLA<sup>8</sup> and (2) the ring-opening polymerization of LA with stannous octoate as the catalyst and hydroxy-terminated PCL as the initiator.<sup>9</sup>

In this article, we report a study of the quasiliving polymerization phenomenon caused by an organic amino calcium catalyst, and the synthesis and characterization of PCL–PLA diblock copolymers with the catalyst.

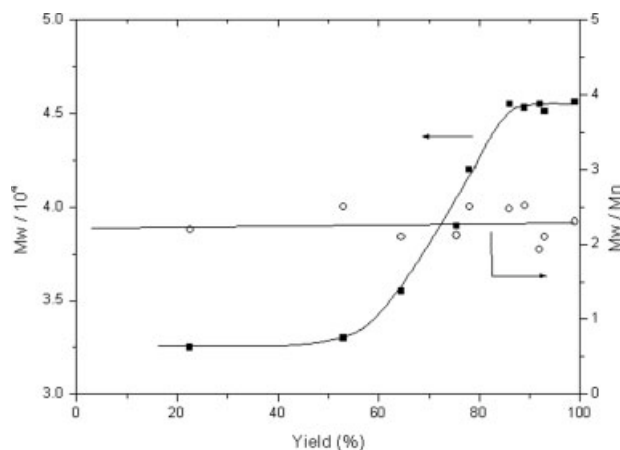
## EXPERIMENTAL

### Materials

CL (Aldrich, Milwaukee, Wisconsin) was dried over CaH<sub>2</sub> and distilled under reduced pressure before use. LA (Purac, Gorinchem, The Netherlands) was recrystallized from ethyl acetate under an argon atmosphere. Xylene and 1,4-dioxane were dried by refluxing over Na/K alloy. Ethyl acetate and propylene oxide (PO) were dried by refluxing over CaH<sub>2</sub>. Metal calcium was used without further treatment.

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**Figure 1** Relationship of molecular weight and molecular weight distribution of PCL with the yield. Polymerization conditions:  $M/I = 200$ , and temperature =  $30^{\circ}\text{C}$ .  $M_w$  = weight-average molecular weight.

### Preparation of the catalyst

Gaseous  $\text{NH}_3$  was purified with a column filled with sodium sulfate to remove residual water and was liquidized with dry ice. The liquidized  $\text{NH}_3$  was introduced into a flask that contained metal Ca and a magnetic stirrer. PO was added dropwise with a syringe. The molar ratio of Ca to PO was 1/1. Ten minutes later, the excess  $\text{NH}_3$  was evaporated by increasing the temperature from  $-40$  to  $100^{\circ}\text{C}$  with a water bath. The obtained white solid was crushed into fine powders under a dried nitrogen atmosphere in a glovebox.

### Polymerization of CL

All polymerizations were carried out in an argon-filled glass reactor that was flame-dried before use. CL, xylene, and the catalyst suspension in xylene were introduced into the reactor with dried syringes in that order. The volume ratio of CL to xylene was 2/5, and the reaction temperature was  $70^{\circ}\text{C}$ . The reaction product was dissolved in  $\text{CHCl}_3$ , precipitated into alcohol, filtered, washed several times with alcohol, and finally dried *in vacuo* at room temperature for 24 h.

### Synthesis of the PCL-PLA block copolymer

The preparation of the PCL prepolymer was similar to the previously discussed homopolymerization of CL, but it was done at volume ratio of xylene to CL of 8/1 and at room temperature for 8 h. A part of the reaction mixture was taken out with a dry syringe for analysis. Then, the second monomer, LA, was introduced in the form of LA/dioxane (weight ratio = 1 : 2) solution. The polymerization was continued at  $40^{\circ}\text{C}$  for 1 h. The product mixture was precipitated into hexane, dried *in vacuo* at room temper-

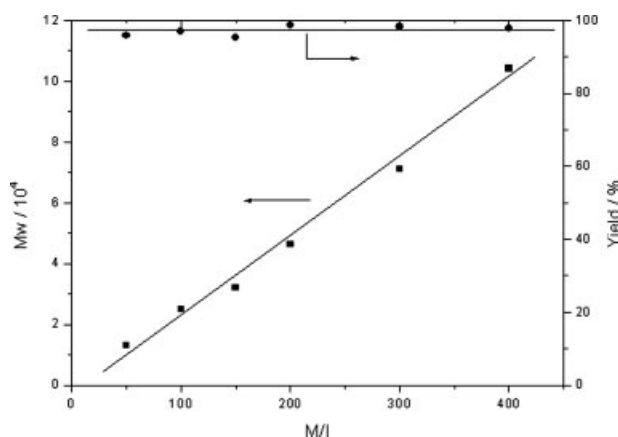
ature for 24 h, and analyzed by NMR and gel permeation chromatography (GPC).

### Characterization

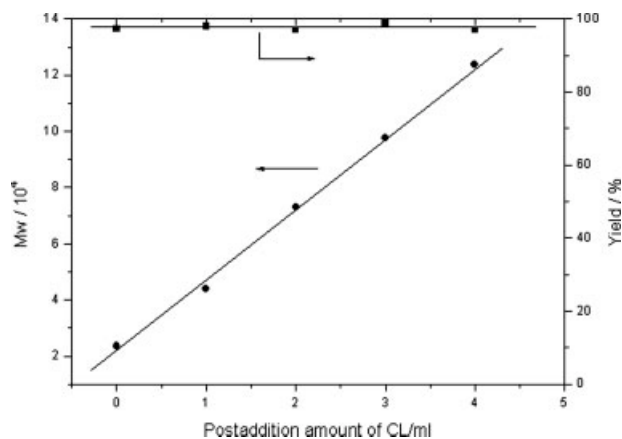
NMR spectra were recorded with a Unity-400 NMR spectrometer (Bruker, Switzerland) at room temperature with  $\text{CDCl}_3$  as the solvent and tetramethylsilane as the internal reference. The GPC measurement was conducted at  $25^{\circ}\text{C}$  with a Waters 410 GPC instrument (Waters, USA) equipped with a Waters Styragel HT6E column and a differential refractometer detector. Tetrahydrofuran (THF) was used as eluent at a flow rate of 1.0 mL/min, and the molecular weights were calibrated with polystyrene standards. Differential scanning calorimetry (DSC) was carried out on a Perkin Elmer DSC-7 instrument (Perkin Elmer, New York) the heating rate was  $10^{\circ}\text{C}/\text{min}$ . Wide-angle X-ray diffraction (WAXD) was performed with a Philips model PW-1820 X-ray diffractometer (Philips, Almelo, The Netherlands) with Ni-filtered  $\text{Cu K}\alpha$  radiation at room temperature. The scanning rate was  $0.01^{\circ}/\text{s}$ .

## RESULTS AND DISCUSSION

Figure 1 shows that the weight-average molecular weight ( $M_w$ ) increased almost linearly with a yield of PCL over the yield range 50–85% and did not change appreciably once the yield was greater than 85%, whereas the molecular weight distribution of PCL remained around 2.3 throughout the polymerization course. When the yield was lower than 50%,  $M_w$  did not increase linearly with yield. This was probably because the low molecular species remained in the solvent when the polymer product was precipitated from the solution. The dependence of the yield and molecular weights of poly( $\epsilon$ -caprolactone) ( $M_{\text{PCL}}$ ) on the weight ratio of monomer to catalyst ( $M/I$ ) is



**Figure 2** Dependence of  $M_{\text{PCL}}$  and yield on  $M/I$ . Polymerization conditions: temperature =  $30^{\circ}\text{C}$ .  $M_w$  = weight-average molecular weight.



**Figure 3** Influence of the postaddition of CL on the molecular weight of the final polymers.  $M_w$  = weight-average molecular weight.

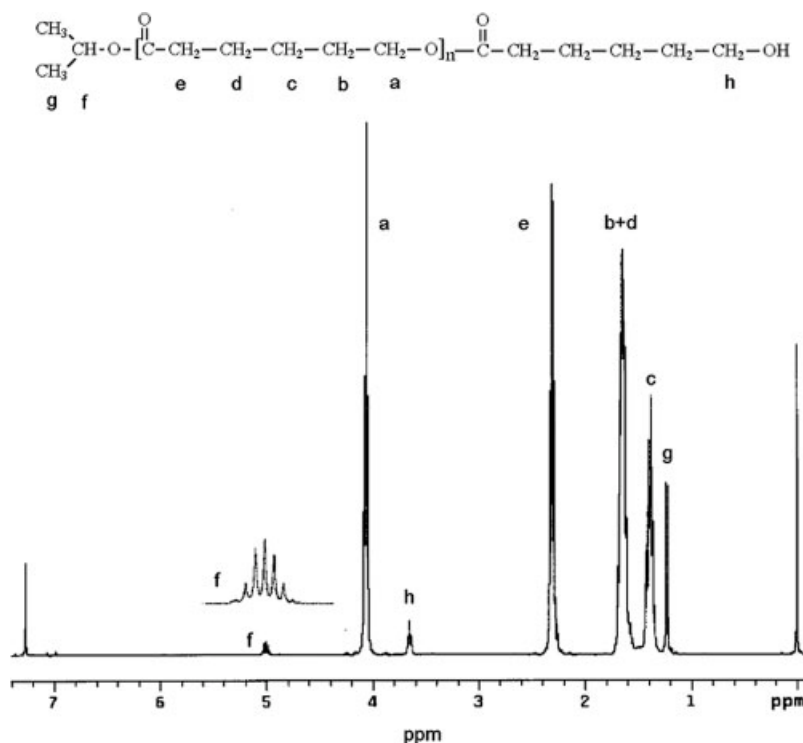
shown in Figure 2, which demonstrates that the polymerization degree of PCL measured by GPC was consistent with the  $M/I$  values. Also, to gain further evidence of the living polymerization character, after 1 mL of CL was prepolymerized, we injected 1, 2, 3, and 4 mL of CL, respectively, to the reactor to continue polymerization. The results are shown in Figure 3. There was a good linear relationship between the molecular weight and the total amount of CL monomer. Obviously, the polymerization of CL with the organic amino calcium catalyst had a quasiling nature.

Taking advantage of the living polymerization nature of Ca/PO catalyst, we successfully synthesized PCL-PLA diblock copolymer by the sequential polymerization of CL and LA.

First, the PCL prepolymer was prepared as described in the Experimental section. The reaction system was in a suspension state in the early stage of the polymerization because of the poor solubility of the catalyst in xylene. Ten minutes later, the reaction mixture became transparent and viscous. Eight hours later, some of the reaction solution was taken out with a dry syringe, and analyzed by  $^1\text{H-NMR}$  and GPC to determine its molecular weight.

Figure 4 shows the  $^1\text{H-NMR}$  spectra of the PCL prepolymer. The peaks at 4.1, 2.3, 1.6, and 1.4 ppm were assigned to the methylene protons (a, e, b + d, and c, respectively) of the PCL repeat unit. The doublet peak at 1.23 ppm (g) was attributed to the isopropoxy end group, and the triplet peak at 3.65 ppm (h) was assigned to the methylene proton adjacent to the hydroxy end group, as described in our previous article.<sup>1</sup>  $M_{\text{PCL}}$  could be calculated by the integration area ratios of peaks a, e, b + d, and c to g. The equation is  $M_{\text{PCL}} = 6 \times 114 \times (A + B + C + D + E)/(10 \times G)$ , where the capital letters represent the areas of the corresponding NMR peaks.

At the end of prepolymerization, the LA/dioxane solution was introduced into the reactor, and the reaction was conducted at 40°C for 1 h. The final product was analyzed with NMR and GPC. The  $^1\text{H-}$



**Figure 4**  $^1\text{H-NMR}$  spectrum of the PCL prepolymer.

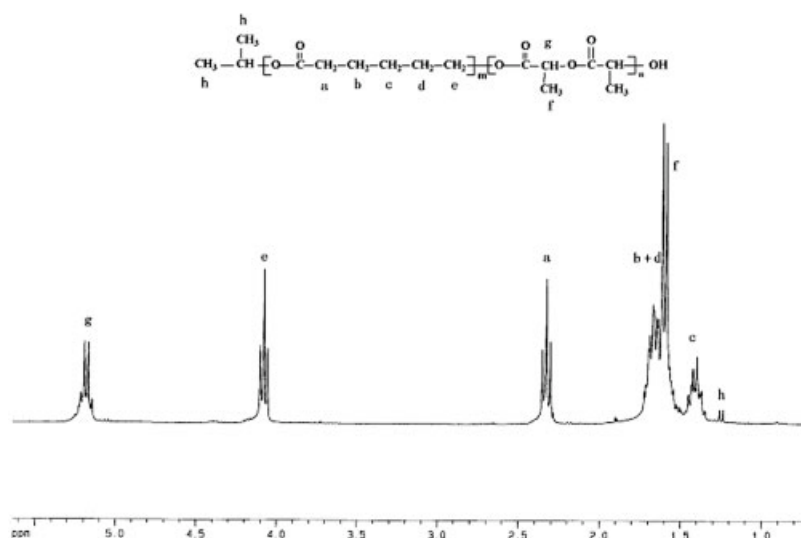


Figure 5  $^1\text{H-NMR}$  spectrum of the PCL-PLA block copolymer (sample 6 in Table I).

NMR spectrum of the PCL-PLA diblock copolymer is shown in Figure 5. The peaks at 4.1, 2.3, 1.6, and 1.4 ppm were assigned to the methylene protons (a, e, b + d, and c, respectively) of the PCL block, and the peaks at 1.6 and 5.2 ppm were assigned to the PLA block. The doublet peaks at 1.23 ppm due to the isopropoxy end group of PCL still existed in the spectrum shown Figure 5, but the triplet peak due to the methylene proton adjacent to the hydroxy end group (peak h in Fig. 4) disappeared, indicating that the PLA block was attached to the living end of PCL prepolymer. The molecular weight of the poly(L-lactide) ( $M_{\text{PLA}}$ ) block could be calculated from the integration area ratio of the peak at 4.06 ppm (e, PCL) to that at 5.16 ppm (g, PLA) and  $M_{\text{PCL}}$  calculated as described previously. The equation is  $M_{\text{PLA}} = M_{\text{PCL}} \times 144 \times G/(E \times 114)$ , where the capital letters represent the areas of the corresponding peaks in Figure 5.

The reaction conditions and compositions of PCL-PLA diblock copolymers are shown in Table I.

The weight-average  $M_{\text{PCL}}$  determined by  $^1\text{H-NMR}$  increased with increasing  $M/I$ .  $M_{\text{PLA}}$  increased with increasing feed ratio of LA and CL. So the composition of the PCL-PLA block copolymer could be controlled by a change in the  $M/I$  and LA/CL feed ratios.

$M_{\text{PCL}}$  and the molecular weight of the PCL-PLA block copolymers were also determined by GPC and calibrated against polystyrene standards. The absolute  $M_w$  values determined by GPC were much higher than those determined by NMR, probably due to the different solution rheological properties between polyesters and the polystyrene standard, but they showed the same dependence of  $M_w$  on  $M/I$  and LA/CL as shown in Table I.  $M_w$  of the PCL-PLA block copolymers were higher than that of the correspond-

TABLE I  
Block Copolymerization of CL and LA

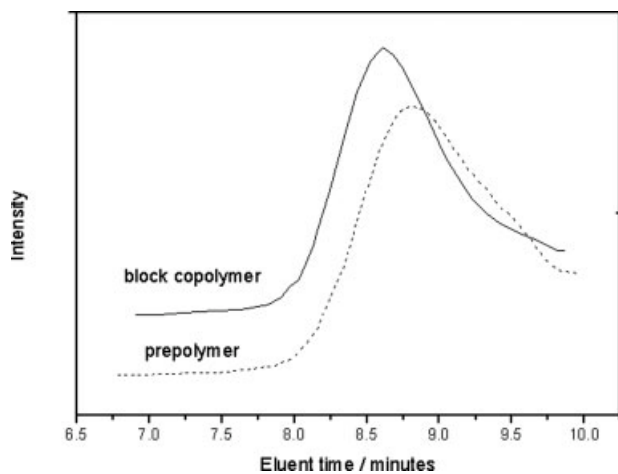
No.	$M/I$	$M_{\text{PCL}}^a$	LA/CL in feed	LA/CL in product <sup>b</sup>	$M_{\text{PLA}}^c$	$M_{w1}^d$	$M_w/M_{n1}$	$M_{w2}^d$	$M_w/M_{n2}$
1	26	2,010	0.51	0.59	1,180	13,500	1.38	13,900	1.39
2	27	2,090	0.79	0.90	1,880	12,700	1.33	14,800	1.35
3	27	1,940	1.92	2.33	4,520	13,400	1.39	19,800	1.43
4	44	3,430	0.44	0.51	1,750	19,100	1.48	19,400	1.50
5	53	3,470	0.88	0.88	3,060	24,400	1.51	26,900	1.77
6	54	3,490	1.82	1.82	6,350	25,600	1.77	31,800	1.45

<sup>a</sup>  $M_{\text{PCL}}$  determined by NMR.  $M_{\text{PCL}} = 6 \times 114 \times (A + B + C + D + E)/(10 \times G)$ , in which the capital letters represent the corresponding peak areas in Figure 4.

<sup>b</sup> Calculated according to the integrated area ratio of the resonance peaks due to the PCL block at 4.06 ppm and due to the PLA block at 5.16 ppm.

<sup>c</sup> Calculated from  $M_{\text{PCL}}$  and the LA/CL weight ratio determined by NMR.

<sup>d</sup> Molecular weight and molecular weight distribution of the PCL-PLA diblock copolymer determined by GPC.



**Figure 6** GPC curves of the PCL prepolymer and PCL-PLA block copolymer (sample 6 in Table I).

ing PCL prepolymers, but the difference between them was not as expected. Take sample 2 in Table I as an example. The block length of PLA determined by NMR was 90% of the PCL block but only 17% according to the GPC data. This implied that the attachment of the PLA block onto the PCL chain end did not cause enough change in hydrodynamic volume of the whole molecule. The reason for that might be the limited or poor solubility of PLA block in THF. On one hand, the PLA block chain was not as extended in the solution as the PCL block. On the other hand, the PCL block chain might have become less extended compared to the PCL prepolymer because of the influence of the PLA block. In the case of samples 5 and 3, the molecular weights calculated from NMR ( $M_{\text{NMR}}$ 's) were similar (sample 5,  $M_{\text{NMR}} = M_{\text{PLA}} + M_{\text{PCL}} = 3470 + 3060 = 6530$ ; sample 3,  $M_{\text{NMR}} = M_{\text{PLA}} + M_{\text{PCL}} = 1940 + 4520 = 6460$ ), but sample 5 had a much longer block length of PCL than sample 3. So the higher  $M_w$  of sample 5 determined by GPC might have been due to the higher solubility of the PCL block in THF; sample 5 might have become more extended compared to

sample 3 because the former had a longer PCL block and had higher a hydrodynamic volume or higher  $M_w$ .

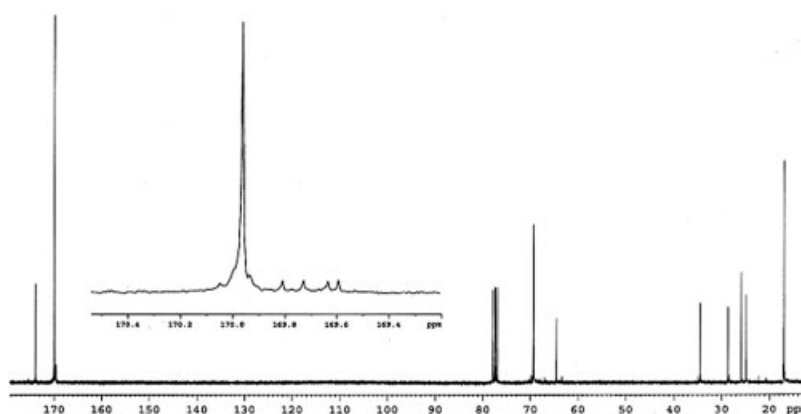
The GPC curves of the prepolymer and block copolymer of sample 6 are shown in Figure 6. The narrow molecular weight distribution and the symmetric GPC profile of the copolymer confirmed the absence of homopolymers in the product.

The  $^{13}\text{C}$ -NMR spectra of the PCL-PLA diblock copolymer (sample 6 in Table I) are shown in Figure 7. The peaks at 173.9, 64.5, 34.5, 28.7, 25.9, and 24.9 ppm were assigned to the PCL block, and the peaks at 169.9, 69.4, and 17.0 ppm were due to the PLA block. No peaks due to the random CL-LA sequences appeared between 173.9 ppm (carbonyl group of PCL block) and 169.9 ppm (carbonyl group in PLA block), which undoubtedly demonstrated that the block copolymer was free of any random sequence.<sup>9</sup>

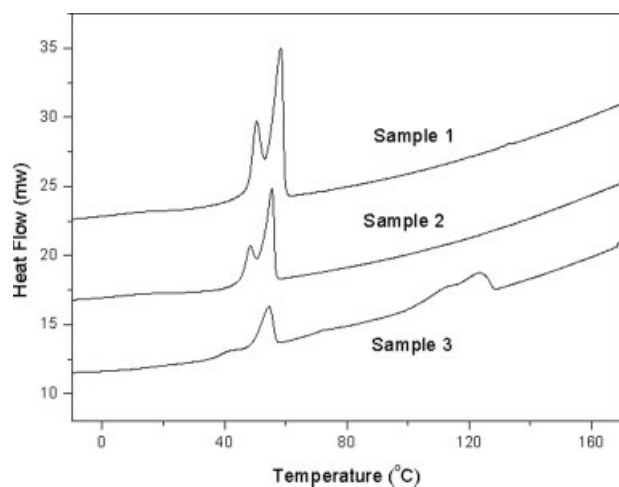
There were four small peaks between 169.9 and 169.5 ppm, which was evidence of the racemization reaction of LA.<sup>10</sup> Their total area was 5% of the peak at 169.9 ppm. Correspondingly, there were approximately 8% D-lactic acid units in the copolymer.<sup>10</sup>

Figure 8 shows the DSC heating curves of samples 1, 2, and 3, which had similar  $M_{\text{PCL}}$  values and different lengths of the PLA block. Samples 1 and 2 only had two melting peaks from the PCL block because the PLA block could not crystallize due to its short length. When the  $M_{\text{PLA}}$  was over 4000, its melting peaks appeared around 120°C. Similar phenomena are shown in Figure 9. Sample 4 showed only one melting peak of PCL, and samples 5 and 6 showed two from the both blocks. From previous analysis, we confirmed that if  $M_{\text{PLA}}$  was high enough, the phase separation took place in the block copolymer to form PCL and PLA domains, respectively.

Table II shows the melting temperature ( $T_m$ ) and the melting enthalpy of the poly( $\epsilon$ -caprolactone) block ( $\Delta H_{m\text{PCL}}$ ).  $\Delta H_{m\text{PCL}}$  was calculated from the following equation:  $\Delta H_{m\text{PCL}} = \Delta H_m(M_{\text{PCL}} + M_{\text{PLA}})/$



**Figure 7**  $^{13}\text{C}$ -NMR spectrum of the PCL-PLA block copolymer (sample 6 in Table I).

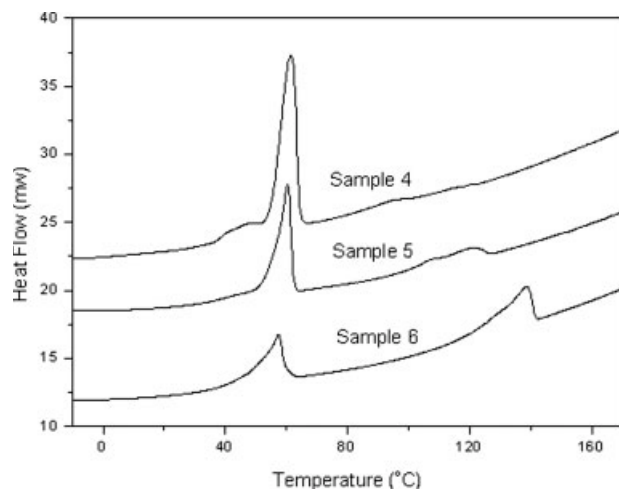


**Figure 8** DSC heating curves of samples 1, 2, and 3 (in Table I).

$M_{\text{PCL}}$ , where  $\Delta H_m$  is the apparent melting enthalpy of the whole specimen determined by DSC and  $M_{\text{PCL}}$  and  $M_{\text{PLA}}$  are the molecular weights of the blocks determined by NMR.

As shown in Table II, the higher  $M_{\text{PLA}}$  was, the lower  $T_m$  and  $\Delta H_{m\text{PCL}}$  were when the copolymers had similar  $M_{\text{PCL}}$  values. This was caused by the strong covalent interconnection between the two domains. The PLA domain had a higher  $T_m$  and glass-transition temperature and crystallized earlier. With one end fixed, the PCL block exhibited less crystallizability, which led to a lower  $T_m$  and a lower  $\Delta H_{m\text{PCL}}$ . The longer the chain length of the PLA block was, the more influence was imposed from the PLA domain on the PCL domain.

The WAXD spectra of the PCL-PLA diblock copolymers and the PCL and PLA homopolymers



**Figure 9** DSC heating curves of samples 4, 5, and 6 (in Table I).

**TABLE II**  
 $T_m$  and  $\Delta H_m$  of the PCL Block

Sample	$M_{\text{PCL}}^a$	$M_{\text{PLA}}^b$	$T_m$ (°C)	$\Delta H_{m\text{PCL}}$ (J/g) <sup>c</sup>
1	2010	1180	58.3	59.5
2	2090	1880	55.5	56.1
3	1940	4520	54.5	40.9
4	3430	1750	61.5	59.1
5	3470	3060	60.3	55.4
6	3490	6350	57.4	42.7

<sup>a</sup>  $M_{\text{PCL}}$  determined by  $^1\text{H-NMR}$  (Fig. 4).

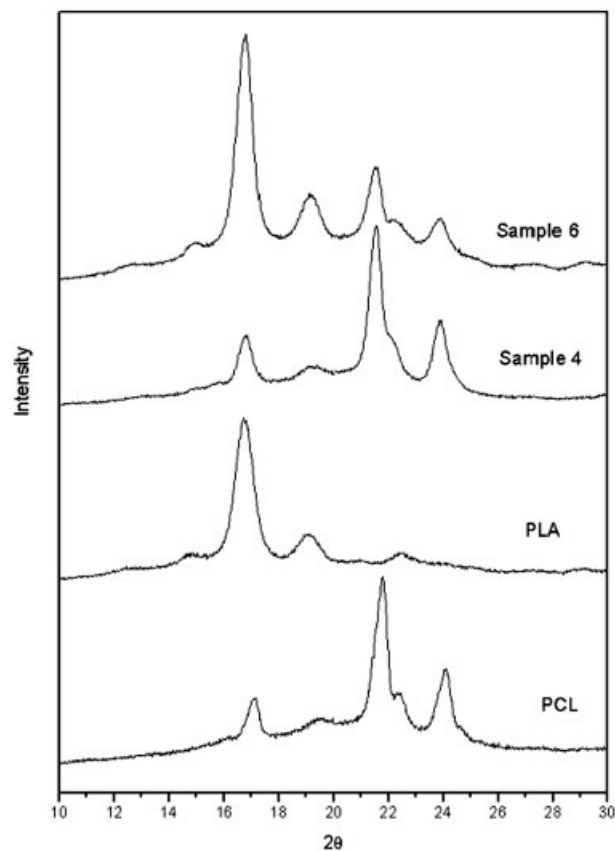
<sup>b</sup> Calculated from  $M_{\text{PCL}}$  and the LA/CL weight ratio determined by NMR.

<sup>c</sup> Calculated from the  $\Delta H_m$  of the PCL melting peak and the weight ratio of the PCL block in the copolymer.

are shown in Figure 10. The crystalline pattern of the PLA block was not observed in sample 4, but it appeared in sample 6, in agreement with the DSC results.

## CONCLUSIONS

In this study, we demonstrated the quasiliving character of the ring-opening polymerization of CL catalyzed by an organic amino calcium catalyst. Also, a



**Figure 10** WAXD curves of samples 4 and 6 and the PCL homopolymers.

series of PCL-PLA diblock copolymers were synthesized with sequential addition of the monomers CL and LA, which took advantage of the quasiliving feature. The block structure was confirmed by  $^1\text{H-NMR}$ ,  $^{13}\text{C-NMR}$ , and GPC analysis. The composition of the block copolymers could be controlled by the modification of changing the  $M/I$  and  $LA/CL$  feed ratios. Furthermore, the crystalline structures of the block copolymers were investigated by DSC and WAXD analysis. We confirmed that if the  $M_{\text{PLA}}$  was high enough, the phase separation took place in the block copolymer to form PCL and PLA domains, respectively. Also, with one end fixed, the PCL block exhibited loss crystallizability. The higher the chain length of the PLA block was, the more influence was imposed from the PLA domain on the PCL domain.

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