

Synthesis and Characterization of Poly(ϵ -caprolactone)-*b*-poly(ethylene glycol) Block Copolymers Prepared by a Salicylaldimine-Aluminum Complex

Zi-Xiu Du, Jun-Ting Xu, Yong Yang, Zhi-Qiang Fan

Key Laboratory of Macromolecular Synthesis and Functionalization, Department of Polymer Science and Engineering, Zhejiang University, Hangzhou 310027, China

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ABSTRACT: A series of poly(ϵ -caprolactone)-*b*-poly(ethylene glycol) (PCL-*b*-PEG) block copolymers with different molecular weights were synthesized with a salicylaldimine-aluminum complex in the presence of monomethoxy poly(ethylene glycol). The block copolymers were characterized by ^1H NMR, GPC, WAXD, and DSC. The ^1H NMR and GPC results verify the block structure and narrow molecular weight distribution of the block copolymers. WAXD and DSC results show that crystallization behavior of the block copolymers varies with the composition. When the PCL block is extremely short, only the PEG

block is crystallizable. With further increase in the length of the PCL block, both blocks can crystallize. The PCL crystallizes prior to the PEG block and has a stronger suppression effect on crystallization of the PEG block, while the PEG block only exerts a relatively weak adverse effect on crystallization of the PCL block. © 2007 Wiley Periodicals, Inc. *J Appl Polym Sci* 105: 771–776, 2007

Key words: block copolymer; poly(ϵ -caprolactone); poly(ethylene glycol); crystallization

INTRODUCTION

Poly(ϵ -caprolactone) (PCL) has been studied intensively due to its good biodegradability and biocompatibility.^{1–3} However, PCL is a type of semicrystalline and hydrophobic material, which hinders the application of PCL. On the other hand, PEG is a hydrophilic and nontoxic material with no antigenicity and immunogenicity, which allow PEG can be used for clinical applications.^{4,5} To improve the hydrophilicity and to regulate the biodegradation rate of PCL, random and block copolymers of PCL with PEG were usually prepared.

Thus extensive studies have been done on the metal catalysts for example, the complexes of Al,^{6–8} Li,^{9,10} Mg,^{11,12} Fe,^{13–15} Sn,¹⁶ Zr,^{17,18} or Y¹⁹, for the ring-opening polymerization (ROP) of cyclic esters. However, when metal alkoxides were used as initiators for ROP of cyclic esters, backbiting side reaction usually occurs, leading to the formation of macrocycles and a broad molecular distribution. On the other hand, living ROP of cyclic esters can be catalyzed by the compounds with sterically bulky substituents on the nitrogen donor atoms of α -diketimi-

nato ligands.^{1,20} However, most of these catalysts are difficult to synthesize or purify. Recently, Nomura reported that PCL with a narrow molecular weight distribution can be prepared by salicylaldimine-aluminum complexes, in which the salicylaldimine ligand can be easily prepared by reaction of salicylaldehyde with aniline.²¹

In this study, we used a salicylaldimine-aluminum complex²¹ as catalyst to prepare PCL-*b*-PEG block copolymers with narrow polydispersity. Synthesis of PCL-*b*-PEG block copolymers has been reported in literature,^{22–27} however, most of the PCL-*b*-PEG block copolymers reported contain large amount of PCL and the PEG block is not crystallized. As we know, PEG and PCL are both crystallizable polymers. The block copolymer systems containing both crystallizable blocks are received many research attentions recently.^{28–35} In this study, a series of PCL-*b*-PEG block copolymers with constant PEG length but different PCL lengths were synthesized and variation of crystallization behavior with composition was investigated.

EXPERIMENTAL

Materials

Toluene was distilled with Na-benzophenone under purified N_2 prior to use. ϵ -CL (from ACROS) was purified by vacuum distillation over CaH_2 .

Correspondence to: J.-T. Xu (xujt@zju.edu.cn).
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Monomethoxy poly(ethylene glycol) (MPEG) with molecular weights of 2000 (from ACROS) were dried by an azeotropic distillation with dry toluene. AlEt_3 was purchased from Aldrich and was diluted with freshly distilled toluene (1.0M). All operations were carried out under a dry Ar atmosphere with a Schlenk technique.

Preparation of *N*-(2-hydroxy-benzylidene) aniline

The solution of aniline (2.82 mL mmol) in dry ethanol (20 mL) was slowly added to the mixture of dry ethanol (40 mL), molecular Sieve (3 Å), and salicyl (2.82 mL, 2.8 mmol). The mixture was stirred at room temperature overnight and filtrated, and the molecular sieve was washed with AcOEt twice (2×10 mL).³⁶ The solvent was evaporated and the crude product was recrystallized in EtOH/AcOEt with a yield of 92%.

Preparation of the catalyst

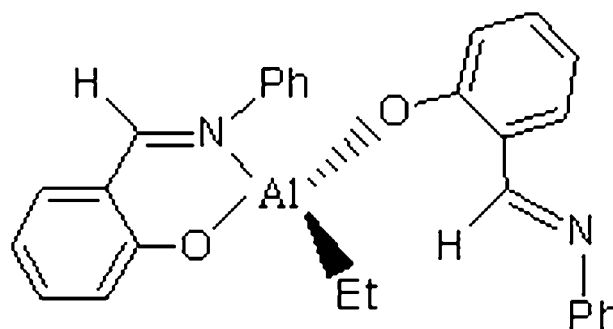
Solution of AlEt_3 in toluene (1.0M) was added to a solution of *N*-(2-hydroxy-benzylidene) aniline in toluene under N_2 at room temperature, then heated to 70°C and held for 2 h.²¹ The obtained catalyst (**1**) (Scheme 1) was used without further purification.

Polymerization

MPEG solution in toluene was added to the catalyst solution at room temperature. The mixture was stirred at 75°C for 2 h, then ϵ -CL was added after it was cooled at room temperature. The reaction was lasted for 16 h at 50°C with stirring. The product was isolated by precipitation into diethyl ether. The polymer was re-dissolved in CHCl_3 and precipitated with 1-hexane, followed by drying in a vacuum at room temperature for 24 h.

Measurements

The molecular weights and polydispersity of the polymers were determined by GPC in a PL 220 GPC



Scheme 1 Structure of catalyst (1).

instrument with tetrahydrofuran as the eluent at 40°C and polystyrene standards for column calibration. ^1H NMR spectra of the polymers in deuterated chloroform solutions were recorded on a Bruker Avance-500 spectrometer with tetramethylsilane as the internal standard. The absolute number-average molecular weights and polymerization degrees of the PCL homopolymers and the block copolymers were calculated from ^1H NMR spectra. The PCL homopolymers and PCL-*b*-PEG block copolymers are also denoted as PCL_n and PCL_n -*b*- PEG_m , where the subscripts *n* and *m* refer to the polymerization degree of the PCL and the PEG. Differential scanning calorimetry (DSC) was carried out on a TA Q100 DSC. All samples are first held at 100°C for 5 min, then cooled to -60°C at a rate of 10°C/min, and finally heated to 80°C at a rate of 10°C/min under a nitrogen atmosphere. Wide-angle X-ray diffraction (WAXD) was carried out by Rigaku D/max 2550PC with a Ni filtered Cu K_α radiation ($\lambda = 0.1546$ nm) at room temperature. The scan rate was 4°(2 θ)/min. The samples were firstly crystallized at -20° for 24 h before WAXD experiments.

RESULTS AND DISCUSSION

The PCL-*b*-PEG block copolymers (shown in Table I) with different molecular weights and compositions were synthesized by changing the feed molar ratio of MPEG/ ϵ -CL in the presence of salicylaldehyde-

TABLE I
Polymerization of CL Initiated by Catalyst (1)/MPEG

Samples	Ligand (mmol)	AlEt_3 (mmol)	PEG ₄₄ ^a (g)	[PEG]/[CL]	Time (h)	Conv. (%)	M_n^b ($\times 10^{-3}$)	M_n^c ($\times 10^{-3}$)	PDI
PCL ₈ PEG ₄₄	0.2	0.1	0.201	5.02	13	92	2.9	3.1	1.09
PCL ₂₄ PEG ₄₄	1.0	0.5	1.005	1.73	13	92	4.8	5.7	1.10
PCL ₄₀ PEG ₄₄	1.0	0.5	1.005	1.05	13	94	6.6	9.2	1.08
PCL ₅₉ PEG ₄₄	1.0	0.5	1.005	0.72	13	95	8.7	10.3	1.05
PCL ₆₈ PEG ₄₄	0.2	0.1	0.201	0.53	13	91	10.7	13.9	1.06

^a Nominal value.

^b Evaluated by ^1H NMR.

^c Determined by GPC (calibrated with polystyrene standards).

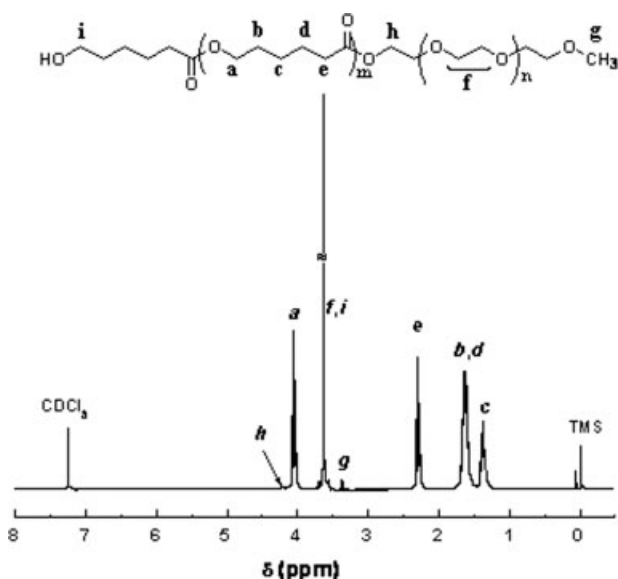


Figure 1 ^1H NMR spectrum of $\text{PCL}_{59}\text{PEG}_{44}$.

aluminum complexes. The results of experiment indicate that this complex is an efficient catalyst for the copolymerization of ϵ -CL and MPEG. The conversion is higher than 90% at 50°C within 13 h.

Figure 1 shows ^1H NMR spectrum of a PCL-*b*-PEG block copolymer and the assignment of the resonances. The signal at 4.20–4.23 ppm (triplet, *h*) is contributed by CH_2 in the PEG unit directly linked to PCL ($-\text{OCH}_2\text{CH}_2\text{OCO}-$). Observation of this signal verifies the block structure of PCL-*b*-PEG. The signal at 3.63–3.70 ppm (multiplet, *f* and *i*) is assigned to the methylene proton of PEG and hydroxymethylene of PCL end group. The singlet for monomethoxy from PEG end group ($-\text{OCH}_2\text{CH}_2\text{OCH}_3$) appears at 3.37 ppm. In addition, no triplet signal for hydroxymethylene of PEG end group ($-\text{OCH}_2\text{CH}_2\text{OH}$) is observed at 3.59–3.61 ppm.¹⁹ This shows that the end group hydroxyl of PEG reacts with the ethyl in the salicylaldimine-aluminum complex and macro-initiator is formed. This macro-initiator contains a structure of $-\text{Al}-\text{OCH}_2\text{CH}_2-$ and is active for polymerization of caprolactone. The structure of the PCL-*b*-PEG block copolymers is also in accordance with the two-step “coordination-insertion” mechanism proposed in literature, which consists of ϵ -caprolactone coordination to the macro-initiator followed by monomer insertion into the aluminum-oxygen bond.^{37–40}

The number-average molecular weights of the PCL-*b*-PEG block copolymers can be calculated from the ^1H NMR spectra⁴¹ based on eqs. (1–3) and the result is listed in Table I.

$$\bar{M}_{n,\text{NMR}} = \bar{DP}_{\text{PEG}} \times 44 + \bar{DP}_{\text{PCL}} \times 114 \quad (1)$$

Where

$$\bar{DP}_{\text{PEG}} = 3(I_f + I_i)/4I_g \quad (2)$$

$$\bar{DP}_{\text{PCL}} = 2\bar{DP}_{\text{PEG}} \times [I_e/(I_f + I_i)] \quad (3)$$

In which $(I_f + I_i)$, I_g and I_e are the integral intensities of proton resonances at 3.63, 3.37, and 2.30 ppm, respectively. The numbers 44 and 114 are the molar masses of the repeating units of the PEG and PCL blocks.

The GPC traces of the PCL-*b*-PEG block copolymers are shown in Figure 2. It is found that all the block copolymers have a narrow molecular weight distribution. This shows that the side reactions during polymerization of caprolactone such as inter- and intramolecular transesterification, which are frequently observed in other catalytic systems,^{6–19} are negligible in the present catalytic system. Otherwise, the block copolymers would have a larger polydispersity. This is probably due to presence of the bulky salicylaldimine ligand.

Figure 3 shows the WAXD patterns of PCL-*b*-PEG block copolymers and PCL and PEG homopolymers. It is found that PEG exhibits two characteristic reflections at $2\theta = 19.0^\circ$ and 23.2° , while the characteristic reflections of PCL appear at $2\theta = 21.1^\circ$ and 23.5° , respectively. We notice that in $\text{PCL}_8\text{PEG}_{44}$, which contains the shortest PCL block among these PCL-*b*-PEG block copolymers, no reflections from the PCL block are observed, indicating that the PCL block in this sample cannot crystallize and is amorphous. In $\text{PCL}_{24}\text{PEG}_{44}$, both characteristic reflections from PCL and PEG blocks can be observed, showing that both blocks are crystalline. However, the inten-

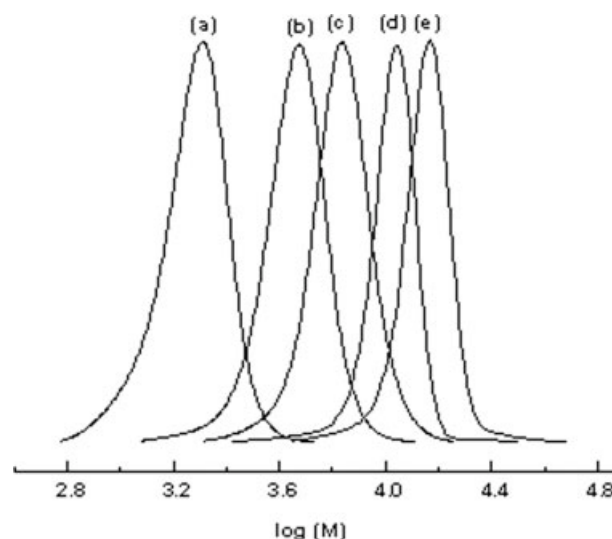


Figure 2 GPC curves of PCL-*b*-PEG block copolymers: (a) $\text{PCL}_8\text{PEG}_{44}$, (b) $\text{PCL}_{24}\text{PEG}_{44}$, (c) $\text{PCL}_{40}\text{PEG}_{44}$, (d) $\text{PCL}_{59}\text{PEG}_{44}$, (e) $\text{PCL}_{68}\text{PEG}_{44}$.

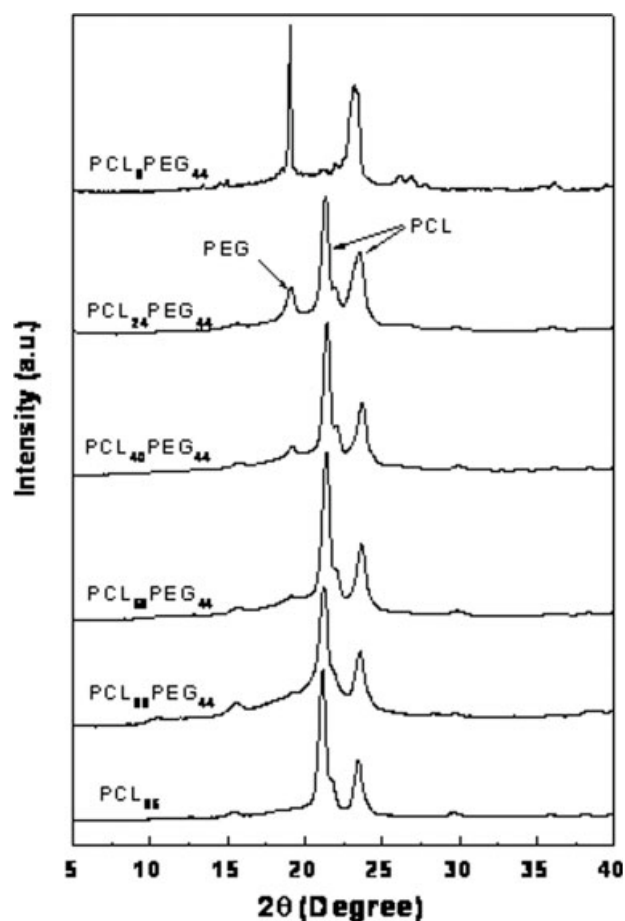


Figure 3 WAXD patterns of PCL, PEG homopolymers, and PCL-*b*-PEG block copolymers.

sities of PEG reflections are lower than those of PCL reflections. With further increase in the length of PCL block, such as in PCL₄₀PEG₄₄ and PCL₅₉PEG₄₄, the reflections from the PEG block become weaker and weaker, and in PCL₆₈PEG₄₄ they are nearly indiscernible. This shows that only when the PCL block is very short, can PEG block suppresses crystallization of the PCL block. Once the PCL block is crystalline, it exerts a great suppression effect on crystallization of the PEG block.

Figure 4 shows nonisothermal crystallization DSC traces of PCL-*b*-PEG block copolymers cooled from melt at a rate of 10°C/min, and the subsequent melting traces are illustrated in Figure 5. The DSC curves of PEG and PCL homopolymers are also included for the purpose of comparison. For PEG₄₄, it has a monomodal peak in both cooling and heating curves with a crystallization point at $T_c = 31.8^\circ\text{C}$ and melting point at $T_m = 52.5^\circ\text{C}$. The PCL₆₅ homopolymer also shows single melting and crystallization peaks at $T_m = 58.8^\circ\text{C}$ and $T_c = 35.5^\circ\text{C}$, respectively. For PCL₈PEG₄₄, one can see that the crystallization peak shifts to lower temperature and becomes broader,

indicating a slower crystallization rate, as compared to PEG₄₄. This shows that the short PCL block still has some adverse effects on crystallization of the PEG block, though WAXD reveals that the short PCL block cannot crystallize. For the other four PCL-*b*-PEG block copolymers, double crystallization peaks are observed. Since in these four samples both PCL and PEG blocks are crystallizable, as shown in Figure 3, the double exothermic peaks are attributed to crystallization of PCL and PEG blocks, respectively. Because PEG block is the minor component in these four block copolymer, the exothermic peak at lower temperature may arise from crystallization of PEG block, while the exothermic peak at higher temperature corresponds to crystallization of the PCL block. The changes of crystallization temperatures and melting temperatures of PCL and PEG blocks with composition of the block copolymers were shown in Figure 6. It is found that crystallization temperature of the PEG block decreases as the PCL block becomes longer. On the contrary, the crystallization temperature of the PCL block increases gradually with increasing its length. However, as compared to corresponding homopolymers, the change of crystallization temperature is more evident for the PEG block. For example, the crystallization peak of the PEG block in PCL₆₈PEG₄₄ shifts to as low as

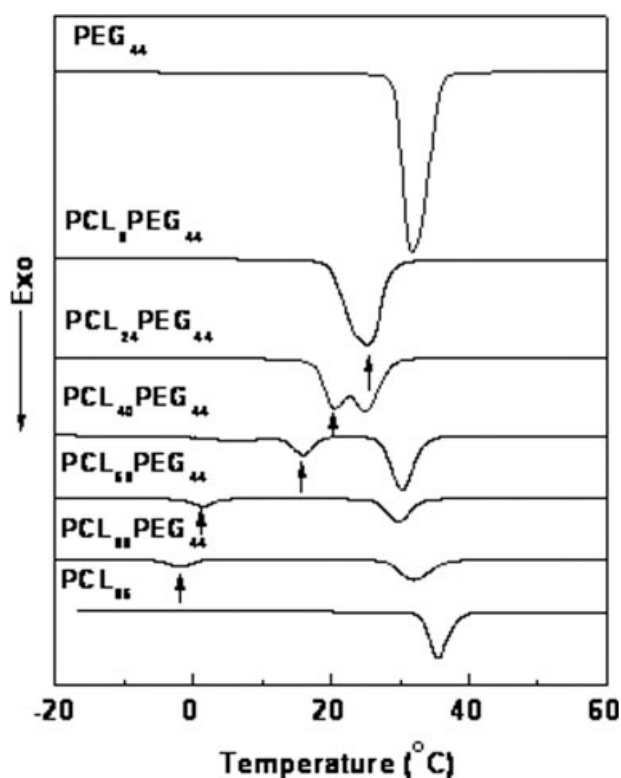


Figure 4 Nonisothermal crystallization DSC traces of PCL-*b*-PEG block copolymers. The cooling rate is 10°C/min.

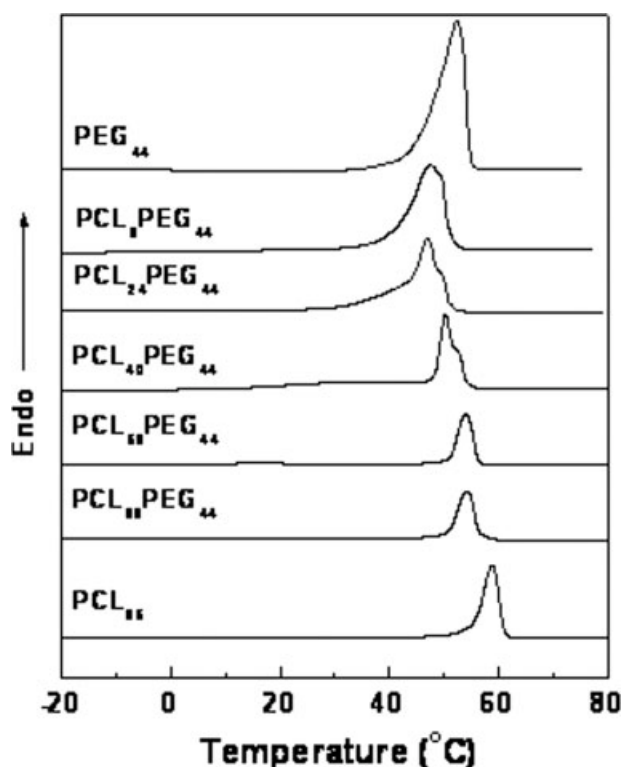


Figure 5 Melting DSC traces of PCL-*b*-PEG block copolymers heated from -60°C at a rate of $10^{\circ}\text{C}/\text{min}$.

-1.9° . This shows that the major component has a greater influence on crystallization of the minor component, though both blocks affect each other.

The melting temperatures exhibit a variation with composition similar to crystallization temperature,

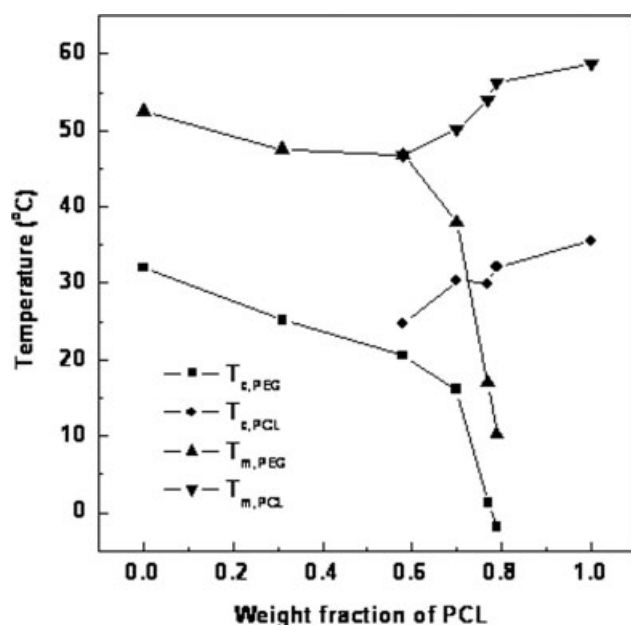


Figure 6 Changes of crystallization temperatures and melting temperatures of the PCL and PEG blocks with composition of the block copolymers.

i.e., the melting temperature of PEG block decreases and the melting temperature of the PCL block increases with increasing in the length of the PCL block. However, one can see from the DSC traces (Fig. 5) that melting peak of PEG block progressively becomes diffused and broad as the length of the PCL block increases and it cannot be determined in $\text{PCL}_{59}\text{PEG}_{44}$ and $\text{PCL}_{68}\text{PEG}_{44}$. This indicates that the perfection degree of the PEG crystals varies in a wide range. Moreover, it is noticed that the PCL block in $\text{PCL}_{24}\text{PEG}_{44}$ and $\text{PCL}_{40}\text{PEG}_{44}$ exhibits double melting peaks. The broadening of melting peaks for both PCL and PEG blocks may be attributed to the retardation in crystallization by the other block, thus crystallization takes place in a broad wide temperature range and crystals with different lamellar thicknesses are formed during nonisothermal crystallization.

Since in crystallization DSC traces of most PCL-*b*-PEG samples the crystallization peaks of the two blocks are well separated, the crystallinity (χ_c) of both blocks are calculated from the crystallization enthalpy based on following equation:

$$\chi_c = \Delta H_c / \Delta H_m^0 / w \quad (4)$$

where ΔH_c is crystallization enthalpy of a given block, ΔH_m^0 is melting enthalpy of the corresponding block with 100% crystallinity, and w is the weight fraction of this block. The values of ΔH_m^0 are 206.2 and 135 J/g for PEG and PCL, respectively.⁴² The changes of crystallinity of PCL and PEG block with composition are shown in Figure 7. It is observed

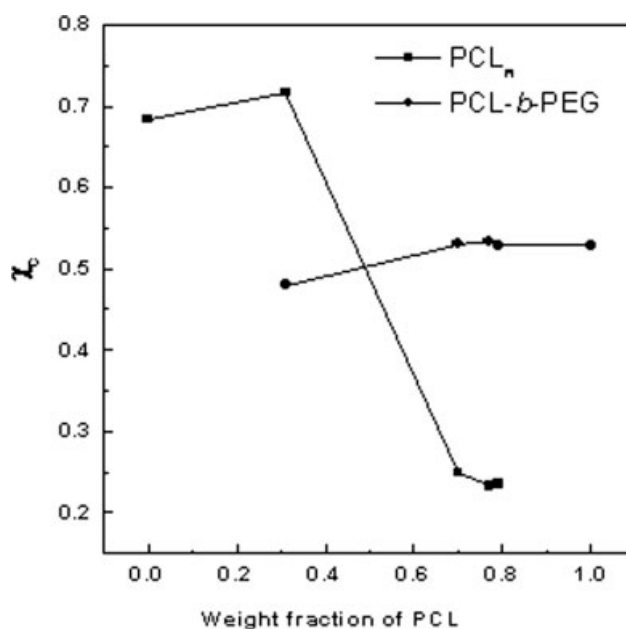


Figure 7 Effect of composition of PCL-*b*-PEG block copolymers on crystallinity of the PCL and PEG blocks.

that the crystallinity of the PEG block decreases drastically when the weight fraction of PCL block exceeds 0.31. In contrast, the crystallinity of the PCL block does not change significantly as the composition of the block copolymers varies. This also shows that in PCL-*b*-PEG block copolymers the PCL block exerts a stronger adverse effect on crystallization of the PEG block, while the PEG block has weaker effect on crystallization of the PCL block.

CONCLUSIONS

In this study, PCL-*b*-PEG block copolymers with controlled molecular weight and narrow polydispersity were synthesized by a salicylaldehyde-aluminum complex in the presence of MPEG. ¹H NMR spectra of the products verify the formation of block structure and show that ROP of caprolactone starts from insertion between the Al and PEG. The WAXD and DSC results show that the PCL block cannot crystallize when it is extremely short. As the PCL block increases, both blocks are crystallizable. However, the PCL block has a more evident adverse effect on crystallization of the PEG block. Crystallization behavior of the PCL-*b*-PEG block copolymers containing both crystallizable blocks will be reported in detail separately.

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