

Synthesis, Characterization, and Hydrolytic Degradation of Biodegradable Poly(ether ester)-Urethane Copolymers Based on ϵ -Caprolactone and Poly(ethylene glycol)

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ABSTRACT: In this article, a new kind of biodegradable poly(ϵ -caprolactone)-poly(ethylene glycol)-poly(ϵ -caprolactone)-based polyurethane (PCEC-U) copolymers were successfully synthesized by melt-polycondensation method from ϵ -caprolactone (ϵ -CL), poly(ethylene glycol) (PEG), 1,4-butanediol (BD), and isophorone diisocyanate (IPDI). The obtained copolymers were characterized by ¹H-nuclear magnetic resonance (¹H-NMR), FTIR, and gel permeation chromatography (GPC). Thermal properties of PCEC-U copolymers were studied by DSC and TGA/DTG under nitrogen atmosphere. Water absorption and hydrolytic degradation behavior of these copolymers were also

investigated. Hydrolytic degradation behavior was studied by weight loss method. ¹H-NMR and GPC were also used to characterize the hydrolytic degradation behavior of PCEC-U copolymers. The molecular weight of PCL block and PEG block in soft segment and the content of hard segment strongly affected the water absorption and hydrolytic degradation behavior of PCEC-U copolymers. © 2009 Wiley Periodicals, Inc. *J Appl Polym Sci* 113: 1111–1119, 2009

Key words: biodegradable; polyurethane; poly(ethylene glycol); poly(ϵ -caprolactone); water absorption; hydrolytic degradation

INTRODUCTION

Over the past decades, biodegradable polymers have been extensively studied because of their industrial and academic requirements. In recent years, many kinds of biodegradable polymers received special attention, including aliphatic polyester,^{1,2} poly(α -amino acid)s,³ poly(ortho ester)s,⁴ polyanhydride,⁵ polyesteramide copolymer,^{6–11} and polyurethane.^{12–14} In particular, polyurethane, which was first synthesized by Bayer in 1937,¹⁵ has gained increasing attention among these biodegradable polymers because of its potential biomedical applications such

as bioabsorbable sutures, implantation, bone fixation, tissue regeneration, and wound treatment.^{16,17}

Poly(ϵ -caprolactone) (PCL) and poly(ethylene glycol) (PEG) are materials that are biocompatible and have been used in several FDA-approved products. PCL is nontoxic and has great permeability. Since Perret and Skoulios¹⁸ first prepared a series of copolymers containing PCL and PEG, these copolymers consisting of PCL blocks and PEG blocks have been widely studied.^{19–28} Because of the combination of great advantages of PCL and PEG, these copolymers might have great potential application in biomedical fields including drug delivery, cell encapsulation, and tissue repair.^{29,30}

In this work, a new kind of biodegradable poly(ether ester)-based polyurethane was prepared by melt-polycondensation method from ϵ -caprolactone (ϵ -CL), PEG, 1,4-butanediol (BD), and isophorone diisocyanate (IPDI). Chemical structure, thermal property, water absorption behavior, and hydrolytic degradation behavior of these copolymers were investigated in detail.

EXPERIMENTAL

Materials

PEG (M_n = 400, 1000, and 1540; Fluka, St. Louis, MO), ϵ -CL (Alfa Aesar, Ward Hill, MA), IPDI

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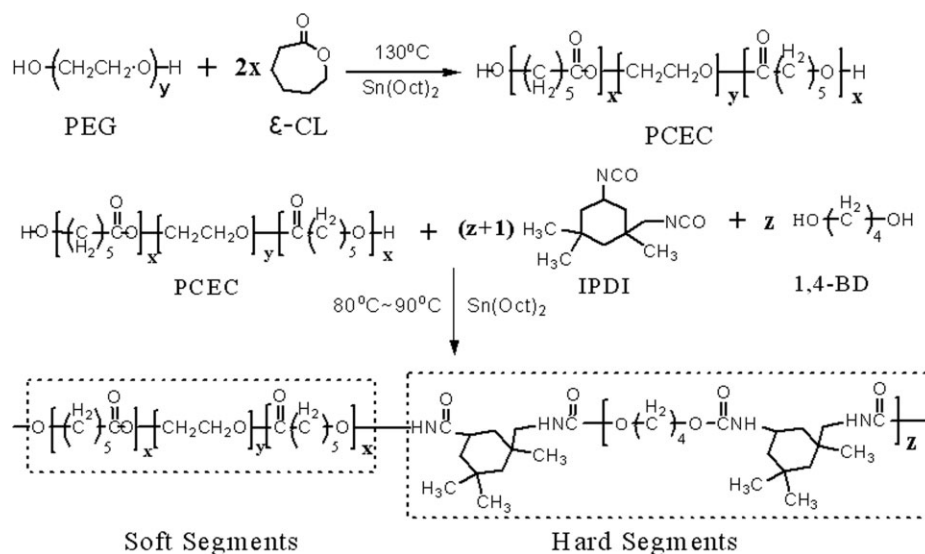
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Scheme 1 The schematic of synthesis of PCEC-U copolymers.

(Aldrich, St. Louis, MO), stannous octoate ($\text{Sn}(\text{Oct})_2$; Sigma, St. Louis, MO), BD (Aldrich, St. Louis, MO), and phosphate buffer saline (PBS, pH = 4.0, 6.8, and 7.4; Zhongshan Golden Bridge Biotechnology, Beijing, China) were used without any further purification. All the materials used were of analytic reagent (AR) grade and used as received.

Synthesis of PCEC and PCEC-U copolymers

The PCEC-based polyurethane copolymers were synthesized from ϵ -CL, PEG, BD, and IPDI by melt-polymerization method according to Scheme 1, which was similar to the protocol reported previously.^{15,16} A typical PCEC-based polyurethane was synthesized as shown in Scheme 1.

The calculated amount of ϵ -CL, PEG, and $\text{Sn}(\text{Oct})_2$ were added into the reaction vessel under dry nitrogen atmosphere, and the reaction system was kept at 130°C for 6 h to synthesize poly(ϵ -caprolactone)-poly(ethylene glycol)-poly(ϵ -caprolactone) (PCEC) copolymers. The as-obtained PCEC copolymers were dissolved in AR-grade dichloromethane and then reprecipitated from the filtrate using excess cold

petroleum ether. After that, the mixture was filtered and vacuum dried to constant weight at room temperature. Then, the PCEC copolymers and a certain amount of $\text{Sn}(\text{Oct})_2$ and IPDI were added into reaction vessel under dry nitrogen atmosphere, and the mixture was stirred at 80°C for 2 h. After the reaction temperature was elevated to 90°C, the calculated amount of BD was added and the mixture was kept for 30 min. At the end, the resultant melt was poured into a steel plate and degassed under vacuum at 130°C for another 3 h. Then, the resultant copolymer was cooled to room temperature and kept in air-tight bags before use.

In this article, the PCEC-based polyurethane was denoted as PCEC-U. All the PCEC and PCEC-U samples synthesized in this work are listed in Tables I and II, respectively.

Intrinsic viscosity measurement

Intrinsic viscosity ($[\eta]$) was measured at 30°C \pm 0.1°C using an Ubbelohde viscometer. All the copolymers were dissolved in *m*-cresol to prepare solutions at a concentration of ca. 0.5 g/dL. $[\eta]$ was

TABLE I
The PCEC Copolymers Prepared in This Work

PCEC copolymers ($\text{PC}_x\text{E}_y\text{C}_z$)	PCL/PEG (wt %)		Total M_n		Solubility ^a
	Theoretical ^b	Calculated ^c	Theoretical ^b	Calculated ^c	
$\text{PC}_{500}\text{E}_{400}\text{C}_{500}$	2.5 : 1	2.29 : 1	1400	1574	Insoluble
$\text{PC}_{500}\text{E}_{1000}\text{C}_{500}$	1 : 1	0.95 : 1	2000	2166	Soluble
$\text{PC}_{500}\text{E}_{1540}\text{C}_{500}$	0.65 : 1	0.55 : 1	2540	2826	Soluble
$\text{PC}_{770}\text{E}_{1000}\text{C}_{770}$	1.54 : 1	1.45 : 1	2540	2631	Soluble
$\text{PC}_{1000}\text{E}_{1000}\text{C}_{1000}$	2 : 1	1.88 : 1	3000	3044	Soluble

^a Solubility in water at 30°C.

^b Theoretical value calculated according to the feed ratio.

^c Calculated from ¹H-NMR of PCEC copolymer.

TABLE II
The PCEC-U Copolymers Prepared in This Work

Samples	Soft segment	PCEC/IPDI/BD (mol/mol/mol) Feed (1/n ₁ /n ₂)	Hard segment content (%)		Molecular weight (×10 ⁴) ^a			[η] (dL/g)
			Feed ^b	Exp ^c	M _w	M _n	M _w /M _n	
PCEC-U1	PC ₅₀₀ E ₁₀₀₀ C ₅₀₀	1/6/5	47.1	48.0	9.75	6.19	1.58	0.30
PCEC-U2	PC ₇₇₀ E ₁₀₀₀ C ₇₇₀	1/8/7	48.7	49.4	8.91	5.62	1.59	0.38
PCEC-U3	PC ₁₀₀₀ E ₁₀₀₀ C ₁₀₀₀	1/9/8	47.6	47.5	8.93	5.59	1.60	0.39
PCEC-U4	PC ₅₀₀ E ₄₀₀ C ₅₀₀	1/5/4	51.2	52.2	11.60	7.79	1.49	0.53
PCEC-U5	PC ₅₀₀ E ₁₀₀₀ C ₅₀₀	1/7/6	51.1	52.2	9.56	5.83	1.64	0.43
PCEC-U6	PC ₅₀₀ E ₁₅₄₀ C ₅₀₀	1/9/8	51.7	53.6	10.32	6.53	1.58	0.49
PCEC-U7	PC ₅₀₀ E ₁₀₀₀ C ₅₀₀	1/10/9	60.3	62.3	12.33	8.17	1.51	0.53

^a Determined from GPC.

^b Theoretical value calculated from the feed ratio.

^c Calculated from ¹H-NMR of PCEC-U according to eqs. (4)–(10).

calculated using eq. (1) according to Solomon-Ciuta method.

$$[\eta] = \frac{\sqrt{2\left(\frac{t}{t_0} - 1 - \ln \frac{t}{t_0}\right)}}{C} \quad (1)$$

where C is the concentration of solution, t is the flow time of solution, and t_0 is the flow time of pure solvent.

Fourier transform infrared spectroscopy

The copolymer samples were dissolved in chloroform and cast on KBr plates. Fourier transform infrared (FTIR) spectra were recorded on a NICOLET-200SXV Infrared Spectrophotometer (Nicolet, Boston, MA).

¹H-Nuclear magnetic resonance analysis

¹H-Nuclear magnetic resonance (¹H-NMR) spectra (in CDCl₃) were recorded on a Varian 400 spectrometer (Varian, Palo Alto, CA) at 400 MHz to characterize the chemical composition and macromolecular weight of the copolymers.

Gel permeation chromatography

Gel permeation chromatography (GPC; Agilent 110 HPLC, Santa Clara, CA) was used to determine the macromolecular weight and macromolecular weight distribution of PCEC-U copolymers. The samples were dissolved in freshly distilled tetrahydrofuran (THF) at a concentration of 2 mg/mL. THF was eluted at a rate of 1.0 mL/min through two Waters Styragel HT columns and a linear column. The external and column temperatures were kept at 35°C. The molecular weights of samples were calculated from polystyrene with narrow molecular weight distribution.

Differential scanning calorimetry

Thermal properties of PCEC-U copolymers were characterized on differential scanning calorimeter (DSC) (NETSCZ 204, NETSCZ, Selb, Germany) in a temperature range of –50 to 100°C under nitrogen atmosphere with a heating and cooling rate of 10°C/min.

Thermogravimetric analysis

Thermogravimetric (TGA) measurements were characterized on TGA analyzer (TA 2910, DuPont, New Castle, DE) coupled with Perkin-Elmer computerized data station under nitrogen atmosphere at a heating rate of 10°C/min in the range of room temperature to 700°C.

Water absorption behavior of PCEC-U copolymers

The copolymer chips were immersed in distilled water at 37°C for predetermined period, and then they were taken out and the surplus surface water was removed by filter paper. The water absorption value was calculated according to eq. (2):

$$\text{Water absorption (\%)} = \frac{W_{ht} - W_d}{W_d} \times 100 \quad (2)$$

where W_d is the initial weight of dry sample, and W_{ht} is the weight of humid sample at time t .

Hydrolytic degradation behavior

In vitro hydrolytic degradation tests were conducted using weight loss method. ¹H-NMR and GPC were used to determine the content of each composition and overall macromolecular weight and distribution of PCEC-U copolymers before and after hydrolytic degradation. The tests were carried out as follows: the copolymer chips (100–200 mg) were placed in

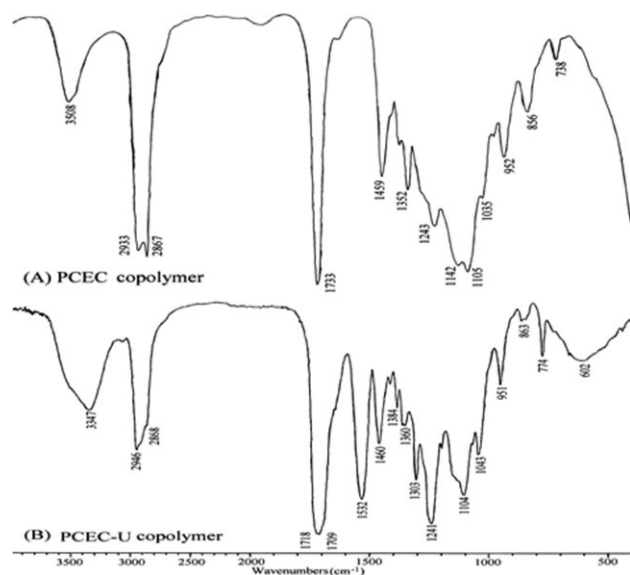


Figure 1 The typical FTIR spectrum of PCEC and PCEC-U copolymers.

10 mL of PBS saline with pH = 4.0, 6.8, and 7.4 at 37°C. The degradation media were refreshed every 2 weeks. The samples were removed from the bottles at predetermined time, rinsed thoroughly with distilled water and dried in vacuum at 35°C for 12 h. The degree of degradation was calculated by GPC and weight loss as follows:

$$\text{Weight loss (\%)} = \frac{W_0 - W_t}{W_0} \times 100 \quad (3)$$

where W_0 is the dry weight before degradation, and W_t is the dry weight at time t .

RESULTS AND DISCUSSION

Synthesis and characterization of PCEC and PCEC-U copolymers

A series of PCEC copolymers were prepared by ring-opening copolymerization of ϵ -CL initiated by PEG using $\text{Sn}(\text{Oct})_2$ as catalyst, and PCEC-U multiblock copolymers were synthesized by melt-polymerization method. FTIR, $^1\text{H-NMR}$, and GPC were used to characterize PCEC and PCEC-U copolymers, and intrinsic viscosity and solubility of PCEC-U copolymers were also investigated. The PCEC and PCEC-U copolymers prepared in this work are summarized in Tables I and II, respectively.

Figure 1 shows the typical FTIR spectra of PCEC (A) and PCEC-U copolymer (B). A strong C=O stretching band appeared at 1733 cm^{-1} [Fig. 1(A)], which was attributed to the ester bond. The absorption bands at 1105 cm^{-1} [Fig. 1(A)] and 1243 cm^{-1} [Fig. 1(A)] were attributed to the characteristic C—O—C stretching vibrations of the repeated

—OCH₂CH₂ units of PEG and the —COO— bands stretching vibrations, respectively. The absorption band at 3508 cm^{-1} [Fig. 1(A)] was assigned to terminal hydroxyl groups (—OH) in the copolymer. There is no absorption in 2250–2270 and 3508 cm^{-1} [Fig. 1(B)], which indicates that the —NCO groups of hexamethylene diisocyanate and terminal —OH groups in PCEC copolymer disappeared completely because of the coupling reaction of —NCO with —OH group. The absorption bands at 1532 cm^{-1} [Fig. 1(B)] were attributed to the N—H bending vibrations, which confirmed the formation of PCEC-U copolymers.

To further confirm the formation of PCEC-U copolymers, $^1\text{H-NMR}$ spectra of PCEC and PCEC-U copolymer were recorded and shown in Figure 2. The characteristic absorption peaks were also designated. In Figure 2(A), peaks at 1.40, 1.65, 2.32, and 4.06 ppm were assigned to methylene protons of —(CH₂)₃—, —OCCH₂—, and —CH₂OOC— in PCL blocks, respectively. The sharp peak at 3.65 ppm was attributed to methylene protons of —CH₂CH₂O— in PEG block. The weak peaks at 4.23 and 3.82 ppm were attributed to methylene protons of —O—CH₂—CH₂— in PEG end block that linked with PCL blocks, respectively.

The number-average macromolecular weight (M_n) of PCEC block copolymers and the PEG/PCL block ratios were calculated from $^1\text{H-NMR}$ spectra according to eqs. (4)–(6)²:

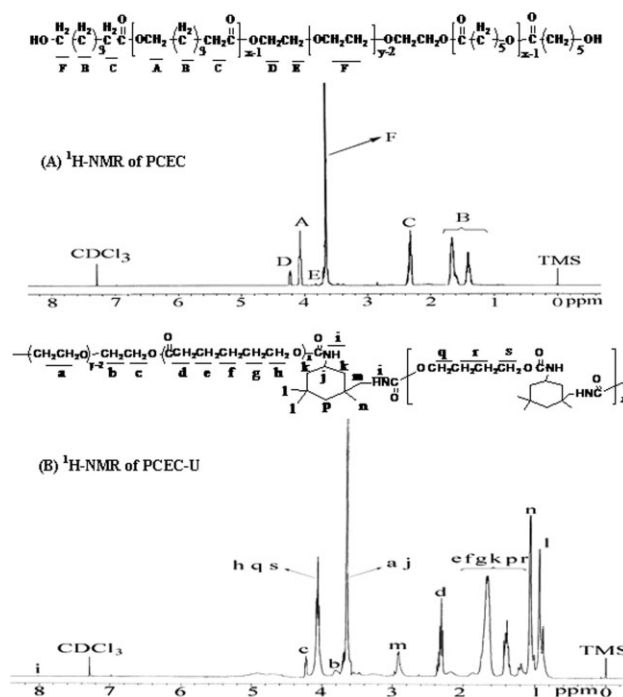


Figure 2 The $^1\text{H-NMR}$ spectra of PCEC and PCEC-U copolymers.

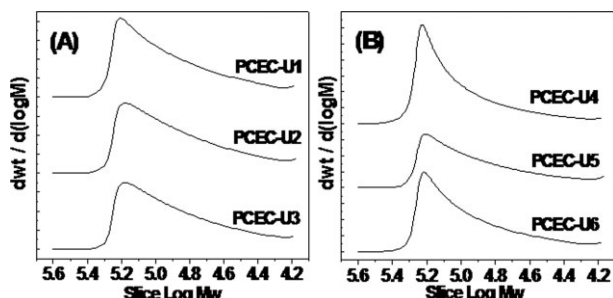


Figure 3 The GPC spectra of PCEC-U copolymers.

$$\frac{2(2(x-1))}{I_A} = \frac{4}{I_D} \quad (4)$$

$$\frac{4(y-2) + 4}{I_F} = \frac{4}{I_D} \quad (5)$$

$$M_n(\text{PCEC}) = M_n(\text{PEG}) + M_n(\text{PCL}) = 44y + 228x \quad (6)$$

where I_A , I_D , and I_F are integral intensities of peaks at about 4.06, 4.23, and 3.65 ppm, respectively, in $^1\text{H-NMR}$ spectrum of PCEC [Fig. 2(A)], and $2x$ and y were the respective block number of PCL and PEG in macromolecular structure of PCEC copolymers as shown in Figure 2(A).

In Figure 2(B), the hard segment content of PCEC-U copolymers was calculated from $^1\text{H-NMR}$ spectra of PCEC-U copolymers according to eqs. (7)–(10)²:

$$\frac{4}{I_c} = \frac{4x + 4z}{I_{\text{hqs}}} \quad (7)$$

$$\frac{4}{I_c} = \frac{4(y-2) + z + 1}{I_{aj}} \quad (8)$$

$$\frac{4}{I_c} = \frac{6(z+1)}{I_i} \quad (9)$$

Hard segment content

$$= \frac{(312z + 224)}{(44y + 228x) + (312z + 224)} \times 100\% \quad (10)$$

where I_c , I_{hqs} , I_{aj} , and I_i were integral intensities of peaks at about 4.23, 4.06, 3.65, and 0.93 ppm, respectively, in $^1\text{H-NMR}$ spectrum of PCEC-U [Fig. 2(B)]. And $2x$, y , and z were the block number of PCL, PEG, and hard segment, respectively, in macromolecular structure of PCEC-U copolymers in Figure 2(B).

Macromolecular weight and distribution of PCEC-U copolymers were also characterized by GPC. The

GPC curves of these copolymers are shown in Figure 3. According to Figure 3, only a single peak existed, which indicated the monodistribution of macromolecular weight and the absence of any homopolymer, and also implied that no transesterification or backbiting reactions occurred during copolymerization. The total molecular weight and polydispersity (PDI, M_w/M_n) of prepared PCEC-U copolymers are summarized in Table II.

The macromolecular weight (M_n) of PCEC and PCEC-U copolymers estimated from $^1\text{H-NMR}$ spectrum are listed in Tables I and II, respectively, which were consistent with theoretical value calculated from feed ratio. So, for simplicity, the feed ratio was used in the following text instead of experimental composition ratio calculated from $^1\text{H-NMR}$ spectra. FTIR, $^1\text{H-NMR}$, and GPC results indicated that the PCEC and PCEC-U copolymers were prepared successfully by controlling the feed composition.

Thermal property of PCEC-U copolymers

A DSC was performed to investigate the thermal properties of PCEC copolymers, and the results are shown in Figure 4. The cooling process displayed one exothermic transition at -20 to 10°C . During the heating process, one melting peak at 20 – 50°C was observed. With the increase in PEG content from PCEC-U3 to PCEC-U1, the melting peaks became wider, and the melting temperature decreased, which might be due to the increase in flexibility of macromolecule main chain when PEG are incorporated. This phenomenon is similar to thermal property of poly(ethylene terephthalate)/PEG copolymers³¹ and the polyetheresteramide copolymers.^{19,21}

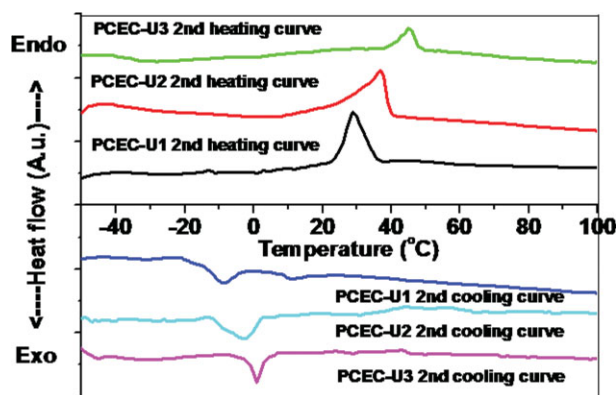


Figure 4 DSC curves of PCEC-U copolymers. Heating and cooling rates were $10^\circ\text{C}/\text{min}$. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

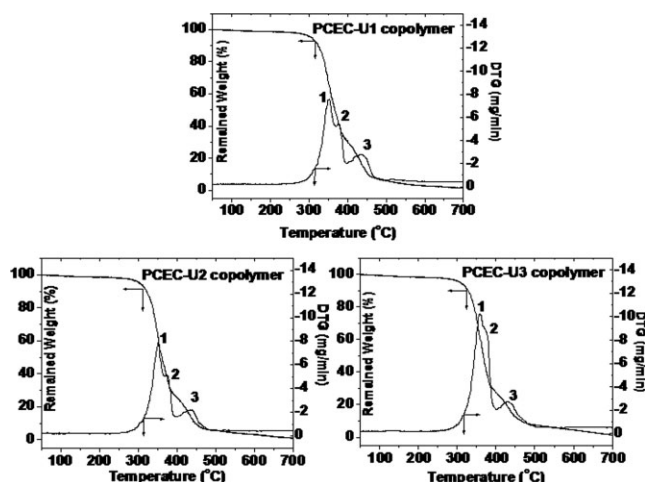


Figure 5 The TGA/DTG curves of PCEC-U copolymers.

Thermal degradation behavior of PCEC-U copolymers

Thermal degradation behavior of PCEC-U copolymers was studied by TGA/DTA method under nitrogen atmosphere, which are shown in Figure 5, and the data are summarized in Table III. As shown in Figure 5, all these copolymers showed a stage-decomposition pattern, which suggested that the structure of PCEC-U copolymers might be partially blocky. The degradation of the soft segment (PCL/PEG block) proceeds at a temperature lower than that of the hard segment (IPDI/BD block).^{10,18,20} The peak at about 350°C could be mainly due to the degradation of soft segments, whereas the other two degradation peaks at about 375 and 430°C should be

TABLE III
TGA/DTG Data of PCEC-U Copolymers at a Heating Rate of 10°C/min in Nitrogen

	Samples		
	PCEC-U1	PCEC-U2	PCEC-U3
$T_{d, 5\%}^a$ (°C)	305.7	303.4	307.7
$T_{d, onset}^b$ (°C)	324.1	326.0	327.5
$T_{d, 1\ max}^c$ (°C)	350.9	351.9	358.2
Weight loss at Stage 1 (%)	48.9	53.5	47.5
$T_{d, 50\%}^d$ (°C)	366.4	362.2	367.4
$T_{d, 2\ max}^c$ (°C)	375.9	374.7	374.2
Weight loss at Stage 2 (%)	18.0	18.9	22.7
$T_{d, 95\%}^e$ (°C)	518.3	526.9	575.1
$T_{d, 3\ max}^c$ (°C)	437.2	438.7	429.1
Weight loss at Stage 3 (%)	25.4	20.1	20.4

^a Temperature at weight loss of 5%.

^b Temperature when the decomposition started.

^c Temperature of the largest decomposition rate during the stage.

^d Temperature at weight loss of 50%.

^e Temperature at weight loss of 95%.

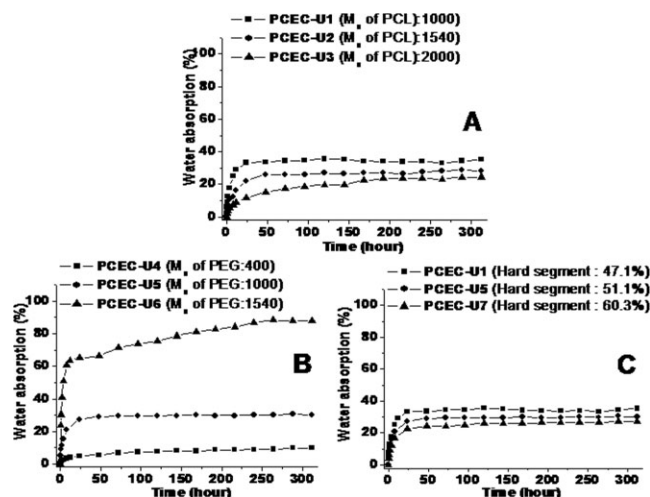


Figure 6 Water absorption behavior of PCEC-U copolymers.

essentially due to hard segments. According to Table III, when the content of hard segment was kept constant, with decrease in molecular weight of PEG blocks, $T_{d, onset}$ and $T_{d, 95\%}$ increased accordingly, which means the elevation in thermal stability of PCEC-U copolymers.

Water absorption behavior of PCEC-U copolymers

PCEC-U copolymers, which were composed of soft and hard segments, were semicrystalline copolymers. When these materials were incubated in aqueous medium, water could permeate into the amorphous region because of the presence of hydrophilic PEG segments in the amorphous domains. The water can penetrate easily into the amorphous phase, but hardly into the crystalline phase. There are three parameters influencing water absorption behavior of PCEC-U copolymers: molecular weight of PCL in soft segment, molecular weight of PEG in soft segment, and the content of hard segment.

Effect of PCL molecular weight in soft segment

In Figure 6(A), all copolymers reached the equilibrium value of water absorption after immersed in water for 48 h. When the weight content of hard segment and PEG molecular weight in PCEC soft segment were kept constant, with increase in molecular weight of hydrophobic PCL from 1000 for PCEC-U1 to 2000 for PCEC-U3, equilibrium water absorption of the three copolymers decreased accordingly. Because the weight content of soft segment and PEG molecular weight in PCEC soft segment were kept constant, increase of PCL molecular weight led to the decrease of PEG content in soft segment. At a constant PEG molecular weight, there is a decrease in amorphous phase with decrease in PEG content.

TABLE IV
The Molecular Weight of PCEC-U Copolymers Before and After Degradation in PBS

Samples	Molecular weight before degradation ($\times 10^4$) ^a			Molecular weight after degradation ($T = 68$ days) ($\times 10^4$) ^a								
				pH = 4.0			pH = 6.8			pH = 7.4		
	M_w	M_n	M_w/M_n	M_w	M_n	M_w/M_n	M_w	M_n	M_w/M_n	M_w	M_n	M_w/M_n
PCEC-U1	9.75	6.19	1.58	— ^b	— ^b	— ^b	8.30	5.47	1.52	8.53	5.67	1.50
PCEC-U2	8.91	5.62	1.59	— ^b	— ^b	— ^b	8.67	5.67	1.53	8.60	5.58	1.54
PCEC-U3	8.93	5.59	1.60	5.88	3.64	1.62	8.84	5.72	1.55	9.19	6.00	1.53

^a Determined from GPC.

^b Not determined.

For this case, the water absorption will decrease with the increase of PCL molecular weight.³¹

Effect of PEG molecular weight in soft segment

According to Table II and Figure 6(B), when hard segment weight content and PCL molecular weight in soft segment were kept constant, with increase in molecular weight of PEG from 400 (PCEC-U4) to 1540 (PCEC-U6), water absorption of the copolymers increased significantly. This phenomenon might be due to increase in amorphous region of PCEC-U copolymers and the enhancement of microphase separation between PCL segment and PEG segment,³¹ which was caused by the increase in the hydrophilic PEG molecular weight. Therefore, the water absorption will increase with the increase of PEG molecular weight.

Effect of hard segment content

For samples PCEC-U1, PCEC-U5, and PCEC-U7, the chemical composition of soft segment was the same ($PC_{500}E_{1000}C_{500}$), and the weight content of hard segment was 48.0%, 52.2%, and 62.3%, respectively. As shown in Figure 6(C), we could find that with the increase in hard segment content, water absorption of these samples decreased accordingly, which is caused by the increase in hydrophobicity and decrease in amorphous region of PCEC-U copolymers. Water penetrates hardly into hard segment region when compared with soft segment region,

and thus increase in hydrophobicity and decrease in amorphous region resulted in the decrease of water absorption.

Hydrolytic degradation behavior of PCEC-U copolymers

The biodegradable PCEC-U copolymers with thickness of about 1 mm were incubated in PBS solution at 37°C (pH = 4.0, 6.8, and 7.4, respectively). The degradation results are shown in Tables IV and V and Figures 7 and 8. According to Malin et al.,^{15,32} the hydrolytic degradation behavior of semicrystalline polymers was determined by the chemical composition, degree of crystallinity, hydrophilicity, and molecular weight.

Effect of PCL molecular weight in soft segment

In Figure 7(A), with increase in PCL molecular weight from 500 (PCEC-U1) to 1000 (PCEC-U3), the degradation rate decreased, which might be due to the increase in hydrophobicity of PCEC-U copolymer. With increase in PCL weight content, the hydrophobicity of PCEC-U copolymers increased accordingly, which meant that water was hard to permeate into the copolymers, and thus the hydrolytic degradation rate was decreased. In PBS (pH = 4.0 and 7.4), the degradation rate of PCEC-U3 was higher than that of PCEC-U2, which might be because the calculated content of hard segment in

TABLE V
The Hard Segments Content of PCEC-U Copolymers Before and After Degradation in PBS

Sample	PCEC/IPDI/BD (mol/mol/mol)	Feed ($1/n_1/n_2$)	Hard segment content (%)				
			Before degradation		After degradation ($T = 68$ days) ^b		
			Theoretical ^a	Calculated ^b	pH = 4.0	pH = 6.8	pH = 7.4
PCEC-U1		1/6/5	47.1	48.0	51.4	49.3	47.5
PCEC-U2		1/8/7	48.7	49.4	51.9	51.2	44.7
PCEC-U3		1/9/8	47.6	47.5	49.7	47.4	45.3

^a Theoretical value calculated from the feed ratio.

^b Calculated from ¹H-NMR of PCEC-U according to eqs. (4)–(10).

PCEC-U2 (49.4%) was higher than that of PCEC-U3 (47.5%).

Effect of PEG molecular weight in soft segment

According to Table II and Figure 7(B), when the molecular weight of PCL in soft segment and weight content of hard segment were kept constant, with the increase in molecular weight of PEG from 400 (PCEC-U4) to 1540 (PCEC-U6), degradation rate of the three copolymers increased accordingly. The increase in PEG molecular weight favors the microphase separation between the PCL and PEG segment, which leads to an increase in water absorption, leads to increase in hydrolytic degradation rate.³¹ Meanwhile, due to the constant content of soft segment and PCL molecular weight in soft segment, increase in PEG molecular means increase in PEG content and amorphous region in soft segment, which could lead water penetrate into the copolymers easily and hence accelerate the hydrolytic degradation. In PBS solution (pH 4.0), weight loss of PCEC-U6 (90%) was much higher than that of PCEC-U4 (1.0%) and PCEC-U5 (3.1%), which was consistent with the highest water absorption value of PCEC-U6 copolymers. Higher water absorption led to higher hydrolytic degradation rate.

Effect of hard segment content on hydrolytic degradation

As shown in Figure 7(C), while the content of soft segment (the content of PEG and PCL) was kept constant, with increase in hard segment content, the degradation rate of these copolymers decreased accordingly, which might be due to the increase of hydrophobicity of PCEC-U copolymer. Because of

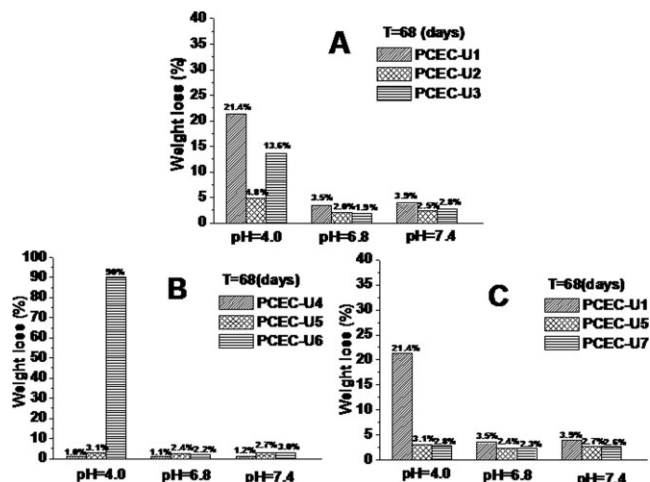


Figure 7 Weight loss of PCEC-U copolymers after degradation in PBS (pH = 4.0, 6.8, 7.4, respectively) at 37°C.

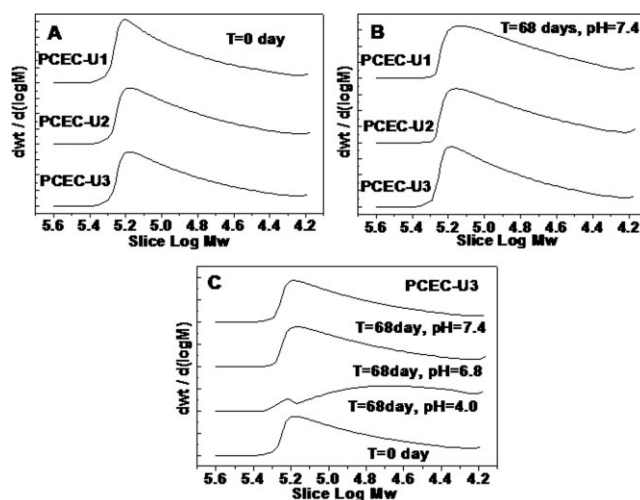


Figure 8 The GPC spectra of PCEC-U copolymers before and after degradation.

the increased hydrophobicity of PCEC-U copolymer, water was harder to permeate in and the hydrolytic degradation rate decreased.

Effect of pH value of degradation medium on hydrolytic degradation

From Figure 7(A–C), we could find that pH value of degradation medium have great effect on degradation rate of PCEC-U copolymers. Degradation rate in acidic medium was much higher than that in neutral medium, which was consistent with our pervious work.^{8,15} In our experiment, an acid catalysis process was found.

Molecular weight before and after degradation

Figure 8(A,B) shows the molecular weight and molecular weight distribution of PCEC-U1, PCEC-U2, and PCEC-U3 copolymers before and after degradation, and the detailed data are summarized in Table IV. From Figure 8 and Table IV, we could find that after degradation, molecular weight and molecular weight distribution of these copolymers were both decreased. After degradation, molecular weight of PCEC-U1 copolymer decreased from 9.75×10^4 to 8.53×10^4 in PBS solution with pH value of 7.4.

Figure 8(C) demonstrates the molecular weight changes of PCEC-U3 copolymer in PBS solution with different pH value after degradation for 68 days. With the decrease in pH value of the degradation medium, the molecular weight of PCEC-U3 copolymer decreased and polymer distribution index (PDI, M_w/M_n) increased. Degradation rate of PCEC-U3 copolymer in acidic medium was higher when compared with the neutral medium.

Hard segment content before and after degradation

Hard segment content before and after degradation is shown in Table V. For these copolymers, with decrease in pH value of degradation medium, hard segment content increased accordingly. Because of the difference in hydrophilicity and crystallinity of soft and hard segment, hydrolytic degradation of these PCEC-U copolymers might occur in the soft segment region preferentially, which caused the increase of hard segment content. Degradation rate of soft segment in these copolymers was higher in acidic medium, and therefore the hard segment content were higher after hydrolytic degradation accordingly.

CONCLUSIONS

In this work, biodegradable poly(ϵ -caprolactone-ethylene glycol- ϵ -caprolactone)-based polyurethane (PCEC-U) copolymers were successfully synthesized by melt-polycondensation method, which were characterized by $^1\text{H-NMR}$, FTIR, GPC, DSC, TGA/DTG, and Ubbelohde viscometer. With increase in molecular weight of PCL blocks, thermal stability of PCEC-U copolymers was increased accordingly. Water absorption and hydrolytic degradation behavior of these copolymers were affected by many factors, including PCL content, PEG content, and hard segment content. With the increase in PCL content, decrease in PEG content, or increase in hard segment content, the water absorption rate and degradation rate decreased accordingly.

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