

Synthesis and Characterization of Novel Biodegradable Aromatic–Aliphatic Poly(ester amide)s Containing Ethylene Oxide Moieties

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ABSTRACT: A series of novel biodegradable aromatic–aliphatic poly(ester amide)s containing approximately equal amounts of amide and ester groups were successfully prepared through the interfacial polycondensation of 1,6-hexanediamine and aromatic diacylchlorides containing ethylene oxide moieties. The structure of the poly(ester amide)s was verified by Fourier transform infrared and NMR spectra. Differential scanning calorimetry and thermogravimetric analysis measurements demonstrated that the obtained polymers

were amorphous and stable up to 300°C under nitrogen. The synthesized poly(ester amide)s showed good hydrophilicity and took up water in amounts up to 50% of their weights when exposed to a humid atmosphere. Under physiological conditions, the poly(ester amide)s were hydrolysable in a rapid and steady way. © 2008 Wiley Periodicals, Inc. *J Appl Polym Sci* 109: 1310–1318, 2008

Key words: biodegradable; synthesis; thermal properties

INTRODUCTION

There has been growing interest in poly(ester amide)s because these polymers may offer an interesting combination of properties: a high degradability caused by the ester linkages and good mechanical properties caused by the establishment of hydrogen bonds between amide groups. A number of poly(ester amide)s varying either in chemical structure and/or microstructure have been described by various authors.^{1–13} Moreover, the product of BAK 1095, which corresponds to a random poly(ester amide) derived from 1,4-butaediol, adipic acid, and caprolactame by Bayer, has recently been commercialized.^{14,15} Wholly aromatic poly(ester amide)s are well known for their superior resistance to heat, outstanding mechanical resistance, poor biodegradability, and poor solubility in common solvents. This extreme behavior is a severe limiting factor for the processing of these materials. Thus, the improve-

ment of their solubility, biodegradability, and melting behavior has attracted considerable attention.

It is well known that processability may be improved by the addition of flexible chains to the aromatic polymer backbone, which enhances molecular mobility, provides better solubility, and reduces the glass-transition temperature (T_g).^{16,17} For this particular purpose, the use of poly(ethylene glycol) (PEG) in the design of polymers with enhanced processability and biodegradability constitutes an interesting strategy.^{18–24} Although poly(ether amide)s containing short sequences PEG alternating with short sequences of aromatic polyamide have attracted much attention,^{25–29} poly(ester amide)s containing segmented oxyethylene or polyoxyethylene have not been studied until now. Another alternative strategy is the synthesis of segmented block copolymers, which contain rigid aromatic and flexible aliphatic sequences; this offers an average of the properties of the corresponding homopolymers. So, compared to aromatic poly(ester amide)s, it is expected that aromatic–aliphatic poly(ester amide)s would produce a chain-separation effect and lower the chain packing, which would improve solubility and lower T_g .

On this basis, the aim of this study was to combine aliphatic units and ethylene oxide chains as flexible spacers into aromatic poly(ester amide) backbones to obtain hydrophilic and processable polymers. In this article, we report the synthesis of a

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family of aromatic-aliphatic poly(ester amide)s containing ethylene oxide units. The effects of the number of oxygen linkages on the thermal properties, solubility, and biodegradability of the novel poly(ester amide)s are explored. We expected that the presence of ethylene oxide units along poly(ester amide)s backbone would increase the hydrophilicity of the polymer and might also enhance the hydrolytic degradability. Moreover, we could tailor the properties of the polymers by controlling the length of the ethylene oxide units.

EXPERIMENTAL

Materials

1,6-Hexanediamine was purchased from Guangzhou Chemical Co. (Guangzhou, China) and was purified by vacuum sublimation. Phthalic anhydride (Guangzhou Chemical Co.) was recrystallized from a chloroform solution at a concentration of 5 mg/mL. PEG150 and PEG200 were purchased from Aldrich (Madison, WI). PEG400, PEG600, and PEG400000 were supplied by Sigma (St. Louis, MO). All diols were dried at 80°C for 24 h *in vacuo* before use. Chloroform (Guangzhou Chemical Co.) was refluxed for 24 h at 65°C from calcium hydride and was distilled before use. Pyridine (Guangzhou Chemical Co.) was refluxed for 24 h at 120°C from KOH, and was distilled before use. Other reagents, such as carbon tetrachloride, acetone, diethyl ether, dimethylformamide (DMF), dimethyl sulfoxide (DMSO), formic acid, chloroform, tetrahydrofuran (THF), ethyl acetate, NaOH, and anhydrous Na₂SO₄, were commercially available from Guangzhou Chemical Co. and were used as received. Thionyl chloride was purchased from Guangzhou Chemical Co. and was distilled *in vacuo* before use.

Measurements

A Varian Unity 300-MHz spectrometer (Palo Alto, CA) was used for ¹H-NMR and ¹³C-NMR investigations at room temperature with tetramethylsilane (TMS) as an internal standard. Fourier transform infrared (FTIR) spectra in the 4000–500-cm⁻¹ range were recorded as KBr pellets on a PerkinElmer 1600 spectrometer. Differential scanning calorimetry (DSC) thermograms were recorded in the range -80 to 300°C on a PerkinElmer Pyris 1 differential scanning calorimeter at a heating rate of 10°C/min under a nitrogen atmosphere. Thermogravimetric analysis (TGA) was carried out with a PerkinElmer TGA-6 under a nitrogen atmosphere at a heating rate of 10°C/min. TGA data of PEG [weight-average molecular weight (M_w) = 400,000 g/mol; Sigma] were recorded on a PerkinElmer TGA-6 analyzer from

8 mg of a sample under a nitrogen atmosphere at 10°C/min scanning conditions.

Dynamic mechanical analysis (DMA) was performed on a PerkinElmer DMA-7 thermal analyzer system. A sample with rectangular films 1 mm thick (length = 10 mm, width = 2 mm) was used. Tan δ was studied when the sample was subjected to temperature scan mode with an extension measuring system (with a stainless steel extension kit) at a programmed heating rate of 5°C/min from 30 to 300°C at a frequency of 1 Hz.

Wide-angle X-ray scattering patterns were obtained from films on a Philips X-ray PW 1130 diffractometer with Cu K α radiation. Static contact angles of 1 μ L of distilled water on the polymer surface were used to evaluate the polymer hydrophobicity with a Krüss DSA-10 contact-angle meter (Germany). The polymer (1.5 g) was dissolved in 30 mL of chloroform, and the solution (50 mg/mL) was cast on dimethyldichlorosilane glass and dried at 40°C *in vacuo*. Contact angles were measured in six different regions of each polymer surface, and an average value was taken.

The intrinsic viscosity of the polymer was determined with a Cannon-Ubbelohde microviscometer (Guangzhou, China) at a temperature of 25°C; dichloroacetic acid was used as a solvent. Hygroscopicities were measured according to the literature³⁰ in a 100% relative humidity atmosphere at room temperature with films samples. We obtained each intrinsic viscosity and hygroscopicity value by averaging the results of three measurements.

The solubility of the poly(ester amide)s in common organic solvents was estimated according to the method of Braun.³¹

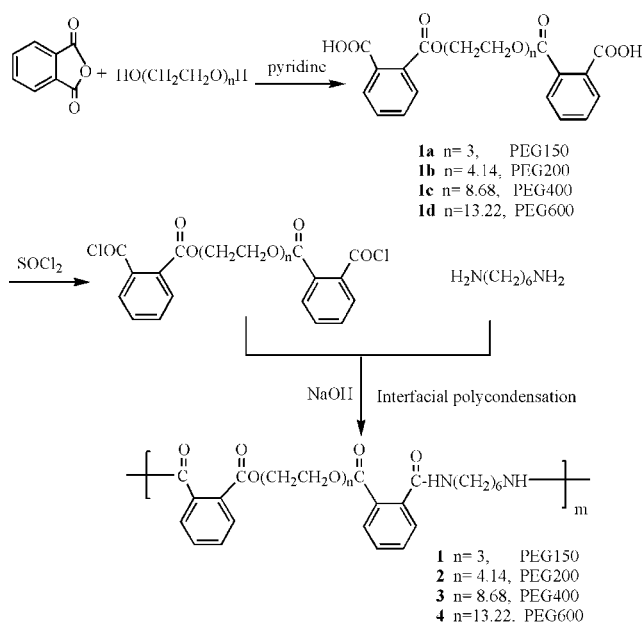
Synthesis

Preparation of dicarboxylic acid monomers containing PEG segments (**1a–1d**)

PEG150 (0.025 mol) was dissolved in dry chloroform (100 mL). Phthalic anhydride (0.1 mol) and dry pyridine (0.05 mol) were added, and the reaction mixture was kept at 60°C for 48 h. The solution was cooled and filtered, and the solvent was fully evaporated *in vacuo*. The crude product was added to acidic water, extracted with chloroform, and dried with 3 g of anhydrous Na₂SO₄ (Guangzhou Chemical Co.), and then, the solvents were removed *in vacuo*. Light yellow oil (monomer **1a**) was obtained. Monomers **1b**, **1c**, and **1d** were synthesized with the same procedure, except PEG150 was replaced with PEG200, PEG400, and PEG600, respectively.

Preparation of diacylchloride

We prepared diacylchloride by refluxing dicarboxylic acid (0.25 mol) in thionyl chloride (1.60 mol) for



Scheme 1 Synthesis of the poly(ester amide)s.

6 h. The excess thionyl chloride was removed, and diacid chloride was distilled *in vacuo*.

Polymerization

A typical procedure for the preparation of the poly(ester amide)s is described as follows (shown in Scheme 1). Diacid chloride (15 mmol) was dissolved in 150 mL of carbon tetrachloride. Under vigorous stirring, the solution was rapidly poured into a 150-mL blender containing an aqueous solution of 1,6-hexanediamine (1.74 g, 15 mmol) and sodium hydroxide (1.2 g, 30 mmol). The precipitated polymer was washed with water (300 mL), carbon tetrachloride (300 mL), acetone (300 mL), and diethyl ether (300 mL) and was finally dried at 80°C *in vacuo* overnight.

In this study, n was the number of repeated ethylene oxide units in PEG and was calculated from the

molecular weight. For example, the values of n for PEG150, PEG200, PEG400, and PEG600 were 3, 4.14, 8.68, and 13.22, respectively.

Hydrolytic degradation

Hydrolytic degradation assays were carried out at 37°C in a pH 7.4 sodium phosphate buffer. Polymeric plates were prepared by the evaporation of polymer solution at a concentration of 60 mg/mL with chloroform as the solvent. A 200-mg plate (1.5 cm × 1.5 cm × 200 μm) was kept in a bottle filled with 100 mL of the sodium phosphate buffer (0.1 mol/L, pH 7.4), which was prepared with 0.01 mol of sodium phosphate dissolved in 100 mL of deionized water. After the immersion time, the retrieved samples were thoroughly rinsed with water, dried to a constant weight *in vacuo* at 80°C for 24 h, and stored over CaCl₂ before analysis. To measure the weight loss, the specimens were weighed at desired intervals, and the degradability (D) was calculated with the following equation:

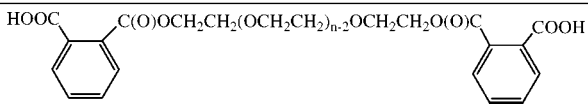
$$D(\%) = (W_0 - W_d) / W_0 \times 100 \quad (1)$$

where W_0 is the weight of the dried specimen before hydrolysis and W_d is the weight of dried specimen after hydrolysis.

RESULTS AND DISCUSSION

The route of synthesis leading to the poly(ester amide)s is depicted in Scheme 1. Excess phthalic anhydride reacted with PEG so that both the ends of each resulting compound were carboxyl groups, which was confirmed by both FTIR and ¹H-NMR spectra, as detailed in Table I. The representative FTIR and ¹H-NMR spectra of monomer **1a** are shown in Figures 1(a) and 2(a), respectively. In Figure 1(a), the O—H stretching band of carboxyl groups and the carbonyl stretching band are shown at 3495 and at 1728 cm⁻¹, respectively. The charac-

TABLE I
Masses, Yields, and Assignments of the ¹H-NMR (CDCl₃, TMS as an Internal Reference, δ, ppm) and FTIR (cm⁻¹) Spectra of Monomers **1a–1d**

Monomer	Mass (g)	Yield (%)	ph-H					
				COOCH ₂	COOCH ₂ CH ₂ , (OCH ₂ CH ₂) _{n-2}	ν_{OH}	$\nu_{C=O}$	ν_{C-O-C}
1a , $n = 3$ (PEG150)	9.81	88.0	8.76–7.56	4.48	3.86, 3.76	3495	1728	1296
1b , $n = 4.14$ (PEG200)	10.19	82.4	8.65–7.53	4.46	3.86–3.76	3437	1714	1293
1c , $n = 8.68$ (PEG400)	13.27	76.3	8.16–7.52	4.44	3.76–3.63	3444	1721	1285
1d , $n = 13.22$ (PEG600)	15.43	68.9	7.76–7.53	4.45	3.77–3.62	3473	1721	1285

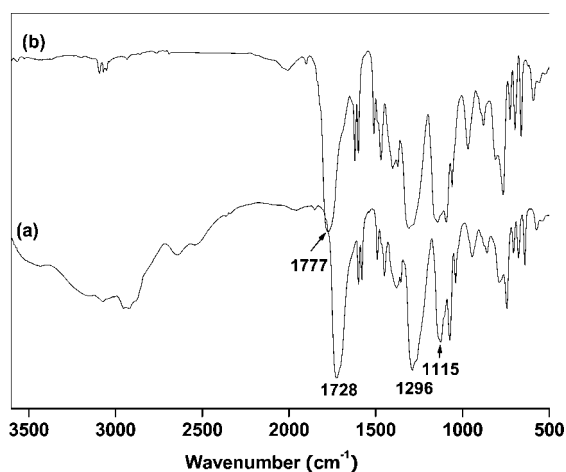


Figure 1 IR spectra of (a) monomer **1a** and (b) diacylchloride of **1a**.

teristic ethylene oxide stretching band at 1115 cm^{-1} is shown as well. From Figure 2(a), the multiple peaks around 8.76–7.56 ppm were assigned to protons of phenyl group. The peak at 4.48 ppm attributed to $-\text{COOCH}_2-$ methylene protons was observed, which indicated that PEG was incorporated into monomer **1a**. Moreover, the peaks at 3.86 and 3.76 ppm were assigned to other methylene protons of $-\text{COOCH}_2\text{CH}_2-$ and the ethylene oxide unit, respectively.

Then, the resulting dicarboxylic acid monomer was reacted with excess thionyl chloride to convert all of the carboxyl ends into acylchloride ends, which was confirmed by FTIR and $^1\text{H-NMR}$ analyses. The representative FTIR and $^1\text{H-NMR}$ spectra of the diacylchloride of monomer **1a** are shown in Figures 1(b) and 2(b), respectively. The broad band at 3495 cm^{-1} assigned to O–H stretching band disappeared, which showed that all of the carboxyl ends were converted into acylchloride ends. Moreover, the carbonyl stretching band was observed at 1777 cm^{-1} because of the presence of electron-withdrawing acylchloride groups. As shown in Figure 2(b), the resonances of protons of phenyl groups shift to a lower field (8.94–7.72 ppm). The same trend was observed for resonances of methylene protons. For example, the methylene protons of $-\text{COOCH}_2-$, $-\text{COOCH}_2\text{CH}_2-$, and ethylene oxide units were observed at 4.61, 3.95, and 3.84 ppm, respectively. For the preparation of the poly(ester amide)s, the interfacial polycondensation method was used. We admit that interfacial method does not impose as many restrictions on the experimental conditions with regard to monomer purity and equimolarity as the solution polycondensation method does. Moreover, excellent results have been attained previously with the interfacial polycondensation method for the preparation of similar aliphatic–aromatic poly(ether

amide)s.²⁵ In this study, the poly(ester amide)s were produced through the interfacial polycondensation method. The poly(ester amide)s began to form immediately upon the addition of diacylchloride in the CCl_4 to diamine in the aqueous phase containing NaOH. Table II summarizes the characteristics of the polymers. Polymers with moderate yields in the range 53–64% were obtained, which were similar to those reported in the literature.⁹

The molecular weights of experimental polymers are seldom measured by absolute methods. Although the improvement of gel permeation chromatography (GPC) has permitted the measurement of the average molecular weight, the lack of suitable monodisperse samples has usually obliged users to refer the measurements to polystyrene monodisperse standards. Considering the very different structure of polystyrene and linear aromatic–aliphatic poly(ester amide),²⁵ we think that their hydrodynamic volumes are quite different, and consequently, the solution properties of aromatic–aliphatic poly(ester amide) and their behavior in GPC can hardly be similar to that of polystyrene. Therefore, the unique values usually reported with regard to the molecular weight of novel polymers are the intrinsic viscosities. The values of the intrinsic viscosities (Table II) ranged from 0.83 to 1.11 dL/g, which indicated that moderate molecular weight poly(ester amide)s were synthesized.

The IR spectra of the polymers were fully consistent with the anticipated chemical constitution. The representative spectrum of sample 3 is shown in Figure 3(A). It showed the characteristic absorptions bands corresponding to the amide (3374 , 3067 , 1643 , and 1545 cm^{-1}) and methylene (2941 , 2858 , and 748 cm^{-1}) groups. The intense $\text{C}=\text{O}$ stretch at 1712 cm^{-1} confirmed the formation of ester bonds. This was similar with reported results for other

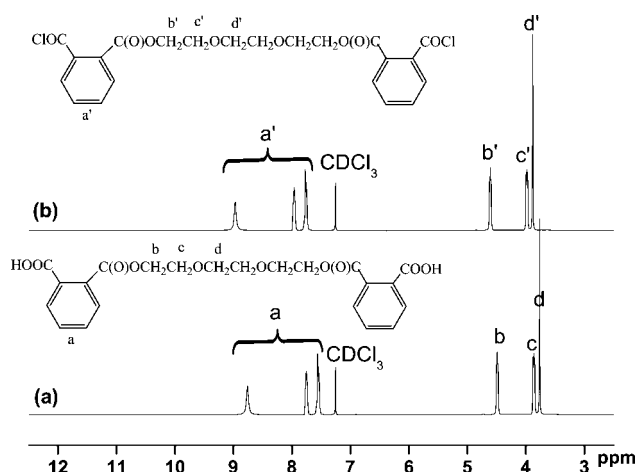


Figure 2 $^1\text{H-NMR}$ spectra of (a) monomer **1a** and (b) diacylchloride of **1a**.

TABLE II
Yields, Compositions, Intrinsic Viscosities, and Contact Angles of the Synthesized Poly(ester amide)s

Sample	<i>n</i>	Yield (%)	Composition (%) ^a	Intrinsic viscosity (dL/g) ^b	Contact angle (°) ^c	Tensile strength (MPa)	Elongation at break (%)
1	3	62.3	0.497	0.83 ± 0.11	56.4 ± 2.3	75 ± 5	12 ± 2
2	4.14	64.6	0.496	0.92 ± 0.13	52.3 ± 1.4	68 ± 6	20 ± 3
3	8.68	56.2	0.497	1.03 ± 0.15	46.6 ± 2.1	56 ± 7	31 ± 3
4	13.22	53.8	0.498	1.11 ± 0.12	41.1 ± 1.9	42 ± 6	43 ± 4

^a Molar ratio of CONH to CONH + COO, as calculated from ¹H-NMR spectroscopy.

^b Measured in dichloroacetic acid at 25°C.

^c Determined with a Krüss DSA-10.

poly(ester amide)s.^{13,27} The characteristic ethylene oxide stretching bands at 1118 cm⁻¹ were observed as well. The IR spectra of all the samples in the wavelength range 1400–1800 cm⁻¹ are also shown in Figure 3(B). Sharp absorption bands arising from the stretching of ester and amide carbonyl groups were observed with similar intensities, as expected from the composition of these copolymers.

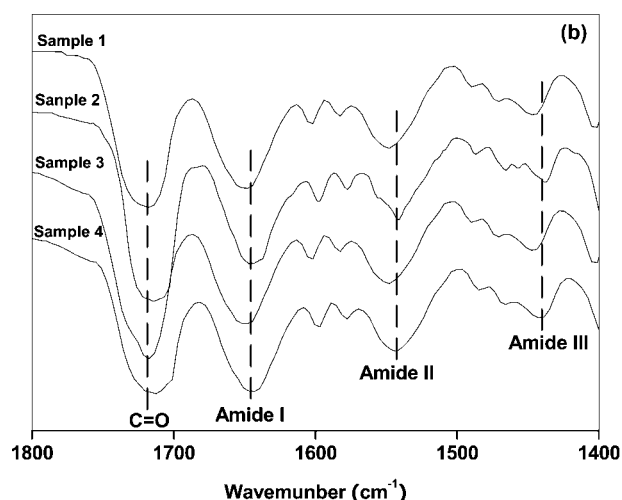
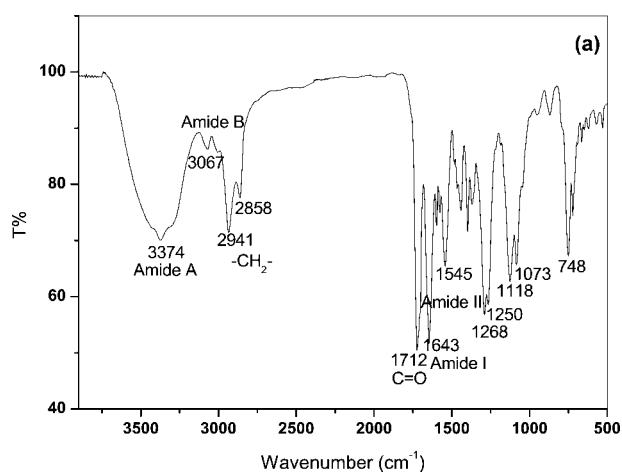


Figure 3 IR spectra of (a) sample 3 and (b) all poly(ester amide)s in the range 1800–1400 cm⁻¹.

A more detailed elucidation of the structure of the polymers could be obtained from the ¹H-NMR spectra. The ¹H-NMR spectrum of sample 3 (with TMS as an internal standard) is shown in Figure 4. The peak at 4.41 ppm assigned to —COOCH₂— methylene protons indicated that the PEG took part in the polycondensation reaction, whereas the resonances of other methylene protons in the PEG main chain shifted to higher fields (3.61 and 3.73 ppm). The resonances at 3.57 ppm were overlaid with peaks of 3.61 and 3.73 ppm belonging to methylene protons of the —NHCH₂— unit, whereas the peaks at 1.36 and 1.65 ppm were assigned to remaining methylene protons of the 1,6-hexanediamine units. The single peak at 7.43 ppm and the multiple peaks at 7.78, 7.67, and 7.50 ppm were attributed to the proton of the —NHCO— unit and the protons of the phenyl group, respectively.

¹H-NMR spectra allowed us to determine the composition of the synthesized poly(ester amide)s. Thus, we used the area of the peak corresponding to the —COOCH₂— protons (*I*₁) and the area of the —NHCO— signal (*I*₂) to obtain the amide molar ratio (*x*):

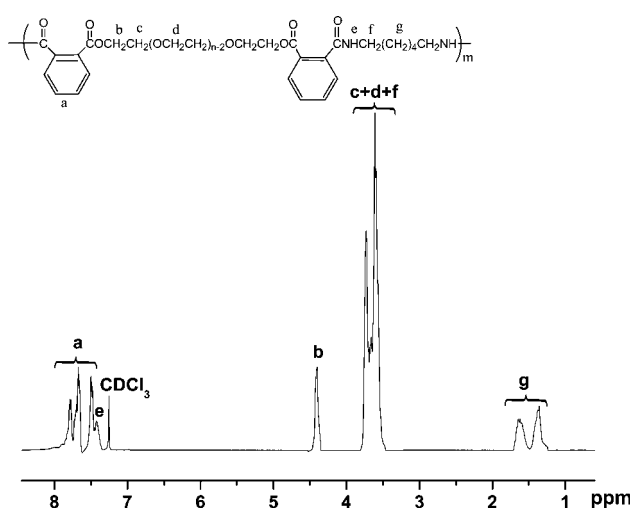


Figure 4 ¹H-NMR spectrum of sample 3.

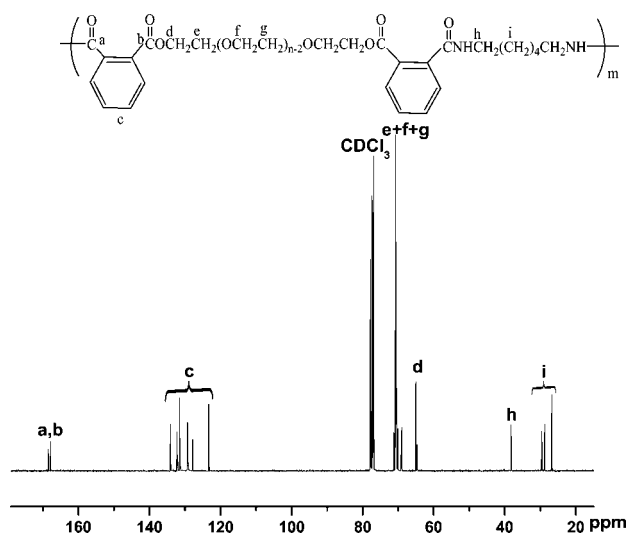


Figure 5 ^{13}C -NMR spectrum of sample 3.

$$x = 2I_2 / (I_1 + 2I_2) \quad (2)$$

The values calculated and reported in Table II were in close agreement with the 1,6-hexanediamine feed ratio, which suggested that the two monomers had similar reactivities.

Analysis of ^{13}C -NMR spectrum was much more definitive for determining the structure of the polymers. The ^{13}C -NMR spectrum of sample 3 (with TMS as an internal standard) is shown in Figure 5. The signals for the carbonyl carbons (a, b) were observed at 169.4, 168.5, and 167.8 ppm. The multiple signals between 134.1 and 123.3 ppm arose from the phenyl carbon atoms (c). The peak at 65.1 ppm corresponded to methylene carbon atoms (d) linked to ester bonds, which further confirmed that ethylene oxide units were incorporated into the polymer main chain. The signals at 71.2, 70.1, and 69.0 ppm were attributed to the remaining carbon atoms of the ethylene oxide units (e + f + g). The chemical shift of the aminomethylene carbon (h) atom appeared at 38.2 ppm, whereas the peaks at 29.6, 28.8, and 26.8 ppm were assigned to the remaining methylene carbon atoms (i) of the 1,6-hexanediamine units. Data of the ^1H -NMR and ^{13}C -NMR spectra showed the characteristic signals observed for the synthesized poly(ester amide)s. Therefore, both the characteristic absorptions bands from the FTIR spectrum and the well-defined assignments of hydrogen and carbon atoms from the NMR spectra confirmed that the anticipated poly(ester amide)s were successfully obtained.

The thermal properties were analyzed by DSC. We found that only a well-defined slope change was observed, and no crystal melting peaks were found for any of the polymers, as shown in Figure 6. This

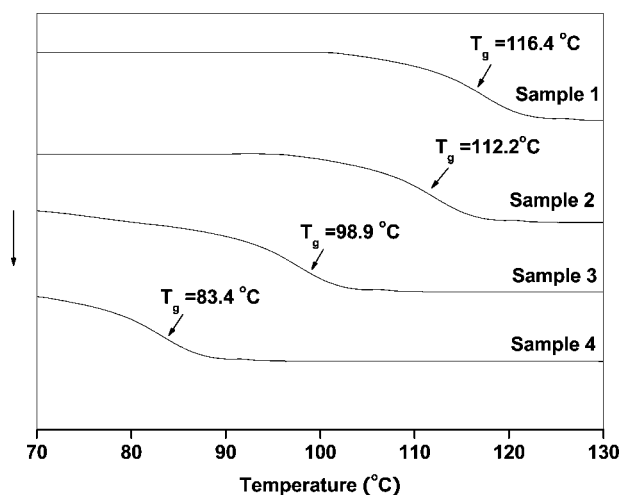


Figure 6 DSC curves for the synthesized poly(ester amide)s.

indicated that the obtained poly(ester amide)s were amorphous. Similar conclusions could be drawn from DMA of the polymers. The DMA, as expressed by the shape of the dissipation factor ($\tan \delta$) versus temperature curves, is illustrated in Figure 7. All of the poly(ester amide)s showed a single transition temperature in the range 118.7–86.3°C. These observations were different from other crystalline or semi-crystalline poly(ester amide)s, which possessed a predominant melting peak with shoulders or small additional peaks.^{7–10} Such a difference could be considered the result of the ethylene oxide units' conformational flexibility and the disturbance provoked by ethylene oxide units in the crystalline structure. As shown in Table III and Figure 7, the DSC and DMA results indicated that the T_g 's of these polymers fell because of the separation of the amide groups by the

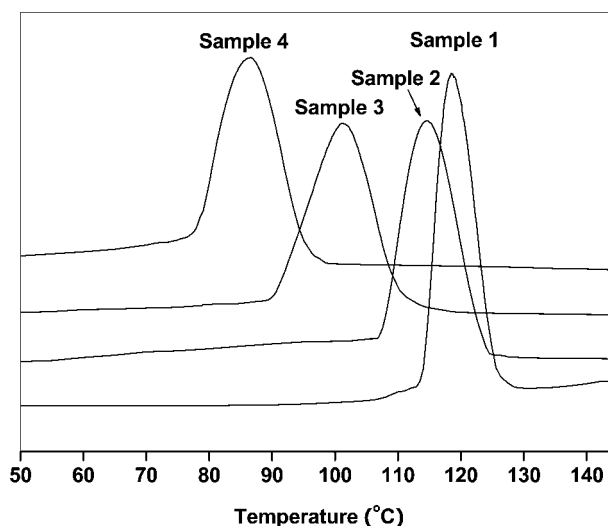


Figure 7 DMA curves for the synthesized poly(ester amide)s

TABLE III
Thermal Properties and Solubility of the Synthesized Poly(ester amide)s^a

Sample	<i>n</i>	Thermal properties		Solubility ^b							
		<i>T_g</i> (°C) ^a	<i>T_{d,onset}</i> (°C)	DMF	DMSO	Formic acid	CHCl ₃	THF	Ethyl acetate	Acetone	Ethyl ether
1	3	116.4	349	+	+	+	+	+	–	–	–
2	4.14	112.2	342	+	+	+	+	+	–	–	–
3	8.68	98.9	336	+	+	+	+	+	–	–	–
4	13.22	83.4	328	+	+	+	+	+	–	–	–
PEG (<i>M_w</i> = 400,000)			325								

^a Measured by DSC.

^b + = soluble; – = insoluble.

lengthening of the flexible ethylene oxide units. The data confirmed that the lengthening of the flexible sequences brought about the decrease in T_g as a result of the increase in molecular mobility.²⁷ It was thought that the energy required for the rotation of a single bond was weaker if ethylene glycol segments were longer.³² Moreover, it is worth noting that sample 4 showed an extra high T_g . A plausible explanation may be that sample 4 possessed longer and more flexible ethylene oxide units and an *o*-orientation phenylene ring in its structure, which favored the interaction of ether with amides. That is, sample 4, with the longest ethylene oxide units, increased the number of intermolecular and intramolecular hydrogen bonds between the ether linkages and amide groups, which thus restricted the molecular mobility and consequently increased the T_g value.

Wide-angle X-ray scattering patterns are important characterization measurements for the determination of polymer crystallinity. All of the poly(ester amide)s showed a typical X-ray halo with no diffraction signals, as shown in Figure 8. Therefore, the presence of single T_g transitions, as demonstrated by DSC and DMA, and the results from wide-angle X-ray diffraction (WAXD) confirmed that these poly(ester amide)s were essentially amorphous. Aromatic polyamides of similar structure containing ethylene oxide moieties have also been reported to be essentially amorphous.²⁷

The thermal stability of these poly(ester amide)s was studied by TGA, and the results are summarized in Table III. With the onset decomposition temperature ($T_{d,onset}$) as a criterion of thermal stability, the novel poly(ester amide)s displayed decomposition temperatures higher than 300°C. To establish the effect of the ethylene oxide moieties on the thermal stability, we studied a sample of PEG ($M_w = 400,000$ g/mol) by TGA. The value of $T_{d,onset}$ was found to be 325°C, which was similar to results reported by Abajo et al.²⁷ Also, an inverse relationship between $T_{d,onset}$ and the ethylene oxide length was observed.

The mechanical properties of the poly(ester amide) films are presented in Table II. The films had tensile strengths in the range 75–42 MPa and elongations at break in the range 12–43%. Sample 4, with the longest ethylene oxide segments in the repeat unit, exhibited the lowest strength and the highest elongation.

The solubility was investigated with several solvents, as summarized in Table III. As shown, the presence of ethylene oxide units improved the polymer solubility. All of the polymers readily dissolved at room temperature in hydrogen-bond-breaking solvents, such as formic, dichloroacetic, and trifluoroacetic acids, and strong aprotic solvents, such as NMP, DMF, and DMSO. Polar solvents, such as THF, dichloromethane, and chloroform, were also good solvents for all of the poly(ester amide)s. Good solubility enhanced the processing facilities from solution. No solubility was observed in nonaggressive solvents, such as acetone, ethyl acetate, or ethyl ether. In general, because strong hydrogen bonds are always established for poly(ester amide)s,

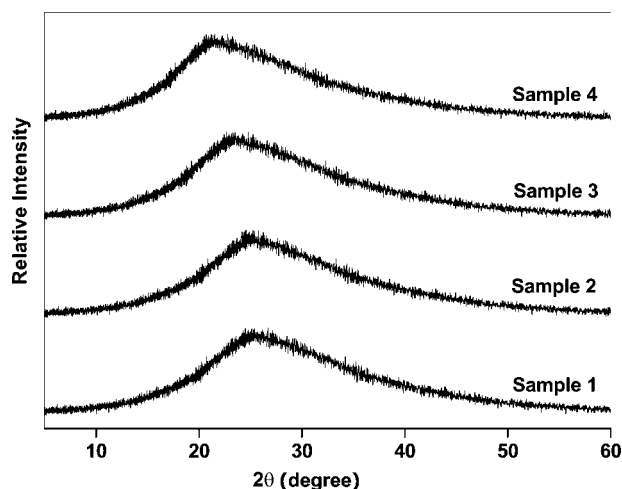


Figure 8 WAXD curves for the synthesized poly(ester amide)s.

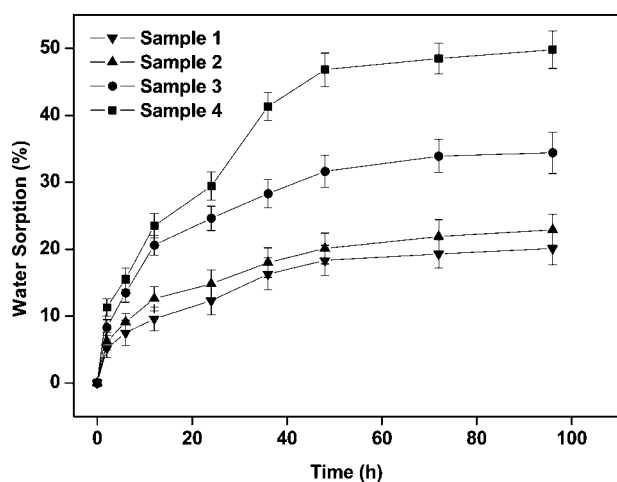


Figure 9 Moisture sorption of the poly(ester amide)s as a function of the exposure time.

nonaggressive solvents, such as acetone, ethyl acetate, or ethyl ether, do not solve poly(ester amide)s. In this study, amorphous and hydrophilic poly(ester amide)s were obtained because of the presence of ethylene oxide units in the polymer structure. However, the synthesized poly(ester amide)s were still insoluble in these nonaggressive solvents. Additionally, these poly(ester amide)s were not soluble in water, although as we could anticipate, they displayed improved hydrophilicity because of the presence of hydrophilic ethylene oxide units in the polymer chain.

Hygroscopicity is a prime property of poly(ester amide)s because it is critical in the determination of the behavior of these materials with regard to biodegradability. The water absorbed by the poly(ester amide)s is represented in Figure 9 as a function of exposure time. A noticeable enhancement of the capacity to take up moisture was close to 50% for sample 4. In this study, from sample 1 to sample 4, a higher density of ethylene oxide units led to more hydrophilic poly(ester amide)s because of the presence of hydrophilic ethylene oxide units in the polymer backbone. Water molecules more easily penetrated into hydrophilic poly(ester amide)s with higher densities of ethylene oxide units. So, water uptake increased with increasing density of ethylene oxide.

In addition, the contact-angle data ranged from 56.4 to 41.1° (Table II) and showed a decrease with increasing density of hydrophilic ethylene oxide units in the poly(ester amide) chains. The contact-angle data from sample 1 to sample 4 decreased with increasing density of ethylene oxide units from PEG150 to PEG600. The possible reason is that because PEG is hydrophilic,^{22–24} the presence of ethylene oxide units in the poly(ester amide)s improved the hydrophilicity of the corresponding polymer.

From sample 1 to sample 4, the increase in the density of ethylene oxide enhanced the hydrophilicity of the poly(ester amide)s and, thus, decreased the contact angle. From the previous results, we could see that the hydrophilicity of the poly(ester amide)s from sample 1 to sample 4 improved. Investigations of both hygroscopicity and contact angle indicated that the obtained poly(ester amide)s possessed good and controllable hydrophilicity through changes in the number of ethylene oxide units in the poly(ester amide) chains.

Hydrolytic degradation under simulated physiological conditions was studied for all of the synthesized polymers. It is well known that the insertion of ester linkages in a polyamide chain enhances the sensitivity of the polymer toward hydrolysis.^{11,13} This is exactly what we found to happen in the poly(ester amide)s, as has been well illustrated by various researchers.^{9,19} The degradation results are presented in Figure 10, where degradability of the samples is plotted against hydrolysis time. The degradability of polymers increased with longer ethylene oxide units in the polymer. When the experiment at 37°C and pH 7.4 was continued for 105 days of incubation, a degradability of 22.3% for sample 1 was obtained. Poly(ester amide) containing longest ethylene oxide units for sample 4 appeared to be degraded very rapidly with 58% of the initial weight being lost in 75 days. This result might be explained by the fact that during the hydrolytic experiment, the water molecules randomly attacked the ester linkages of the poly(ester amide) molecule. Therefore, more hydrophilic poly(ester amide)s were more easily attacked by water molecules. As the amount of ethylene oxide increased in the poly(ester amide), more fragments more soluble in the medium were produced by the process, and these easily left the samples. That is, poly(ester amide)s containing

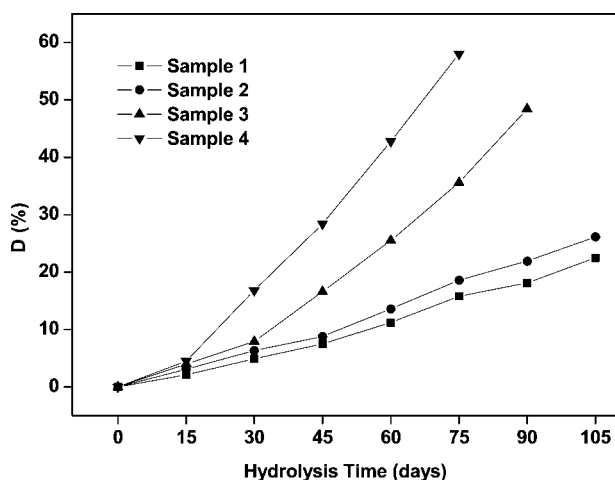


Figure 10 Hydrolytic degradation of the poly(ester amide)s: the degradability (*D*) versus the incubation time.

longer ethylene oxide units led to faster degradation. Figure 9 clearly demonstrates that poly(ester amide)s containing ethylene oxide units degraded at 37°C in a rapid and steady way. It is generally accepted that the degradation process of biodegradable polymers occurs in two ways, bulk degradation and surface erosion. Bulk-eroding polymers have nonlinear erosion kinetics and degrade all over their cross section. In the first stage, chain scission occurs preferentially in the amorphous regions of the semicrystalline polymer.^{33,34} The initially random chain scissions result in a decrease in the degree of entanglement, which thus facilitates and even considerably promotes the mobility of nonbiodegradable chain segments in those regions. However, during the surface erosion process, degradation and erosion are limited to the surface of a polymer only. In an ideal scenario, the kinetics of mass loss is linear.³⁵ The degradation curves displayed in Figure 10 suggest that a bulk degradation mechanism was operating. Moreover, water diffusion will be facilitated in essentially amorphous poly(ester amide)s because a more loose chain packing in the polymers is expected to occur.

CONCLUSIONS

Novel poly(ester amide)s containing ethylene oxide units were successfully prepared by the interfacial polycondensation of 1,6-hexanediamine and diacylchlorides. The composition and properties of the poly(ester amide)s were characterized by various methods. The DSC and TGA measurements demonstrated that the obtained polymers were amorphous and possessed good thermal stability to 300°C. Because of the presence of ethylene oxide units in the polymer chains, the synthesized poly(ester amide)s showed good and controllable hydrophilicity and excellent solubility in organic solvents. The results of hydrolytic degradation indicate that the poly(ester amide)s degraded in a rapid and steady way.

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