

Structure-Property Relationships of Degradable Polyurethane Elastomers Containing an Amino Acid-Based Chain Extender

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ABSTRACT: A series of degradable polyurethanes of variable soft segment chemistry and content were synthesized and characterized. An amino acid-based diester chain extender was used to confer degradability and both polycaprolactone diol (PCL) and polyethylene oxide (PEO) were used as soft segments. In addition, the diisocyanate component was a potentially nontoxic diisocyanate (2,6-diisocyanato methyl caproate, LDI). The physicochemical properties of these unique series of polyurethanes were investigated. It was found that the PEO containing polyurethanes were generally weak, tacky amorphous materials. In contrast, the PCL polyurethanes were relatively strong, elastomeric materials which ranged from completely amorphous to semicrystalline as noted by differential scanning calorimetry. The PCL containing polyurethanes exhibited increasing tensile strength, modulus, and ultimate strain with increasing PCL molecular weight because of increasing phase separation and increasing soft segment crystallinity. Fourier transform infrared analysis showed significant hard segment urea and urethane hydrogen bonding which increased with hard segment content, although interphase bonding is believed to be significant for the PCL polyurethanes. Surface characterization carried out by contact angle analysis and X-ray photoelectron spectroscopy indicated soft segment surface enrichment for all of the polyurethanes. The PEO-based polymers were very hydrophilic whereas the PCL-based polymers displayed significantly higher contact angles, indicating greater surface hydrophobicity. The observed diversity in material properties suggests that these polyurethanes may be useful for a wide range of applications. © 2000 John Wiley & Sons, Inc. *J Appl Polym Sci* 75: 1522–1534, 2000

Key words: degradable; polyurethane; elastomer; amino acid

INTRODUCTION

The development of biodegradable polymers suitable for a variety of biomedical applications, including tissue engineering, is currently of great interest. Biodegradable polymers may act as tem-

porary scaffolds that facilitate tissue regeneration or replacement and may also be used for temporary therapeutic purposes, thereby eliminating the need for subsequent removal.^{1,2} Thus, a variety of biodegradable polymers have been developed in the last two decades. However, the majority of these polymers were aimed at either drug delivery systems or orthopedic applications such as fracture fixation and are typically hard, rigid materials.³ In contrast, few biodegradable elastomeric polymers have been synthesized. With the current increased interest in biodegrad-

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able polymers for a wide range of applications, new materials are required to satisfy an increasingly diverse range of physical properties. Biodegradable elastomers are expected to be suited for any application requiring the use of a flexible, elastic material such as soft tissue engineering (e.g., skin, vasculature).

Segmented polyurethane elastomers have been used as biomaterials for several decades because of their unique physical properties and relatively good biocompatibility.⁴ Segmented polyurethanes are a unique class of elastomeric block copolymers that generally exhibit a phase-segregated morphology made up of "soft" rubbery segments and "hard" glassy or semicrystalline segments. The soft segment usually consists of polyether or polyester diols of moderate molecular weight (1000 to 3000) whereas the hard segment consists of the diisocyanate component and a low molecular weight chain extender (usually a diamine or diol).

Degradable polyurethanes may be produced through the introduction of hydrolyzable linkages into the backbone in a variety of ways. The most common method of introducing these hydrolyzable linkages into polyurethanes has been to utilize hydrolyzable soft segment polymers such as polylactides and ϵ -polycaprolactone.⁵⁻⁹ In this way, a degradable polyurethane may be produced which consists of known degradable polymers (nonelastomeric) joined together via urethane and possibly urea linkages to form an elastomeric material. These polyurethanes have been synthesized as linear and network polymers of variable physical and degradation properties. The other means of producing degradable polyurethane elastomers involves the introduction of hydrolyzable groups via the hard segment. Because relatively few diisocyanates are currently available for polyurethane synthesis,¹⁰ the use of hydrolyzable chain extenders is the most feasible method of producing hydrolyzable hard segments. Examples of this approach are less common, however, than degradable polyurethanes containing hydrolyzable soft segments.¹¹⁻¹³

Degradable polyurethanes containing hydrolyzable hard segments have advantages over those utilizing hydrolyzable soft segments. Because most polyurethane elastomers generally consist of a high percentage of soft segment (50–75%), the material properties (e.g., bulk hydrophilicity) are dominated by the choice of soft segment. For example, degradable polyurethanes containing polylactide soft segments are generally stiff, high-strength materials which exhibit

relatively low extensibility (for polyurethanes),^{7,8} typical of polylactide homopolymers. Degradable polyurethanes which use a hydrolyzable hard segment may also contain a wide variety of soft segment chemistries that increases the range of material properties attainable without altering the degradable portion of the polymer.

Traditional polyurethane synthetic chemistry has used toxic precursors¹⁴ (e.g., toluene diisocyanate and methylene di-*p*-phenyl diisocyanate) which may liberate potentially carcinogenic compounds. The recent development of diisocyanates based on L-lysine¹⁵ as well as other amino acids¹⁶ has removed a major obstacle to synthesizing degradable polyurethanes expected to yield nontoxic degradation products. Bruin et al.¹⁵ reported on the development of biodegradable poly(ester-urethane) elastomer networks synthesized using ethyl 2,6-diisocyanatohexanoate, a diisocyanate prepared by converting the α and ϵ amine groups of L-lysine ethyl ester to isocyanates via phosgenation (referred to as L-lysine diisocyanate or LDI). It was surmised that if the diisocyanate were liberated by hydrolysis of the urethane bonds of the polymer during degradation the isocyanate functionalities would react with water to regenerate the L-lysine ethyl ester, an essentially nontoxic product. Subcutaneous implantations in guinea pigs elicited what the authors described as no adverse tissue reactions.⁶ Subsequently, other researchers have utilized LDI to develop both network and linear degradable polyurethane elastomers for biomedical applications and have not described any significant toxic or tumorigenic responses to the materials upon implantation.¹⁷

The work reported herein involves the synthesis and characterization of a series of biodegradable linear polyurethane elastomers with potential for use in soft tissue repair applications. The degradable polymers were synthesized using 2,6-diisocyanato methyl caproate (LDI), polycaprolactone diol (PCL), or polyethylene oxide (PEO) and an amino acid-based diester chain extender described previously.¹³ The amino acid-based diester chain extender was used to introduce hydrolyzable linkages into the hard segment. Kartvelishvili et al.¹⁸ have recently described degradable polyurethanes containing similar amino acid-based diester compounds. However, these compounds were incorporated into nonsegmented, and therefore, nonelastomeric polyurethanes.

Because polyurethane elastomers exhibit complex phase structuring depending on the type and size of segments used, it is reasonable to assume

that the phase-segregated morphology will impact both their physical and degradation properties. For example, it has been well documented that increased phase separation can lead to enhanced mechanical properties^{19,20} and may impart greater resistance to hard segment degradation.²¹ Previously, we reported on the physicochemical and degradation properties of a series of degradable polyurethanes containing an amino acid-based diester chain extender and 1,6-hexamethylene diisocyanate (HDI) as the hard segment. It was found that a wide range of physical and degradation properties was attained by altering the type and size of the soft segment. This report describes the physicochemical properties of similar polymers containing LDI as the diisocyanate component. Again, by varying the type and molecular weight of the soft segment diols (PCL and PEO), it was possible to dramatically alter the subsequent polyurethane physicochemical properties. In addition, substitution of LDI for HDI in the polyurethanes resulted in significant differences in material properties.

MATERIALS AND METHODS

Materials

Polycaprolactone diol (molecular weights 530, 1250, and 2000) and polyethylene oxide (molecular weights 600 and 1000) were obtained from Aldrich Chemicals (Milwaukee, WI). The soft segment diols were placed in a vacuum oven at 60°C for at least 48 h with molecular sieves (size 4A; Aldrich) to remove residual water before reaction. LDI was obtained from Kyowa Hakko Kogyo Co., Ltd., Tokyo Japan and was distilled under vacuum before use. Stannous octoate, used as a catalyst for the prepolymer reaction, was obtained from Sigma (St. Louis, MO). An experimental phenylalanine-based chain extender described previously¹³ was synthesized and used in all of the polyurethane reactions. Polyurethane solvents dimethyl formamide (anhydrous grade DMF) and chloroform were obtained from Aldrich and ACP Chemicals Inc., Montreal PQ, respectively.

Polymer Synthesis and Film Casting

Polyurethanes were synthesized via a standard, two-step reaction procedure described previously.¹³ Briefly, LDI was reacted with either PEO or PCL

at a 2:1 molar ratio in anhydrous DMF at 85°C. The prepolymer reaction proceeded for 150 min in the presence of 0.1% stannous octoate catalyst. The reaction temperature was subsequently lowered to 25°C, the chain extender was added at a 1:1 molar ratio with the prepolymer and allowed to react for approximately 18 h. The polymer was precipitated in saturated aqueous KCl and vacuum filtered. The polymer was then immersed in distilled water for 48 h, refiltered, and dried under vacuum at 60°C for 48 h, and stored in a desiccator until use.

All solid films were prepared by solution casting. The polyurethanes were dissolved in chloroform at a concentration of 3–5% w/v. The polymer films cast for the water uptake and differential scanning calorimetry (DSC) studies were obtained by pouring the polymer solution (20 mL) into level 5 cm polytetrafluorethylene (PTFE) casting dishes and cast at room temperature. Polyurethane films cast for tensile testing were obtained by pouring the polymer solution (200 mL) into a leveled 20 × 25 cm PTFE casting dish. The dishes were covered to prevent dust from contaminating the film and excessively fast casting, which can result in surface defects. The cast films were removed from the casting dishes and dried under vacuum at 60°C for 48 h to remove residual solvent.

The polymer nomenclature used in this study is based on the type and molecular weight of the soft segment and the chain extender. For example, PCL1250/Phe refers to a polyurethane consisting of 1250 molecular weight PCL, chain extended with the novel phenylalanine-based chain extender. All of the polyurethanes use LDI as the diisocyanate component.

Polyurethane Characterization

Gel permeation chromatography (GPC) was used to determine polyurethane molecular weights. The polymers were dissolved at 0.25% w/v in the GPC carrier solvent (0.1M LiBr in DMF) and 200 μ L samples were injected. The number and weight average molecular weights were determined from the retention time data with Waters Baseline™ software (Waters Chromatography, Mississauga, ON) using a calibration curve generated with polystyrene standards (Varian, Sunnyvale, CA).

DSC was performed using a Thermal Analyst 2100 thermal analyzer at the Brockhouse Institute for Materials Research (McMaster Univer-

sity, Hamilton, ON) to determine the phase-segregated morphology of the polyurethanes. Scan rates of 15°C per min were used over a temperature range of -100 to 250°C.

Fourier transform infrared (FTIR) spectra were obtained at room temperature using a Nicolet Impact 410 FTIR spectrometer. Spectra were generated from 256 scans at 4 cm⁻¹ resolution. A 5% solution of polymer in chloroform was placed directly onto NaCl plates. Subsequent evaporation of the chloroform at room temperature under vacuum was performed for 20 min. The coated plates were then stored in a desiccator until and between analyses. None of the spectra showed any traces of residual solvent.

Uniaxial stress-strain measurements were obtained using an Instron testing machine. A cross-head speed of 500 mm/min was used. Samples were cut from films cast to 30–60 μm thickness using an ASTM D638M die. Tests were performed in a temperature- and humidity-controlled environment (23°C, 50% relative humidity) after sample preconditioning for at least 48 h.

Water contact angles were measured on polymer coated 18 × 18 mm glass microscope cover slides. The cover slides were coated by three sequential dips in a solution of polymer in chloroform (5% w/v) and dried at 55°C for 24 h. The samples were washed with a 0.1% detergent solution (Alconox, New York, NY), rinsed with distilled water, and dried at 55°C for 2 h. The samples were subsequently washed with 1,1,2-trichlorotrifluoroethane (Aldrich) to remove silicon containing surface contaminants and dried under vacuum at 60°C overnight (J. P. Santerre, personal communication, 1997). The advancing and receding water contact angles were measured by goniometer using the sessile drop technique. Ten measurements of both advancing and receding angles were made.

X-ray photoelectron spectroscopy (XPS) was performed at the Surface Science Laboratory at the University of Toronto. Take-off angles of 90,

Table I Molecular Weight Data Obtained by GPC (Polystyrene Equivalents)

Polymer	M_n	M_w	M_w/M_n
PCL530/Phe	34,600	75,270	2.18
PCL1250/Phe	73,680	130,380	1.77
PCL2000/Phe	90,140	185,750	2.06
PEO600/Phe	24,220	46,140	1.91
PEO1000/Phe	73,150	173,720	2.37

Table II DSC Data for Polyurethanes

Polymer	Soft Segment		
	T_g (°C)	T_m (°C)	Crystallinity (%)
PCL530/Phe	-6.2		
PCL1250/Phe	-34.2	43.1	40.8
PCL2000/Phe	-51.9	45.1	46.5
PEO600/Phe	-3.4		
PEO1000/Phe	-30.0		

30, and 20° were used to obtain a compositional depth profile of the polymer surfaces. Polymer-coated cover slides were prepared as described for the contact angle studies. Low resolution spectra were performed to generate elemental composition data while high resolution analysis of the carbon 1s peak was performed to determine the relative contributions of the urethane, urea, ester, and ether groups.

RESULTS AND DISCUSSION

Polyurethane molecular weights as measured by GPC are shown in Table I. The PCL containing polymers generally exhibit higher molecular weights than the PEO containing polyurethanes. This difference is believed to result from the presence of water in the highly hydrophilic PEO soft segment during polymerization, despite efforts to remove water before reaction. Water will competitively react with the diisocyanate in undesirable urea-forming and branching side reactions, thus limiting ultimate polymer molecular weight.²⁰ As may be expected, the higher molecular weight PCL containing polyurethanes are substantially stronger than the PEO containing polyurethanes. In fact, the PEO containing polyurethanes were tacky, semiviscous materials that deformed easily and were very difficult to handle.

DSC results are given in Table II. As was noted previously for similar polyurethanes containing HDI, the soft segment glass transition temperature (T_g) decreases with increasing soft segment molecular weight indicating increasing phase separation. However, the LDI containing polyurethanes appear to exhibit a greater degree of phase mixing as the soft segment molecular weight is decreased because the PCL530/Phe and PEO600/Phe T_g s are significantly higher than was noted

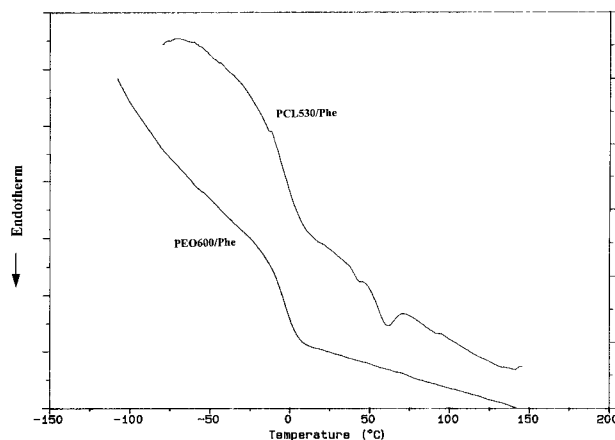


Figure 1 DSC scans of PCL530/Phe and PEO600/Phe.

for the corresponding HDI containing polymers.¹³ This increased phase mixing at low soft segment molecular weight may result from hard segment disruption caused by LDI or increased chemical compatibility between the LDI containing hard segment and the polyester and polyether soft segments. LDI is less symmetric than HDI and also contains a methyl ester side chain, both of which may inhibit chain packing in the hard segment. An absence of any distinguishable hard segment glass transitions in the LDI polyurethanes also supports the notion of reduced hard segment cohesion.

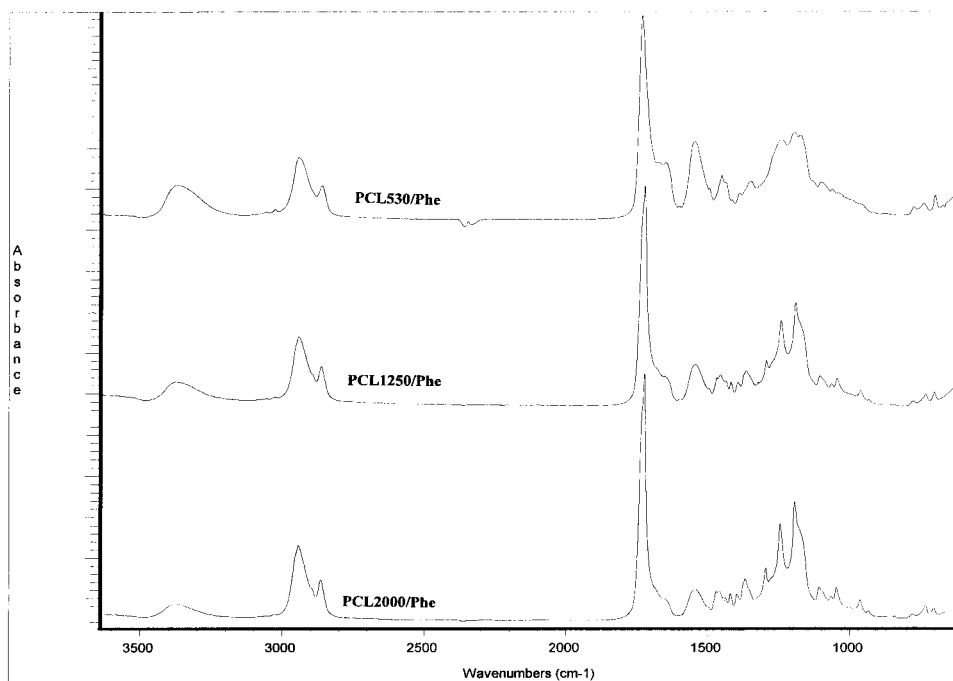
However, the PCL 530 polyurethane does exhibit a thermal transition at 60°C (Fig. 1). van Bogart et al.²² described similar transitions at 50–60°C in PCL-based polyurethanes containing H₁₂MDI/butane diol hard segments. Because the polyurethanes showed no hard segment crystallinity, it was concluded that the endotherms resulted from the disruption of ordered, noncrystalline hard segment aggregates. Alternatively, other researchers have attributed transitions in this region to the following: bimodal hard segment distributions, the presence of a mixed interfacial region, a β transition, and the T_g of a mixed phase.²³ In this case, the high hard segment content (62%) and largely phase-mixed morphology of the PCL530 polyurethane (as evidenced by the high soft segment T_g value) may be expected to lead to significant hard to soft segment hydrogen bonding. The transition may then be attributed to either a mixed phase T_g and/or the dissociation of urethane/urea-soft segment hydrogen bonds. Unlike the PCL530 polyurethane, no transition was noted at 60°C for the PEO600 polymer, despite

the similar hard segment contents (62 and 59%, respectively). The lack of an endotherm at 60°C for the PEO600 polyurethane may suggest that this transition results from hard segment/soft segment ester interactions. Reduced interphase molecular interactions are typical for polyether-based polyurethanes because of the weaker hydrogen bonding potential of the ether oxygen in comparison with the ester carbonyl oxygen.²⁴

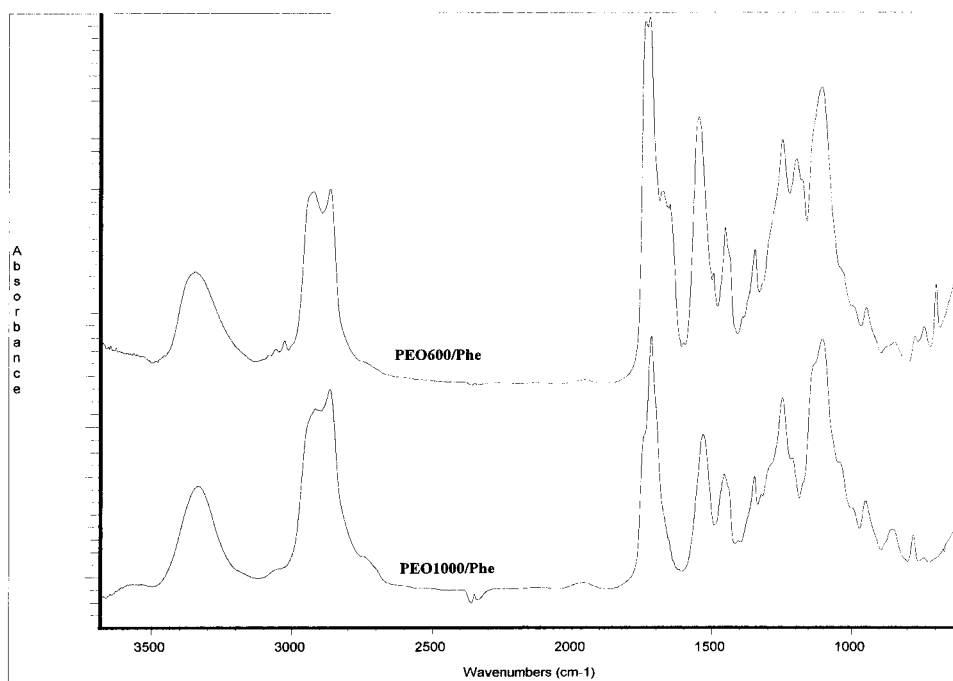
The PCL1250 and PCL2000 containing polyurethanes also exhibit soft segment crystallization with the crystal melt temperature increasing with PCL molecular weight, suggesting increased phase separation with PCL molecular weight. In addition, the percent crystallinity of the soft segment increases with increasing PCL molecular weight (Table II). The percent crystallinity of the soft segments of both PCL2000/Phe and PCL1250/Phe were calculated assuming an enthalpy of fusion of 32.4 cal/g for 100% crystalline PCL as determined by melting point depression of PCL with ethyl benzoate.²⁵ The degrees of soft segment crystallization are similar to those noted by Li et al.²⁶ for PCL containing polyurethanes.

The significant degree of soft segment crystallinity for the PCL1250/Phe polyurethane is somewhat surprising because other researchers have indicated that a PCL molecular weight of 2000 to 3000 was necessary for soft segment crystallization.^{22,24,26} This difference is difficult to explain, because the degree of phase separation, as noted by soft segment T_g , is similar for the polymers described herein and those of Li et al.²⁶ and van Bogart et al.²² Therefore, it may be surmised that differences in hard segment chemistry may have some impact on the ability of the PCL soft segment to organize into crystals, possibly by increasing the conformational mobility of the polymer chains inasmuch as the hard segments were noncrystalline.²⁷ In contrast, the PEO containing polyurethanes contain no soft segment crystallinity and appear to be completely amorphous.

FTIR spectra for the polyurethanes synthesized are shown in Figure 2. A large carbonyl peak is noted at ≈ 1735 to 1724 cm^{-1} , resulting from the ester groups of PCL polyurethanes whereas the PEO polyurethanes exhibit a distinct ether peak at ≈ 1100 cm^{-1} . For the PCL polyurethanes, the carbonyl stretching region (1650 to 1800 cm^{-1}) is dominated by the intense soft segment ester band which is located at 1724 to 1735 cm^{-1} depending on the presence or absence of soft segment crystallinity [Fig. 3(a)]. Soft segment crystallinity was found to shift the main PCL



(a)

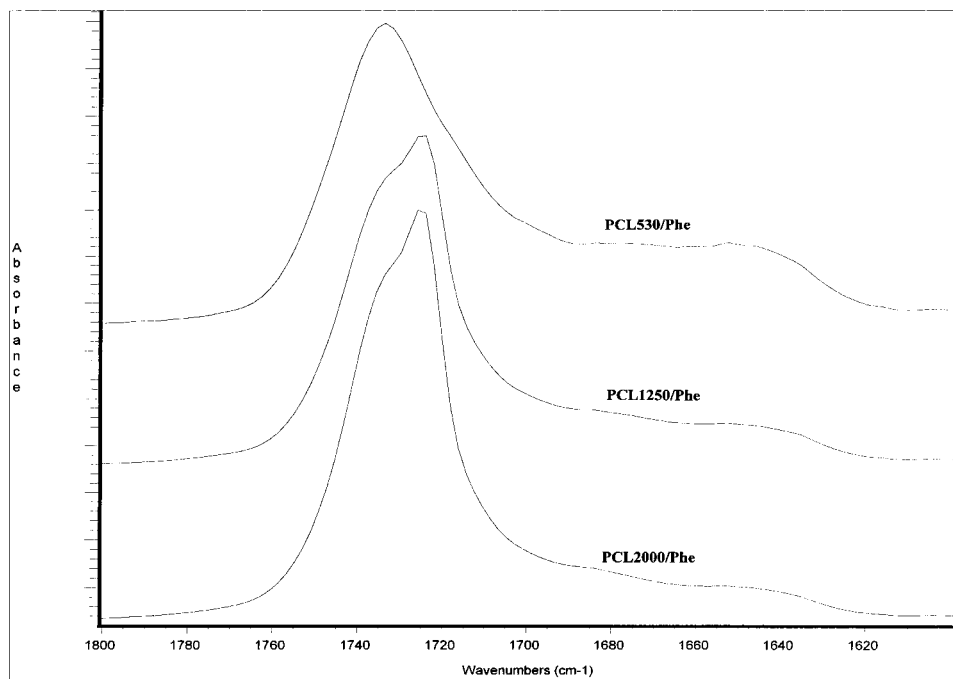


(b)

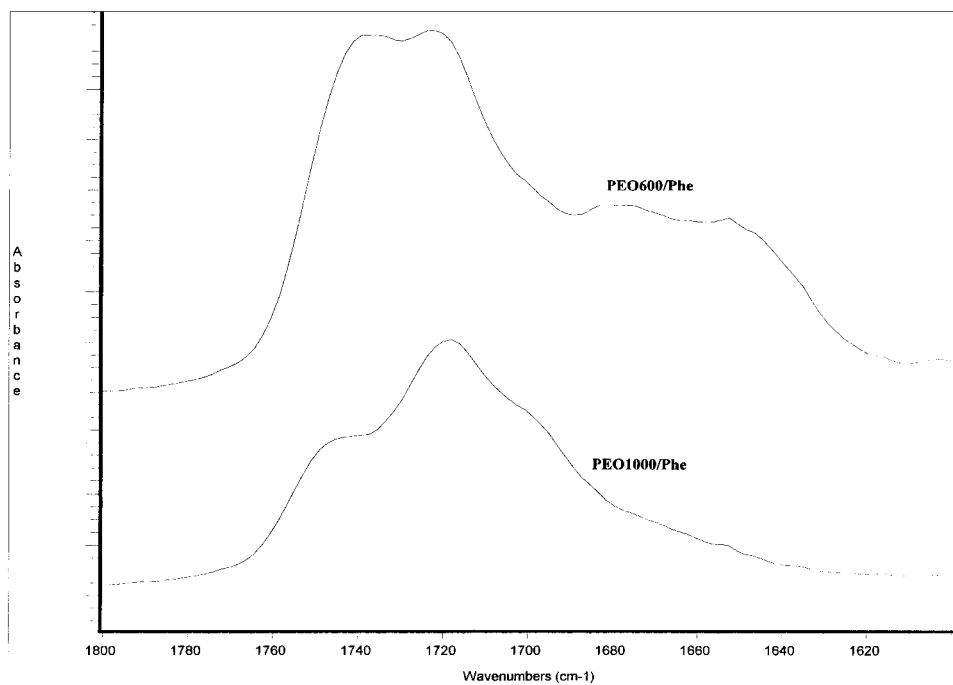
Figure 2 FTIR absorbance spectra of polyurethanes. (a) PCL series, (b) PEO series.

ester band from 1735 cm^{-1} in the amorphous PCL 530 polyurethane to 1724 cm^{-1} in the semicrystalline PCL1250 and 2000 polyurethanes. Carbonyl stretching frequencies are typically lowered

in crystalline solids because of lattice field effects and association.²⁸ However, a shoulder at 1735 cm^{-1} remains because of the presence of noncrystalline ester functionalities. It is apparent that



(a)



(b)

Figure 3 FTIR absorbance spectra of carbonyl stretching region of the polyurethanes. (a) PCL series, (b) PEO series.

although relatively bulky side chain groups were located adjacent to the urea functionalities, these groups were still able to participate in hydrogen

bonding interactions as noted by the H-bonded urea shoulder at $\approx 1650\text{ cm}^{-1}$. A relatively broad shoulder is evident from $1630\text{--}1700\text{ cm}^{-1}$ which

presumably results from both hydrogen bonded and free carbonyl stretching frequencies for urea and H-bonded urethane functionalities. The shape of the carbonyl region is similar to that found by Xiao et al.²⁹ for PCL polyurethanes. A series of peaks may be present here because of the multiple hydrogen bonding interactions possible between the urea and urethane N—H groups and the various carbonyls of both the hard and soft segments.^{30–33} For the PCL series of polyurethanes, the relative size of the bands attributed to free and H-bonded urethane and urea carbonyls increases with decreasing PCL molecular weight, as expected, because decreasing PCL molecular weight leads to increasing relative hard segment content and thus increasing urethane and urea content.

Analysis of the N—H stretching region [Fig. 4(a)] of the PCL polyurethanes indicates that the N—H band shifts from $\approx 3375\text{ cm}^{-1}$ for both the PCL1250 and 2000 polyurethanes to 3365 cm^{-1} for the PCL530 polymer. This suggests that the PCL530 polymer's urea and urethane N—H groups are hydrogen bonded to a greater degree than the PCL1250 and 2000 ones.²⁸ However, the enhanced phase mixing noted for the PCL530 polymer by DSC would indicate that the hydrogen bonding noted for the N—H groups is largely of the urea and urethane to soft segment ester variety.

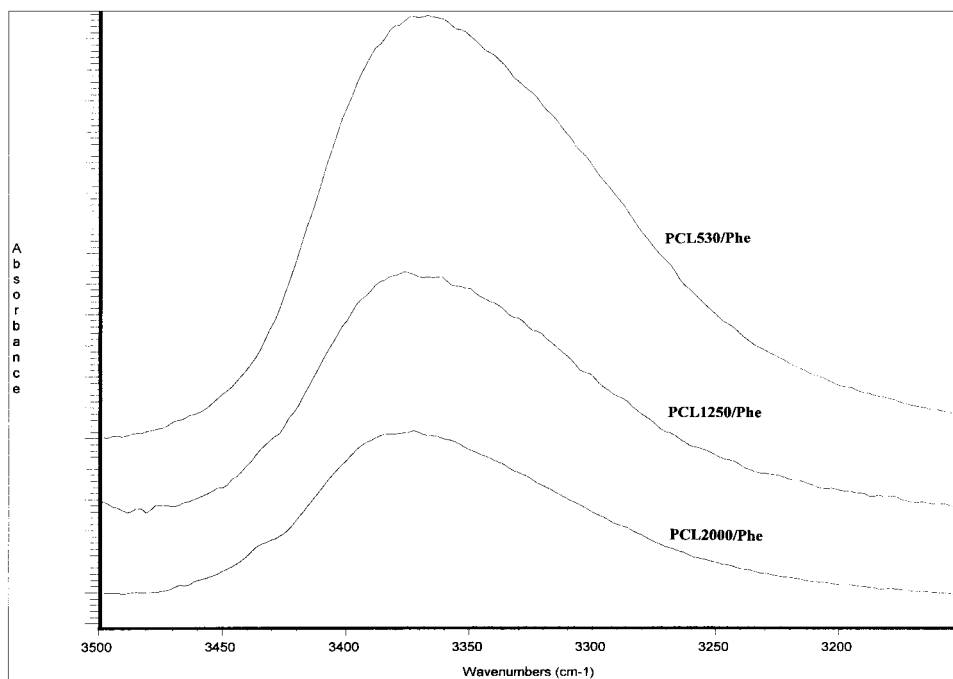
The PEO containing polyurethanes also exhibit increasing urea and urethane bands as PEO molecular weight is decreased [Fig. 2(b)]. Again, it appears that a significant number of the urea and urethane carbonyl groups are hydrogen bonded as noted by the bands at 1650 and 1700 cm^{-1} , respectively [Fig. 3(b)]. However, the N—H bands shift from 3348 to 3334 cm^{-1} as the PEO molecular weight is increased from 600 to 1000, indicating increasing hydrogen bonding [Fig. 4(b)]. In addition, the PEO 1000 polyurethane does not exhibit a significant band at 1650 cm^{-1} [Fig. 4(b)], indicating a lack of H-bonded urea carbonyl functionalities. Therefore, the increased hydrogen bonding noted for the N—H region must be primarily attributed to urethane hydrogen bonding interactions with the ether and ester functionalities of the polymer. The lack of urea hydrogen bonding in this polymer is confusing, but may result from branching or biuret formation caused by the presence of significant quantities of water in the reaction medium. Thus, it appears that the synthesis of PEO containing polyurethanes of a specified stoichiometry may be difficult and in-

creasing the PEO molecular weight further exacerbates the problem.

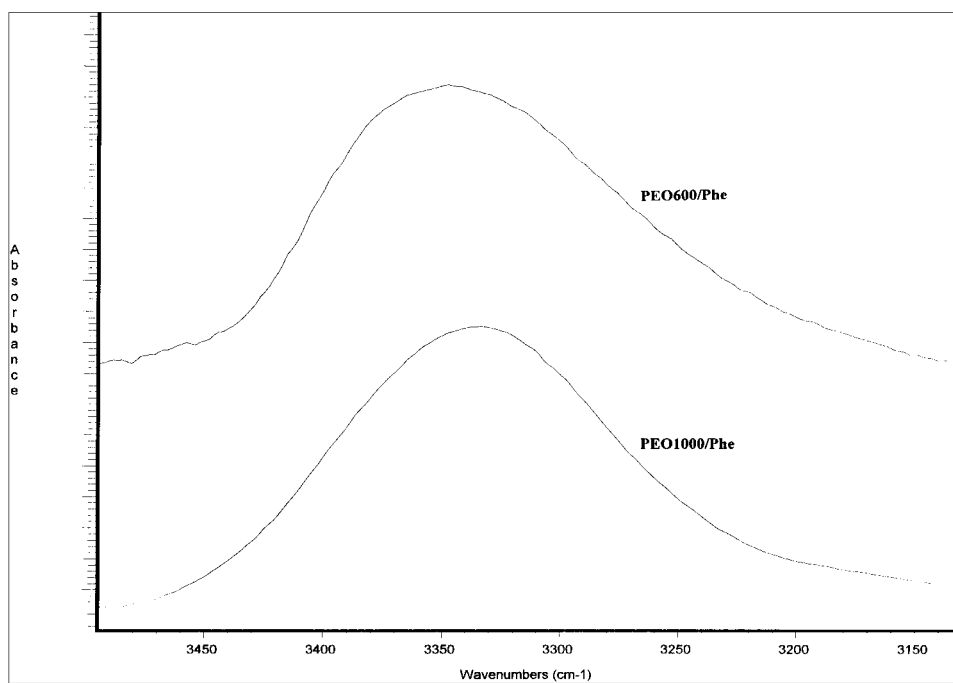
Stress-strain curves for the PCL-based polyurethanes are shown in Figure 5. The shape of the curves for PCL1250 and PCL2000 polymers are typical for semicrystalline polymers above their T_g , in agreement with DSC results.¹⁹ These polymers display a pronounced yield point followed by necking and drawing indicative of semicrystalline PCL polyurethanes.^{22,34} In contrast, the completely amorphous PCL530 polyurethane displays a smooth transition in stress-strain behavior from the elastic to plastic deformation regions similar to lightly crosslinked rubbers.²⁴

Uniaxial stress-strain testing results are given in Table III. No tensile data was collected for the PEO-based polyurethanes because they were too weak and tacky to handle and prepare for analysis. The data collected on the PCL polyurethanes indicates that ultimate tensile strength, initial modulus, and ultimate strain all increase with increasing PCL molecular weight. This result was somewhat surprising, because segmented polyurethane elastomers typically exhibit decreasing ultimate tensile stress and initial modulus with increasing soft segment content. Increasing PCL molecular weight leads to increasing polyurethane molecular weight (Table I) and this may be expected to result in increasing tensile properties, as observed. However, previous research has indicated that increasing total polymer molecular weight above 25,000 has little effect on resulting polyurethane elastomer physical properties.¹⁴ Thus, the increasing polymer molecular weight with PCL content is not believed to be the cause of the trend noted in the tensile properties.

The trend of increasing tensile properties with increasing soft segment content could be attributed to three factors. First, the lack of hard segment crystallization, because of the asymmetric diisocyanate and large side chain containing chain extender, reduces the ability of the hard segment to act as a reinforcing filler or physical crosslinking site. Thus, increasing the hard segment content by decreasing the soft segment molecular weight may not be expected to significantly impact the ultimate mechanical properties. Second, the presence of soft segment crystallization at 1250 and 2000 molecular weight may have an overriding effect on the overall polymer tensile strength and stiffness. Soft segment crystal structures may act as physical crosslinks in a manner similar to that normally ascribed to the hard segment. As was noted by DSC, increasing PCL mo-



(a)



(b)

Figure 4 FTIR absorbance spectra of N—H stretching region of the polyurethanes. (a) PCL series, (b) PEO series.

lecular weight leads to increasing crystal content and thus presumably increasing tensile properties. Yen and Cheng³⁵ have shown that increased

polyester soft segment (polybutylene adipate glycol) crystallinity with increased molecular weight resulted in both increased ultimate tensile

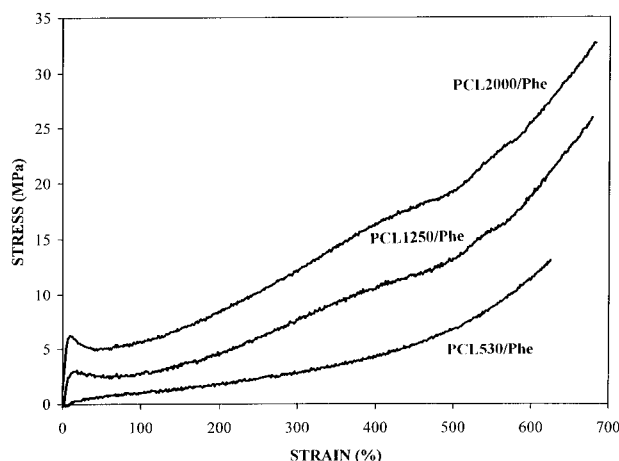


Figure 5 Uniaxial stress-strain curves for PCL polyurethanes.

strength and ultimate elongation as seen herein. Finally, the increasing degree of phase separation noted with increasing PCL content may also significantly impact the resultant tensile properties. Increasing phase separation has been found to lead to enhanced tensile properties for both polyether- and polyester-based polyurethanes and this phenomenon is believed to result from the increased hard domain cohesion which results from a phase segregated morphology.³⁴ The importance of both soft segment crystallinity and phase separation is highlighted by the low tensile properties of the PCL 530 polyurethane. This polyurethane is significantly weaker than the more phase-separated semicrystalline polyurethanes (PCL1250 and 2000) although it has the highest hard segment content (62% vs 41% and 30%, respectively).

A comparison of PCL1250 polymers containing HDI and LDI is also given in Table III. No significant difference in ultimate tensile strength was observed. However, both the ultimate strain and initial modulus were significantly reduced in the HDI containing polyurethane. The cause of the

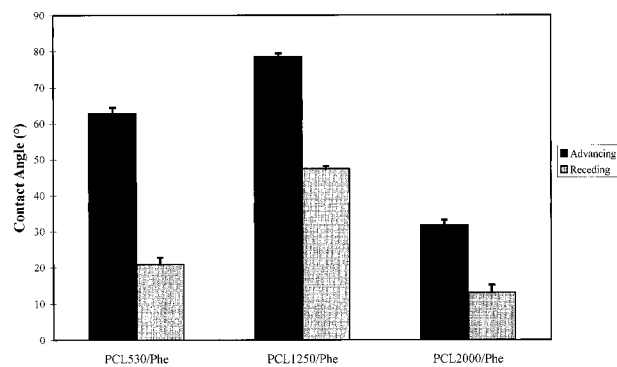


Figure 6 Advancing and receding water contact angle data (mean \pm SD, $n = 10$).

enhanced stiffness and elongation of the LDI containing polymer is unclear. The LDI containing polymer has a slightly higher hard segment content than the HDI containing polymer (40.6 vs 34.8%, respectively) and this may be expected to lend slightly greater strength. However, hard segment content alone was not found to be a determining factor for the mechanical properties of the LDI-based polyurethanes of varying PCL molecular weight, as discussed above. Previous reports have indicated that using side chain containing molecules in the hard segment leads to increased phase mixing, as evidenced by elevated soft segment T_g values,²⁴ which may lead to weaker materials. However, in this case, the LDI and HDI polyurethanes display similar soft segment T_g values, indicating similar levels of phase separation (-34.2 and -33.1°C , respectively). The inclusion of a methyl ester side chain in LDI may serve to strengthen the polymer by providing an additional site in the hard segment for hydrogen bonding. In addition, use of LDI leads to higher crystalline content (40.8% for LDI vs 34.8% for HDI polyurethanes containing PCL1250 and Phe-based chain extender) which can also result in enhanced tensile properties.^{26,34}

Contact angle data is given in Figure 6. The

Table III Tensile Properties of Polyurethanes (mean \pm SD, $n = 8$)

Polymer	Tensile Strength (MPa)	Ultimate Strain (%)	Initial Modulus (MPa)
PCL530/Phe	12.5 \pm 2.7	618 \pm 39.0	6.6 \pm 0.8
PCL1250/Phe	25.8 \pm 1.6	682 \pm 26.9	54.3 \pm 9.4
PCL2000/Phe	30.8 \pm 2.7	676 \pm 8.8	81.9 \pm 4.3
PCL1250/HDI/Phe	28.0 \pm 3.9	580 \pm 22.0	20.2 \pm 3.8

Table IV Angle-Resolved XPS Data for Polyurethanes (Data Precision \pm 10%)

Polymer	Take-Off Angle	C 1s	N 1s	O 1s	Si 2p	C—C	C—O	O—C=O
PCL530/Phe	20	76.7	2.6	19.0	1.7	47.2	43.0	9.8
	30	75.1	4.0	20.7	0.2	55.0	32.5	12.5
	90	73.6	4.7	21.5	0.2	60.7	24.5	14.8
PCL1250/Phe	20	77.2	1.5	20.0	1.3	67.4	24.2	8.4
	30	77.1	2.1	20.2	0.6	56.5	32.1	11.4
	90	75.2	2.7	21.8	0.3	56.5	30.5	13.0
PCL2000/Phe	20	79.9	1.1	18.0	1.0	70.8	19.5	9.7
	30	80.8	1.3	17.7	0.2	64.7	24.9	10.4
	90	78.2	1.9	19.9	0.0	64.6	23.4	12.0
PEO600/Phe	20	73.6	5.4	20.5	0.5	54.6	36.2	9.2
	30	72.5	6.2	21.2	0.1	49.6	40.4	10.0
	90	70.3	6.4	23.3	0.0	39.2	48.8	12.0
PEO1000/Phe	20	70.3	4.1	24.7	0.9	42.3	47.4	10.3
	30	69.2	4.9	25.6	0.3	40.9	47.6	11.5
	90	66.3	5.3	28.3	0.1	34.7	50.9	14.4

PCL containing polyurethanes exhibit variable advancing contact angles, ranging from \approx 30 to 80°, suggesting significant differences in surface hydrophilicity. Contact angles for the PEO polyurethanes could not be measured because these films spontaneously deformed at the contact line, thereby making any readings impossible. The deformation of the PEO polyurethane films at the contact line presumably results from the fact that these soft, tacky polymers were physically unable to resist the contractile force resulting from the surface tension of the liquid droplet.³⁶ The amount of hysteresis between advancing and receding contact angles is similar for the PCL polyurethanes, indicating similar propensity for surface reorientation upon exposure to the polar water droplet, although other factors may affect hysteresis such as roughness and swelling.³⁷

The PCL polyurethanes appear to exhibit a maximum in advancing and receding contact angles at PCL1250. Similar results were described for analogous HDI containing polyurethanes, although the values are quantitatively different.¹³ It is hypothesized that the trend noted in contact angles with PCL molecular weight results from two competing phenomena. First, it was noted by DSC that phase separation increases with increasing PCL molecular weight and XPS results described below indicate PCL surface enrichment. Thus, increasing phase separation may be expected to lead to a “purer” PCL surface region. Because PCL is hydrophobic in comparison with the polar hard segment, increasing its content at

the surface would be expected to lead to increasing contact angles. However, DSC analysis indicated that increasing PCL molecular weight leads to increasing soft segment crystallinity. The increase in crystalline content at the surface may be expected to lead to increased surface free energy and thus decreased contact angles. Thus, the competing effects of phase separation and soft segment crystallinity may explain the results observed. As PCL molecular weight increases, phase separation increases leading to a “purer” PCL enriched surface region, which causes an increase in contact angle. However, at PCL2000 the degree of surface phase separation and PCL chain length is sufficient to allow significant surface PCL crystallinity, which leads to a reduction in contact angle. Preliminary atomic force microscopy observations appear to support the interpretation given above. Atomic force microscopy shows apparent spherulitic structure at the surface of the PCL2000 but not the PCL1250 polyurethane.

Elemental surface analysis provided by XPS is given in Table IV. The take-off angle was varied (90, 30, and 20° relative to the surface) to obtain a compositional depth profile. Because nitrogen is present in the hard segment only, nitrogen content can be used to indicate the relative amount of hard and soft segment in the surface region. Table IV shows decreasing nitrogen content with decreasing depth of analysis for all polymers, indicating soft segment surface enrichment. In addition, decreasing soft segment content (resulting

from decreasing soft segment molecular weight) leads to increasing nitrogen content indicating increasing hard segment content, as expected. The depth dependence of hard segment content also indicates the presence of a phase-separated morphology for all of the polyurethanes studied herein. The substantially higher nitrogen surface content noted for the PEO polyurethanes may be indicative of two phenomena. First, the PEO soft segment may exhibit a lower surface activity than the PCL soft segment, particularly in the high vacuum environment of XPS. This would lead to an elevated hard segment, and therefore nitrogen, content at the surface. Several other researchers have noted a reduced tendency for PEO to concentrate at the surface region under XPS measurement conditions.^{38,39} Second, the possibility for increased nitrogen content due to branching and urea forming side reactions because of the presence of water in the reaction vessel must be acknowledged. These undesirable side reactions which were indicated by FTIR as well as low molecular weights would likely result in the introduction of a higher than predicted proportion of nitrogen into the polyurethane chains.

The high-resolution carbon 1s data shows a trend of decreasing contribution of the urea/ester/urethane component with decreasing depth of analysis. This data provides additional evidence for the depletion of hard segment domains at the polymer surface, at least in the vacuum environment of XPS. It is important to note that the hard segment surface depletion noted by XPS might not be indicative of the surface composition which prevails in an aqueous biological environment. Previous research indicates that polyurethane surfaces are mobile and able to rearrange in response to a change in environment.⁴⁰ The rearrangement serves to reduce the surface free energy of the system. Thus, in a polar aqueous environment, surface reorientation should result in the preferential placement of polar hard segment domains at the interface. Because the hard segment contains hydrolyzable ester bonds, the speed of degradation will likely be impacted by the amount of these groups at the surface, particularly for surface mediated enzymatic degradation.

CONCLUSIONS

Linear biodegradable polyurethane elastomers containing a lysine methyl ester derived diisocya-

nate were synthesized and subsequently characterized. Polyurethanes containing polycaprolactone and polyethylene oxide soft segments exhibited a wide range of physicochemical properties. Increasing soft segment molecular weight generally led to increasing phase separation and crystallinity (for PCL polyurethanes). The PEO polyurethanes were soft, tacky materials. In contrast, the PCL polyurethanes were high molecular weight materials of low hydrophilicity and good tensile strength. PCL polyurethane properties were found to depend strongly on soft segment crystallinity and overall phase separation which both increased with increased PCL content. The use of both an asymmetric diisocyanate and a bulky side chain containing chain extender combine to effectively inhibit any hard segment crystallinity. However, the significant hydrogen bonding of the urea and urethane carbonyls noted by FTIR spectroscopy as well as soft segment T_g values obtained by DSC indicate that the polyurethanes were phase segregated to varying degrees. The wide range of material properties that were achieved through relatively minor modifications in chemistry, as well as the use of a potentially nontoxic diisocyanate, makes these degradable polymers useful for a variety of biomaterials applications. Further investigations into the polyurethane degradation rates in both buffer and enzyme solutions, as well as other physical characteristics such as water uptake and water vapor permeance are currently under investigation.

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