Enhanced Hydrolytic Stability of Poly(*p*-dioxanone) with Polycarbodiimide

Zhong-Ping Liu, Song-Dong Ding, Ying-Jia Sui, Yu-Zhong Wang

Center for Degradable and Flame-Retardant Polymeric Materials, College of Chemistry, Key Laboratory of Green Chemistry and Technology (Ministry of Education), Sichuan University, Chengdu 610064, People's Republic of China

ABSTRACT: The effect of polycarbodiimide (PCD) on hydrolytic stability of poly(*p*-dioxanone) (PPDO) was investigated by hydrolytic degradation of PPDO and PPDO added with PCD (PPDOCD) in phosphate buffer solution (pH = 7.4) at 37°C. The variation of weight, water absorption, pH, molecular weight, tensile properties, surface morphologies, and thermal properties with degradation time were evaluated. After 11 weeks, the weight loss and water absorption of PPDO was 24 and 30%, respectively, but the corresponding values were only 3 and 5% for PPDOCD5, where 5 represents the weight percentage of PCD added; the molecular weight of PPDO decreased much faster than that of PPDOCD. The pH of the solution was monitored for 15 weeks and a final pH value of the solution involving PPDOCD5 was 6.81 whereas that of PPDO solution was 3.77, indicating that more acid fragments from PPDO samples migrate into the buffer solution. Surface morphological changes showed a better physical integrity for PPDOCD samples and they also kept their mechanical properties for a longer time than PPDO samples. These results revealed that PCD can retard the hydrolysis degradation of PPDO and enhance its hydrolytic stability. © 2009 Wiley Periodicals, Inc. J Appl Polym Sci 112: 3079–3086, 2009

Key words: poly(*p*-dioxanone); polycarbodiimide; degradation; hydrolysis; stabilization

INTRODUCTION

Poly(*p*-dioxanone) (PPDO) is a degradable poly(ether-ester) with good biocompatibility and mechanical properties.[1] It has been used in medical field such as sutures, bone repair devices, and drug delivery systems.[2–4] During recent years, owing to the great progress on the catalytic synthesis technology of *p*-dioxanone (PDO) monomer from diethylene glycol,[5] the production cost of PDO and its polymer PPDO decreased significantly. PPDO has been viewed as a candidate not only for medical use but also for general applications such as film, molded products, laminates, foams, unwoven materials, adhesives, and coatings.[6] However, because of its sensitivity to moisture, it is not used in other fields except for medical field now. Even in air atmosphere, it will completely lose its mechanical performance in a short time (about several weeks). For PPDO sutures, about 76% of its original tensile strength was lost after 28 days degradation in phosphate buffer solutions of pH 7.44 at 37°C.[7] Ooi and Cameron[8] presented a two-stage model for PPDO suture degradation in phosphate buffer solution (pH = 7.4) at 37°C. In this model, scission of tie chains begins in the first (dormant) stage as soon as the chains are hydrated and progresses at a faster rate in the second (active) stage; in the active stage, the effects of chain scission on the physical properties become measurable and the fiber starts to lose its tensile properties. This fast degradation rate hampers its applications greatly, especially as environmental-friendly material. Therefore, it is very important to enhance its hydrolytic stability for widespread availability.

In general, the hydrolytic degradation of PPDO is ascribed to the break of ester bonds under water conditions, generating low molecular weight acid species (Scheme 1) which can further catalyze the scission of ester bonds and accelerate the hydrolysis of PPDO.[9–12] According to this mechanism, if the catalytic activity of acid species is restrained, the hydrolytic stability of PPDO can be enhanced. During recent years, it was found that this suppression can be carried out by means of addition of some additives. For example, carbodiimide compounds have been successfully used for antihydrolysis of poly(ester-urethane), polyethylene terephthalate, and polybutylene terephthalate.[13–16] On the basis of the
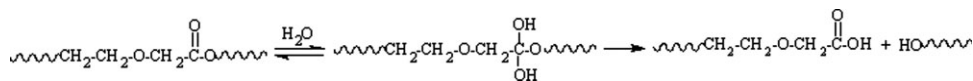
Scheme 1 Hydrolysis process for PPDO in aqueous medium.

good effectiveness obtained, in this article, carbodiimide was employed to improve the hydrolytic stability of PPDO. Among the carbodiimide compounds, one kind of polycarbodiimide (PCD, Scheme 2) was adopted because of its suitable melting point ($M_n = 550$, $T_m = 85°C$, matching with that of PPDO $110°C$), low toxicity as well as no volatility. As far as the authors know, no available data have been reported on antihydrolysis for PPDO by using carbodiimide as stabilizer. To examine its effects on the hydrolytic stability of PPDO, a hydrolysis degradation was performed and the weight loss, molecular weight, pH, thermal properties, morphologies, and mechanical properties were evaluated during the degradation process.

EXPERIMENTAL

Materials and preparation of samples

By reference to literature,[17] PPDO was prepared through ring opening polymerization of PDO in the presence of stannous octoate initiator in bulk at 80°C for 72 h. The crude polymer obtained was milled into powder, which were then purified by removing the unreacted monomers in Soxhlet extractor with toluene and dried under vacuum at 50°C to constant weight. PCD was provided by Jianxin Chemical Factory (Zhenjiang, Jiangsu province, China) and used as received. The samples containing desired weight percentage of PCD (1, 3, and 5%, abbreviated to PPDOCD1, PPDOCD3, and PPDOCD5, respectively) were prepared through the following procedures. First, PPDO was melted in a reactor equipped with a mechanical agitator under nitrogen atmosphere at 130°C. Then PCD in anhydride tetrahydrofuran (THF) solution was added with a syringe. The blend was mixed for 15 min at the above temperature. Finally, THF was removed under vacuum. The blend obtained and PPDO was cut into test samples with the size of $30 \times 10 \times 0.5$ mm^3, after compression molding at a pressure of 10 MPa at 110°C for 2 min and cooling rapidly at room temperature. The samples for mechanical testing were cut into dumb-bell pieces with a size of 5×0.5 mm^2 for the middle cross section.

Degradation conditions

For the hydrolysis degradation, a buffer solution (0.2 mol/L, based on KH_2PO_4 and Na_2HPO_4) with an initial pH of 7.4 was used for hydrolysis medium. Samples were placed in test tubes containing the buffer solution (1.0 g samples in 25 mL buffer solution for each test tube), which were in turn placed into a thermostatic oven at a temperature of 37°C for predetermined time periods.

### Determination of weight loss, water absorption, and pH

Before immersed in the buffer solution, each sample was weighed on an AL204 analytical balance (Mettler Toledo Corporation, Swiss). Each week, samples were taken out of the hydrolysis medium and rinsed with distilled water to remove the phosphate. After wiping, the samples were weighed and dried under vacuum at ambient temperature to constant weight. Total remaining weight and water absorption were calculated from the following relationships: weight retention % = W_r/W_i, water absorption % = $(W_w - W_r)/W_r$, with W_i and W_r representing the initial and remaining weights of the dried samples, and W_w representing the wet weight of the samples after wiping. The pH changes were measured by a Leici pH meter (Shanghai precision and scientific instrument Co. LTD. China).

Intrinsic viscosity

PPDO with middle or high molecular weight cannot be measured by gel permeation chromatography (GPC) due to its poor solubility in the common solvents employed to perform GPC at room temperature. Therefore, Ubbelohde viscometer was employed to determine the viscosity average molecular weight. The tests were performed at 25°C with phenol/1,1,2,2-tetrachloroethane (2 : 3, $w : w$) as solvent.

Infrared analysis

The infrared absorption spectra were performed on a FTIR 170SX infrared spectrometer (Thermo Nicolet Corporation, Wisconsin) using KBr wafer.
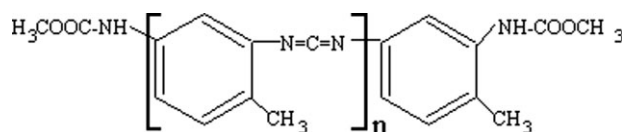
Scheme 2 Chemical structure of PCD.
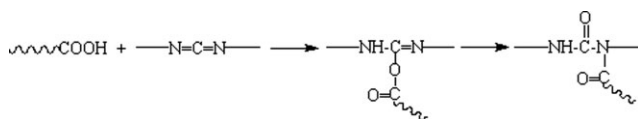
Scheme 3 Reaction of carboxyl acid with carbodiimide.

Tensile strength

An Instron 4302 mechanical tester with a load cell of 500-N (Instron Corporation, Massachusetts) was employed to perform the tensile tests. After drying under vacuum, the samples were tested at room temperature. The crosshead speed was 30 mm/min and the gage length was 20 mm. Four samples per hydrolysis week were tested.

Scanning electron microscopy

Scanning electron microscopy (SEM) evaluation was carried out to examining the surface morphology of the samples. A SEM JSM-5900LV (JEOL Corporation, Japan) was used to observe the surfaces of the gold sputter-coated samples.

Differential scanning calorimetry

A differential scanning calorimetry (DSC) Q100 apparatus (TA Corporation, Delaware) was used to determining the changes in melting characteristics (the melting temperature and the heat of fusion) of the samples with the hydrolysis time. Tests were carried out under an ultrahigh purity nitrogen atmosphere. Samples (7–10 mg) were placed in aluminum pans and a study of the thermal history (first heating scan) from 40 to 140°C at a scanning rate of 10°C /min was performed.

RESULTS AND DISCUSSION

Degradation

The ester bonds in PPDO molecules, which are sensitive when suffering from water, can hydrolyze and generate low molecular weight acid products.[9–11] During the hydrolysis process, the acid molecules can migrate to the surface of the samples and perhaps dissolve in aqueous medium, resulting in a decrease in pH of the solution. If these carboxyl groups exist in polymers, they will be scavenged by the carbodiimide groups (Scheme 3) and a slower decrease in pH of the solution can be detected.[13] To confirm this presumption, pH of the buffer solution was monitored and the results are shown in Figure 1. With the increase of hydrolysis time, pH values of all samples decreased. The pH value decreased slowly in the first few weeks for the solution of PPDO sample. After the initial 4 weeks, pH
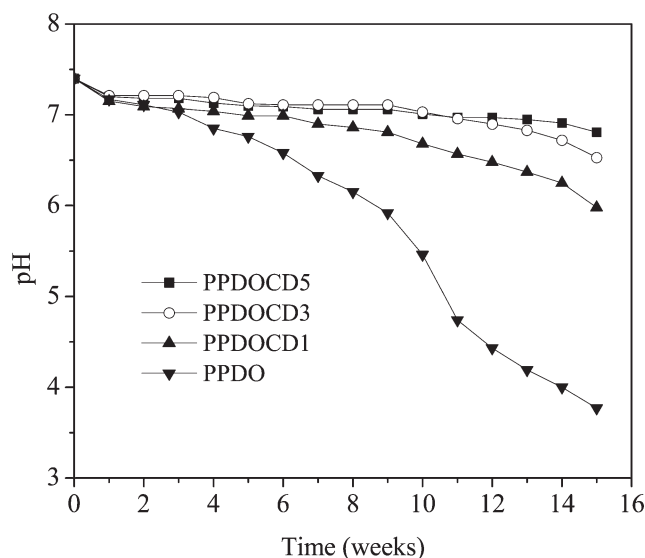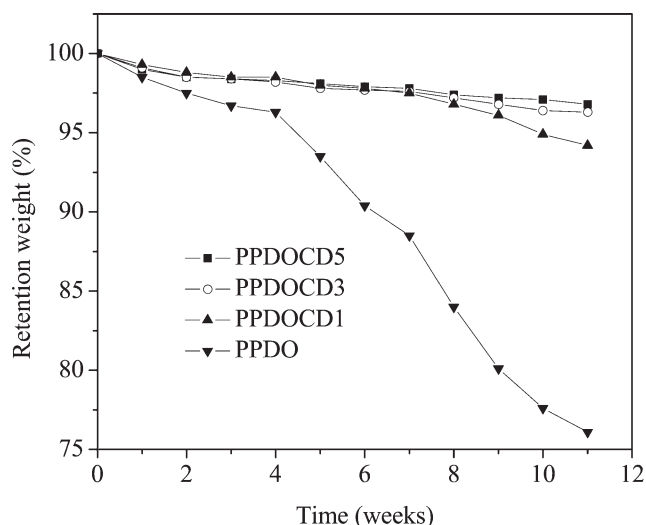

Figure 1 Variation of solution pH during the hydrolysis of PPDO and PPDOCD samples in phosphate buffer solution (pH = 7.4) at 37°C as a function of hydrolysis time.

decreased rapidly and a sharp drop occurred from 9th to 11th week. A final pH value of 3.77 was obtained after 15 weeks. This result is similar to that reported by Sabino et al.[9,10] The decrease of pH value suggested that the hydrolysis of PPDO produces acid molecules with low molecular weight. It is also seen from this drop that the degradation accelerated after 4th week, probably because of the autocatalysis of carboxyl groups.[12] When compared with the fast decrease in pH of PPDO, that of PPDOCD decreased slowly, indicating a reduction of acid soluble molecules in the medium. During the initial 11 weeks, the pH values of PPDOCD5 and
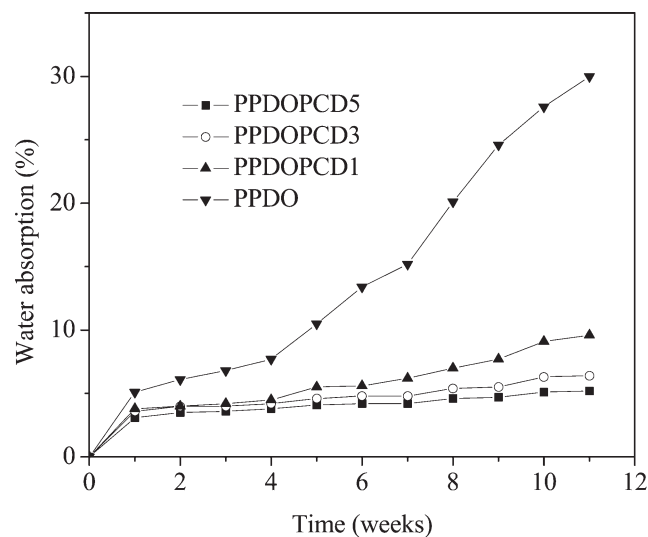
Figure 2 Variation of water absorption during the hydrolysis of PPDO and PPDOCD samples in the phosphate buffer solution (pH = 7.4) at 37°C as a function of hydrolysis time.

Figure 3 Variation of retention weight during the hydrolysis of PPDO and PPDOCD samples in phosphate buffer solution (pH = 7.4) at 37°C as a function of hydrolysis time.

PPDOCD3 changed a little, only from 7.20 at 1st week to 6.97 at 11th week, but after that time, PPDOCD3 had a higher degradation rate than PPDOCD5. In the whole process, PPDOCD1 degraded faster than PPDOCD5 and PPDOCD3, to a pH value of 5.98 after 15 weeks. From these results, a conclusion can be drawn that better hydrolysis resistance can be achieved with more content of carboxyl scavenger PCD.

When the samples are in contact with the aqueous medium, water absorption is the first thing. Figure 2 shows the evolution of water absorption with degradation time. As can be seen from this figure, there was a dramatic increase of water absorption for PPDO from 4th to 11th week and 30% of water absorption had attained after 11 weeks; whereas PPDOCD5, PPDOCD3, and PPDOCD1 had a water absorption of 5, 6, and 10%, respectively, in the same time span.

After water diffuses into the samples, hydrolysis of ester bonds begins and then the low molecular weight molecules (oligomers) produced in the hydrolysis degradation dissolve in the aqueous medium, leading to a weight loss of the samples. Weight loss is a simple evaluation for the hydrolysis progress of PPDO during the exposure to hydrolytic medium. Figure 3 shows the retention weight of the samples as a function of degradation time. After 11 weeks, PPDO had a weight loss of 24%. This result is in good concordance with that reported by Sabino et al.[10] who found a weight loss of 25% after 10 weeks of degradation in phosphate buffer solution of pH 7.44 at 37°C. During the period investigated, PPDO lost its weight faster than the PPDOCD samples, especially after 4th week. The weight loss of

PPDOCD5, PPDOCD3, and PPDOCD1 were 3, 4, and 6%, respectively, after 11 weeks. Before 7th week, the three samples showed little difference, but after that time, PPDOCD1 lost its weight faster than the others because of the exhaustion of PCD which can be confirmed by FTIR analysis. In Figure 4(a) showing the FTIR spectra of PCD, the absorption bands at 3324, 1710, and 1229, 1066 cm^{-1} are attributed to the vibrations of N—H, C=O, and C—O—C groups, respectively. The peaks at 1594, 1527, and 2133 cm^{-1} are the characteristic absorption of phenyl group and carbodiimide group, respectively. In Figure 4(b,c), the absorption bands of terminal O—H, C=O, and C—O—CO—H groups in PPDO, are located at 3430 (3452), 1732 (1732), and 1206 (1203), 1123 (1126) cm^{-1}, respectively. The peaks at 1626 (1616) and 1530 (1530) cm^{-1} are the characteristic absorption of phenyl group introduced by the addition of PCD. After 6 weeks of hydrolysis, the disappearance of absorption band of carbodiimide group at 2133 cm^{-1} was clearly observed, which indicates that PCD has been exhausted during the hydrolysis of PPDO.

Another important indication of hydrolysis is the change of molecular weight. In this work, intrinsic viscosity was employed to illustrate the viscosity average molecular weight (M_v) of PPDOCD and PPDO samples (Mark-Howwink constants $k = 79 \times 10^{-3}$ and $\alpha = 0.69$ can be used to calculate the M_v of PPDO,[9] whereas the M_v of PPDOCD cannot be calculated by the constants used for PPDO because of PPDOCD being a blend). The intrinsic viscosity changes of the samples as a function of degradation time are plotted in Figure 5. As can be observed, the intrinsic viscosity of PPDO dropped rapidly from 1.45 dL/g at origin to 0.57 dL/g at 2nd week, and
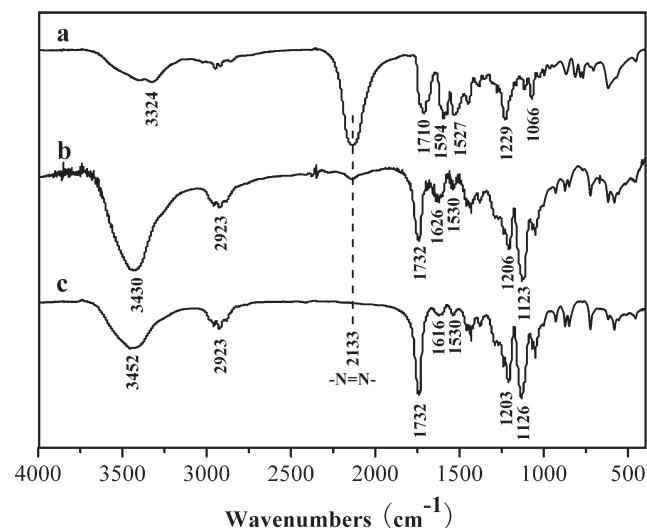
Figure 4 FTIR spectra of PCD (a), PPDOCD1 at origin (b), and PPDOCD1 after hydrolysis for 6 weeks (c).
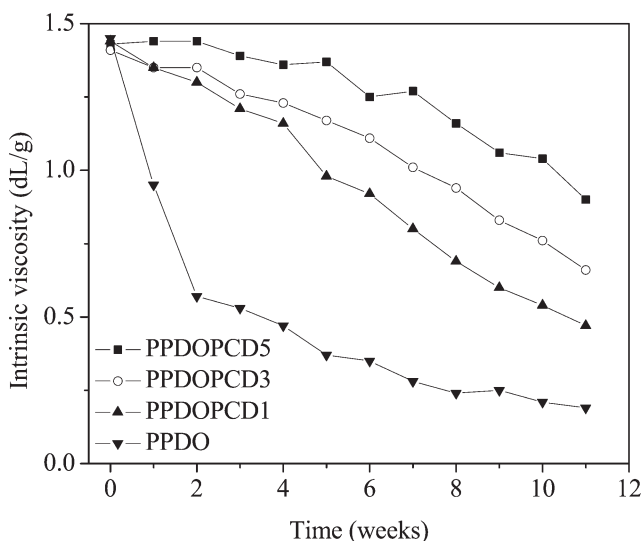
Figure 5 Variation of intrinsic viscosity during the hydrolysis of PPDO and PPDOCD samples in phosphate buffer solution (pH = 7.4) at 37°C as a function of hydrolysis time.

then decreased slowly. Similar results have been reported previously for PPDO and for other aliphatic polyesters such as polylactic acid and poly (lactic-co-glycolic acid) copolymers.[9,10,18,19] Compared with PPDO, the intrinsic viscosity of PPDOCD decreased slowly during the hydrolysis process. PPDOCD5 almost kept at a nearly stable level at the initial 5 weeks and then decreased slowly from 1.37 to 0.90 dL/g after 11 weeks.

These changes in pH, water absorption, weight loss, and intrinsic viscosity clearly show that the hydrolysis of PPDO occurs. As others have suggested, the degradation initially occurs in the amorphous areas, resulting in scission of chains (a decrease in molecule weight shown).[8–10] Further hydrolysis produces fragments of molecular chains (oligomers) which are soluble in the hydrolysis medium. When the degraded fragments diffuse and dissolve in the medium, a weight loss of the samples and decrease of pH of the solution occurs at the same time. This migration of fragments encourages the absorption of water as water fills the spaces left behind. For the hydrolysis of PPDO in the initial 4 weeks, only molecular weight had a sharp drop, whereas after 4th week, rapid weight loss, pH decrease, and water absorption increase indicated that lots of degraded fragments dissolved in the medium.

From the above results, it was found that PCD played a role of suppressing the hydrolysis of PPDO. This phenomenon can be explained as lowering the autocatalysis effect of carboxyl groups on breaking ester bonds because of the reaction between the carbodiimide groups and carboxyl groups.

Tensile properties

Mechanical properties are considered to be very important for materials. In this study, dried samples were tested to exclude the influence of water which can be considered as a plasticizer, though the ones in wet conditions are of practical significance. Figure 6 indicates the breaking strength and elongation of the samples as a function of hydrolysis time. Here, PPDOCD1 and PPDO were tested. The samples of PPDO after 4 weeks and PPDOCD1 after 6 weeks cannot be tested because of their fragility. Figure 6(a) shows that tensile breaking strength of PPDO kept a nearly constant value for 1 week and then dropped dramatically, whereas PPDOCD1 kept at a nearly stable stage for 4 weeks and then dropped a lot, too. From Figure 6(b), it can be seen that the
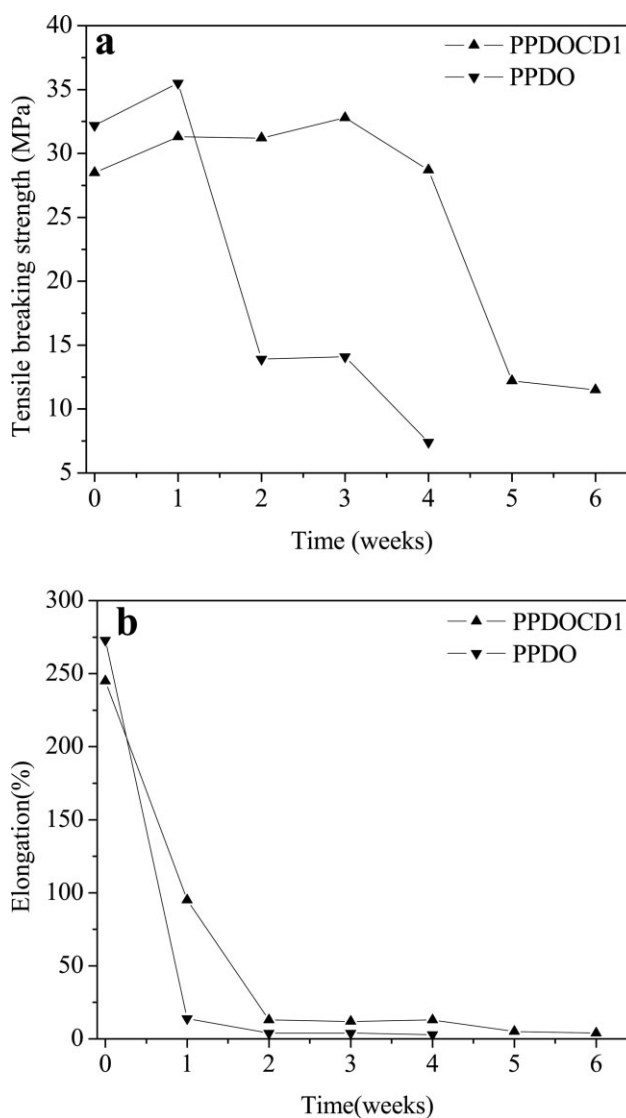
Figure 6 Variation of tensile properties of PPDO and PPDOCD1 during the hydrolysis process in phosphate buffer solution (pH = 7.4) at 37°C as a function of hydrolysis time: (a) breaking strength and (b) elongation.
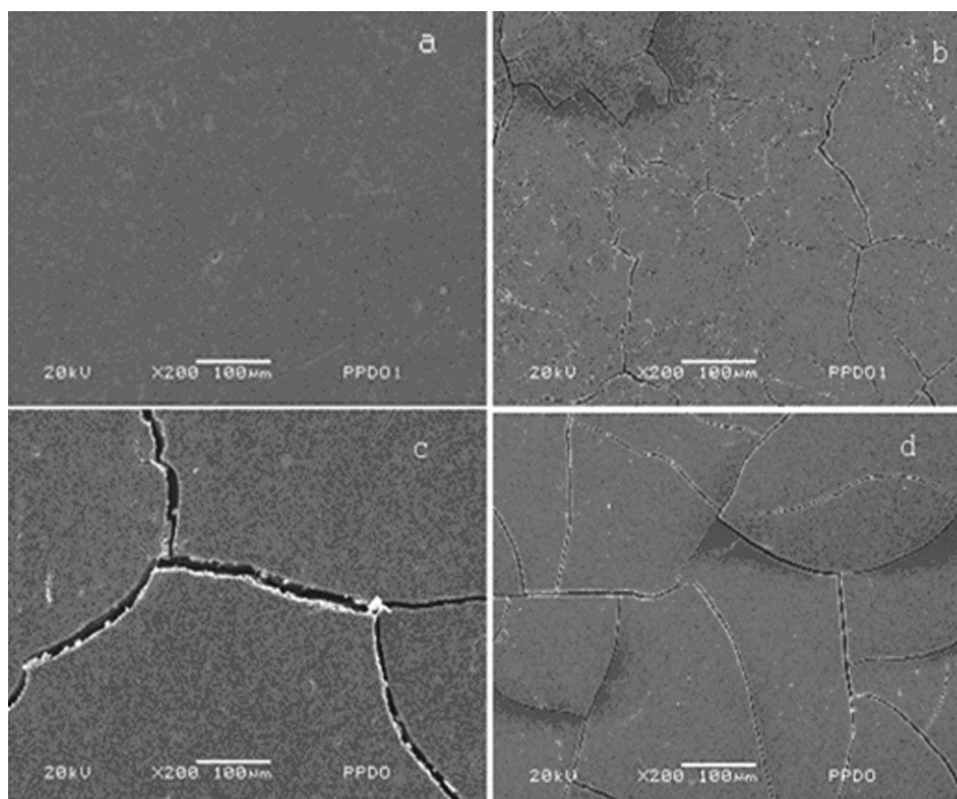
Figure 7 SEM micrographs of PPDO and PPDOCD1 during the hydrolysis in phosphate buffer solution (pH = 7.4) at 37°C: (a) PPDOCD1 after 7 weeks, (b) PPDOCD1 after 10 weeks, (c) PPDO after 5 weeks, and (d) PPDO after 7 weeks.

elongation of PPDO ranged from 270% at origin to 14% at 1st week, whereas that of PPDOCD1 changed from 245% to about 100% in the same time span and after 2 weeks decreased dramatically, too. This result can be explained as follows. PPDO is a semicrystalline polymer. The crystalline regions contribute to the materials strength and inflexibility and the amorphous regions contribute to the materials flexibility, particularly when the material is above its T_g.[20] The rapid drop in tensile strength and elongation was caused by the deterioration of amorphous regions. In the initial hydrolysis stage, the scission of ester linkages produces short chains, which may reorganize themselves and induce further crystallization at the temperature above T_g of PPDO (about −10°C). The further crystallization and deterioration of amorphous regions makes the materials fragile and results in a decrease of elongation, but in the early stage, a nearly constant tensile strength may be obtained if there are enough tied chains in the amorphous regions, which can support and transmit tensile loads to the crystalline regions.[20] While the amorphous areas are destroyed severely, tensile strength decreases simultaneously.

As mentioned earlier, PCD can suppress the autocatalysis of carboxyl groups, so it made the intrinsic viscosity decreased slowly and the tensile strength kept at a constant stage for a longer time. With the hydrolysis proceeding, the carbodiimide groups are gradually consumed because of the reaction with carboxyl groups. When the carbodiimide groups drop to a low level, their effects are not enough to scavenge the large amount of broken acid molecules and the hydrolysis degradation accelerates, so the tensile breaking strength of PPDOCD1 decline sharply as PPDO.

Scanning electronic microscopy

While the hydrolysis progresses, the fragments of chains involved in this hydrolysis can migrate to the aqueous medium (translating into a weight loss in the samples) or they can incorporate into the crystal, thanks to the mobility induced by the test temperature (37°C, above T_g of PPDO), leaving empty spaces on the surface (cracks).[9] If PCD can inhibit the hydrolysis of PPDO, there will be less fragments produced and less cracks detected. So some morphological differences probably exist between PPDO and PPDOCD samples as the hydrolysis proceeds. The surface morphology was examined by SEM and the graphs are shown in Figure 7. After 5 weeks, small cracks were detected on the surface of PPDO samples, and more cracks were produced after 7 weeks, indicating that water diffusion to the inside occurred to particular regions, especially the
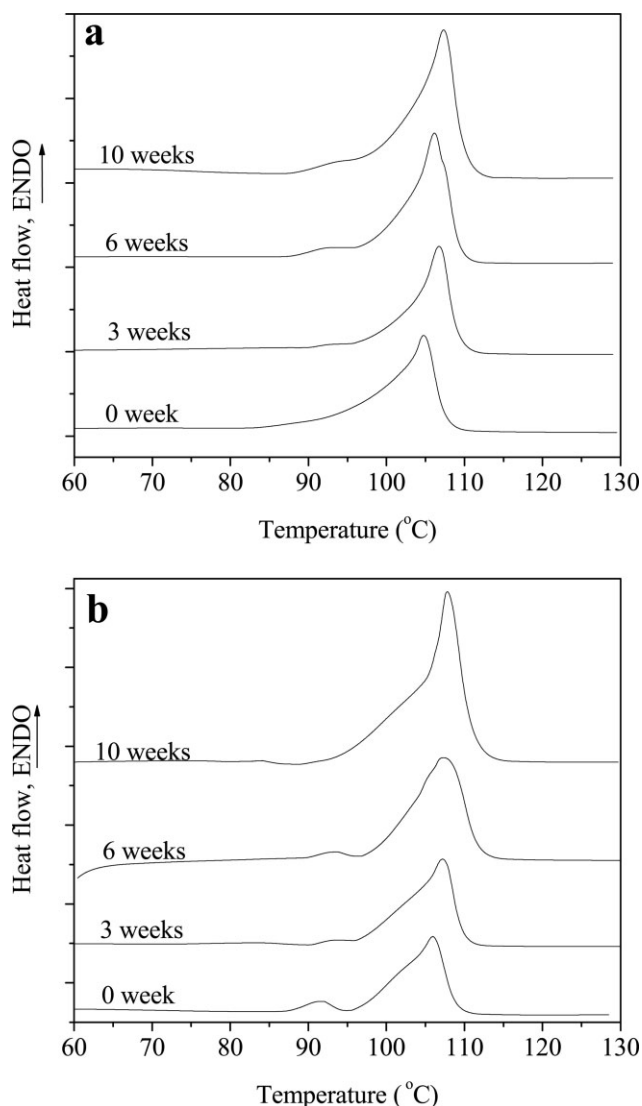
Figure 8 DSC heating curves during the hydrolysis process in phosphate buffer solution (pH = 7.4) at 37°C: (a) PPDO and (b) PPDOCD1.

amorphous regions.[9,21] Whereas, on the surface of PPDOCD1 samples, no cracks were detected after 7 weeks of hydrolysis, so PPDOCD1 had better physical integrity than PPDO of 5th week. Even PPDOCD1 of 10th week was not as fragile as PPDO of 7th week, although it seems that PPDOCD1 of 10th week degraded worse than PPDO of 7th week from the SEM graphs (SEM graphs of PPDO after

10 weeks were not taken because the samples became too fragile to keep their physical integrity). After 10 weeks, PPDOCD1 had a weight loss of 5%, pH of 6.68, and intrinsic viscosity of 0.54 dL/g, but the corresponding indices of PPDO after 7 weeks were 11.5%, 6.33, and 0.28 dL/g, respectively. The surface morphologic changes observed coincide with the above results such as weight loss in samples. These changes in morphology also indicate a suppression of hydrolysis because of PCD in the samples.

Thermal analysis

Once the ester bonds in the amorphous areas are broken, the short chains involved in this breaking can incorporate into the crystal, causing an increase in crystallization at the initial stage of hydrolysis; at the later stage of hydrolysis, most of hydrolysis occurs in the crystal regions and gradually destroys these regions.[7–10] The introduction of PCD is able to induce the changes of the crystallization behaviors of PPDO. In this section, the crystallization in the hydrolysis degradation process has been studied. The samples of PPDO and PPDOCD were characterized by DSC to evaluate the variation of melting peak temperature (T_m) and melting enthalpy as a function of the degradation time. The degrees of crystallization (Dc) are calculated by the following formula:

$$Dc = \frac{\Delta H_m}{\Delta H_m^o}$$

where ΔH_m^o is the melting enthalpy of 100% crystalline PPDO (14.4 kJ/mol) and ΔH_m represents the enthalpy obtained by integrating the melting peak between 80 and 120°C.[22] Figure 8 shows the DSC thermograms for the first heating scans of PPDO and PPDOCD1. The results calculated from Figure 8 are listed in Table I. It is observed that the melting peak temperatures of the two samples were almost invariable. Both the crystallinity of PPDO and that of PPDOCD increased. The original crystallinity degree was 40.3% for PPDO and increased to 57.2% after 10 weeks. The corresponding crystallinity values for PPDOCD1 were 31.4 and 47.1%, respectively.

TABLE I
Thermal Characteristics of PPDO and PPDOCD1 Samples Obtained from DSC Curves

Time (weeks)	PPDO			PPDOCD1		
	T_m (°C)	ΔH_m (J/g)	Dc (%)	T_m (°C)	ΔH_m (J/g)	Dc (%)
0	104.7	58.0	40.3	106.0	45.2	31.4
3	106.7	53.7	37.3	107.2	58.7	40.8
6	106.1	75.7	52.6	107.4	62.5	43.4
10	107.3	82.3	57.2	107.8	67.8	47.1

PPDOCD1 had a smaller initial crystallinity value than PPDO, perhaps because of the restriction of mobility for PPDO chains, which link with rigid ends by the reaction with PCD. An increase in crystallinity has been reported for PPDO and other polyesters.[7–11,23] The increase in crystallinity can be explained by the "cleavage-induced crystallization" mechanism.[11,23] When water diffuses into the samples, the attack happens on both amorphous and crystalline areas, but preferentially on the amorphous areas because of their less density. Then chain scission occurs and subsequently results in less entangled chain segments. These short segments can organize themselves to the crystal at the employed hydrolysis temperature (above the T_g of PPDO), which causes an increase in crystallinity.

CONCLUSIONS

It has been shown that PCD can be used as a stabilizer for the hydrolysis of PPDO. When compared with PPDO, the changes of weight loss, water absorption, molecular weight, and pH of medium were much slower than PPDOCD. These differences indicate that less acid fragments of molecular chains, which are produced by the hydrolysis scission of ester bonds, diffuse and dissolve into the hydrolysis medium. At the same time, the mechanical properties of PPDOCD keep at a stage for a longer time than those of PPDO. Furthermore, SEM micrographs show that the former has better physical integrity than the latter. These results reveal that PCD can enhance the hydrolysis stability of PPDO to some extent. The main reason is that PCD can retard the autocatalysis effect of carboxyl groups on breaking

ester bonds because of the reaction between the carbodiimide groups and carboxyl groups.

References

1. Yang, K. K.; Wang, X. L.; Wang, Y. Z. J Macromol Sci Polym Rev 2002, 42, 373.
2. Doddi, N.; Versfelt, C. C. Wasserman, D. U.S. Pat. 4,052,988, 1977.
3. Gertzman, A.; Thompson, D. R. U.S. Pat. 4,591,630, 1986.
4. Cachia, V. V.; Juan, M. S. U.S. Pat. 5,893,850, 1999.
5. Wang, Y. Z.; Zhou, Q.; Zheng, C. Y. C.N. Pat. 1,325,162, 2007.
6. Lipinsky, E. S.; Sinclair, R. G.; Browning, J. D. U.S. Pat. 5,767,222, 1993.
7. Lin, H. L.; Chu, C. C.; Grubb, D. J Biomed Mater Res 1993, 27, 153.
8. Ooi, C. P.; Cameron, R. E. J Biomed Mater Res (Appl Biomater) 2002, 63, 280.
9. Sabino, M. A.; González, S.; Márquez, L.; Feijoo, J. L. Polym Degrad and Stab 2000, 69, 209.
10. Sabino, M. A.; Albuerne, J.; Müller, A. J.; Brisson, J.; Prud'homme, R. E. Biomacromolecules 2004, 5, 358.
11. Chu, C. C. J Appl Polym Sci 1981, 26, 1727.
12. Nishida, H.; Yamashita, M.; Nagashima, M.; Hattori, N.; Endo, T.; Tokiwa, Y. Macromolecules 2000, 33, 6595.
13. Williams, A.; Ibrahim, I. T. Chem Rev 1981, 81, 589.
14. Lehrich, F.; Pohl, S. U.S. Pat. 5,532,414, 1996.
15. Ossefort, Z. T.; Testroet, F. B. Rubber Chem Technol 1966, 39, 1308.
16. Magnus, G.; Dunleavy, R. A.; Critchfield, F. E. Rubber Chem Technol 1966, 39, 1328.
17. Yang, K. K.; Wang, X. L.; Wang, Y. Z.; Wu, B.; Jin, Y. D.; Yang, B. Eur Polym J 2003, 39, 1567.
18. Li, S.; McCarthy, S. Biomaterials 1999, 20, 35.
19. Park, T. G. Biomaterials 1995, 16, 1123.
20. Carraher, C. E., Jr., Ed. Giant Molecules, 2nd ed.; Wiley: New York, 2003; Chapter 4.
21. Willianms, D. F.; Chu, C. C.; Dwyer, J. J Appl Polym Sci 1984, 29, 1865.
22. Ishikiriyama, K.; Pyda, M.; Zhang, G.; Forschner, T.; Grebowicz, J.; Wunderlich, B. J Macromol Sci Phys 1998, 37, 27.
23. Zong, X. H.; Wang, Z. G.; Hsiao, B. S.; Chu, B. Macromolecules 1999, 32, 8107.