

In Vitro Degradation of Poly(L-lactic acid) Fibers in Phosphate Buffered Saline

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ABSTRACT: *In vitro* degradation of poly(L-lactic acid) (PLLA) fibers was studied by incubating the fibers in phosphate buffered saline (pH 7.4) at 37°C for 35–45 weeks. Three kinds of PLLA fibers with different diameters and different initial viscosity-average molecular weights were tested. The viscosity-average molecular weight, crystallinity, morphology, and tensile properties of the PLLA fibers were monitored along the degradation period. The results showed that the viscosity-average molecular weight of the PLLA fibers dropped gradually during the *in vitro* degradation period, and it decreased by 40–60% at the end of the experimental period. The crystallinity of the PLLA fibers measured by differential scanning calorimetry was noted to increase slightly. The tensile moduli, ultimate strengths, and elongations of the fibers did not exhibit significant changes in 35 weeks of degradation but PLLA fibers with a smaller diameter of 113 μm showed significant decreases in their ultimate strengths with respect to the initial value after 35–45 weeks of degradation. Microcracks appeared on part of the fiber surfaces, which might ultimately lead to the decrease of the mechanical strength of the PLLA fibers. The spotty defects reported in this study apparently did not affect the mechanical properties of the fibers. The results suggested that the tensile properties of the PLLA fibers were mechanically stable in 35 weeks of *in vitro* degradation, although their molecular weights decreased remarkably and obvious spotty defects appeared on their surfaces. © 2002 Wiley Periodicals, Inc. *J Appl Polym Sci* 85: 936–943, 2002

Key words: poly(L-lactic acid); fiber; *in vitro* degradation; viscosity-average molecular weight; tensile properties

INTRODUCTION

Poly(L-lactic acid) (PLLA) can degrade by nonspecific scissions of the ester bonds in its backbone via hydrolysis. The final product (lactic acid) can enter the tricarboxylic acid cycle and be disposed of as carbon dioxide and water.¹ PLLA is consid-

ered as a good biodegradable and biocompatible polymer. Because PLLA also exhibits reasonably good processability and appropriate mechanical properties, it has often been studied for its applications in bone fracture fixation and tissue engineering.^{2–4}

The degradation kinetics of biodegradable polymers are critical properties that probably determine or even limit their applications. PLLA is a long-term biodegradable polymer. Many factors can affect its degradation, for example, geometri-

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cal shape, size, crystallinity, pH value of the medium, temperature, irradiation, and so on. Many previous studies on the degradation of PLLA or poly(DL-lactic acid) involved specimens in the form of films, foams, rods, or plates.^{5–11}

PLLA fibers can be produced by means of melt spinning^{12,13} or solution spinning^{14,15} for use as sutures^{16,17} and in ligament reconstruction.¹⁸ The *in vitro* degradation of PLLA fibers in phosphate buffered saline (PBS, pH 7.4) was investigated previously.^{19,20} Hyon et al. reported that the PLLA fibers produced by melt spinning underwent almost no degradation in PBS at 37°C over 6 months, but these fibers degraded very fast at 100°C and lost their mechanical strength completely after 20 h.¹⁹ Joziassse et al. reported that the PLLA fibers prepared by solution spinning exhibited very stable mechanical properties under a static load at room temperature in PBS; these fibers were noted to retain 75% of their initial strength after 5.3 years.²⁰ The degradation of PLLA fibers in Ringer's lactate solution at 37°C was studied by Pegoretti et al.²¹ The results showed that the thinner the PLLA fibers, the faster was their degradation. The tensile modulus reportedly changed only slightly but the ultimate strength dropped by 20% after 16 weeks of degradation.²¹ The *in vitro* degradation of PLLA fibers as braided yarns for ligament reconstruction was also studied.^{18,22}

In this work PLLA fibers produced by melt spinning with three different molecular weights were studied in PBS at 37°C. Characterizations of the viscosity-average molecular weight, thermal behavior, morphology, and tensile properties of the PLLA fibers following 35–45 weeks of the *in vitro* degradation period are presented.

EXPERIMENTAL

PLLA Fibers

PLLA fibers with three viscosity-average molecular weights (M_η) were produced by melt spinning in our laboratory.²³ These three kinds of PLLA fibers were designated as PLLA-a ($M_\eta = 121,000$), PLLA-b ($M_\eta = 151,700$), and PLLA-c ($M_\eta = 112,900$), which had diameters of 113 ± 9 , 148 ± 16 , and 143 ± 14 μm , respectively.

In Vitro Degradation

The *in vitro* degradation of PLLA fibers was carried out in 0.1M Na₂HPO₄/KH₂PO₄ buffered 0.9%

NaCl solution (i.e., PBS) at pH 7.4 and 37°C. In the experiments 7–12 fibers of each kind were cut into about 10-cm lengths and bundled together. Each bundle of the fibers was about 20 mg. Three of the bundles was considered as a group, and they were immersed in 30 mL of PBS and incubated in an air-circulation oven at 37°C. The PBS solution was renewed every other week. After a certain period of degradation one group of the fibers was removed from the PBS, washed with water, and dried in a vacuum oven at 48°C for 2 h for further measurements. The masses of the fibers before and after degradation were weighed in an electronic balance with a resolution of 0.1 mg. The mass decrease percentage of the PLLA fibers was calculated as the ratio of the mass difference before and after degradation to their original mass.

Molecular Weight

The molecular weight was measured by the viscosity method in a dilute polymer/chloroform solution (0.1 g/dL) using an Ubbelohde viscometer (type 0c) at 25°C. The viscosity-average molecular weight was then calculated from the intrinsic viscosity ($[\eta]$) by using the following equation²⁴:

$$[\eta] = 5.45 \times 10^{-4} M_\eta^{0.73}$$

The extent of decrease in the viscosity-average molecular weight was defined by the difference of the viscosity-average molecular weights of PLLA before and after a certain period of degradation.

Thermal Analysis

Differential scanning calorimetry (DSC) was performed using a Perkin Elmer DSC 7 calorimeter with a heating rate of 10°C/min by flushing nitrogen. Samples consisted of approximately 10 mg of the PLLA fibers that had been cut into about 1-mm lengths. They were carefully put into aluminum pans. The melting temperature (T_m) was the temperature at the maximum value of the melting peak. The melting enthalpy of the fibers was referred to as the corresponding energies (J/g, peak areas above the baseline) during the melting range. The crystallinity of the PLLA fibers was then determined by rating the melting enthalpy of the PLLA fibers to 93 J/g, which is the melting enthalpy of 100% crystalline PLLA in the literature.²⁵

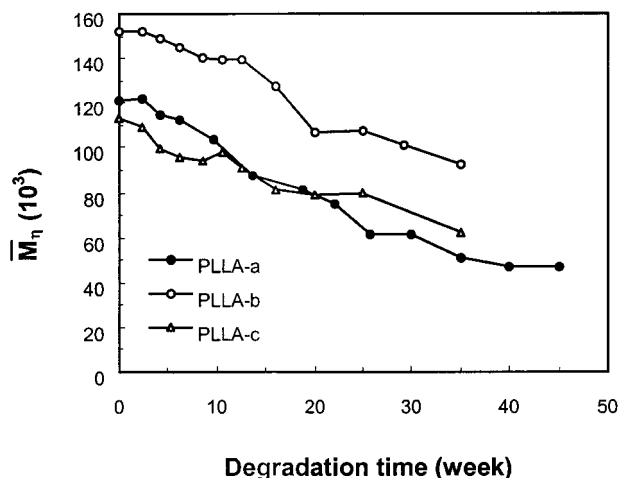


Figure 1 The changes in the viscosity-average molecular weights of the PLLA fibers after different periods of *in vitro* degradation.

Morphology

The morphology of the PLLA fibers was observed under a Leica scanning electron microscope (SEM, Stereoscan 440) after gold coating.

Tensile Properties

The tensile properties of the PLLA fibers were tested in a Hounsfield tensile tester (model H10KM/03) with a 100-N load cell. All tests were conducted at room temperature at a crosshead speed of 12 mm/min. The diameter of the fibers was measured using a micrometer. Specimens with a gauge length of 25 mm were carefully mounted. All the reported tensile properties and diameters represented average values of five or six tests.

RESULTS AND DISCUSSION

Molecular Weight

As a hydrolytically biodegradable polymer, PLLA is sensitive to humid conditions. It can degrade *in vivo* or in humid environments by hydrolysis of its ester bonds. In this study the *in vitro* degradation of three kinds of PLLA fibers with different diameters and different initial molecular weights was studied in PBS at pH 7.4 and 37°C for 35–45 weeks. The changes of the viscosity-average molecular weights of the PLLA fibers following the *in vitro* degradation period are shown in Figure 1. The results showed that the viscosity-average mo-

lecular weight of the PLLA fibers decreased gradually along the degradation period. After 35 weeks of degradation the PLLA-a, PLLA-b, and PLLA-c fibers showed a decrease in their viscosity-average molecular weights from 121,000 to 50,980 (57.9%), 151,700 to 92,110 (39.3%), and 112,900 to 61,750 (43.5%), respectively. Furthermore, the viscosity-average molecular weight of the PLLA-a fibers decreased by 61.0% after 45 weeks of degradation.

The molecular weight of the PLLA fibers decreased in a gradual manner, but the masses of each kind of PLLA fibers after the various degradation periods did not change much (Fig. 2). This suggested that the fibers followed typical bulk degradation behavior. Because the PLLA-b and PLLA-c fibers had similar diameters, the extent of decrease in the viscosity-average molecular weight was also similar, even though they had different initial viscosity-average molecular weights. The PLLA-a fibers exhibited a higher decreasing rate in the viscosity-average molecular weight than the PLLA-b and PLLA-c fibers. This was probably caused by the smaller diameters of the PLLA-a fibers, which is the bigger surface area per unit mass. The fact that the degradation rate of the PLLA fibers was affected by their diameters was consistent with the previous report of degradation in Ringer's solution.²¹

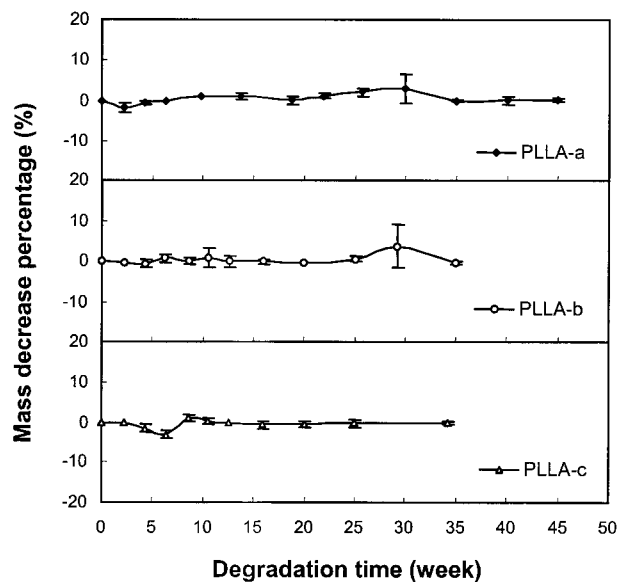


Figure 2 The mass decrease percentage of the PLLA fibers during *in vitro* degradation.

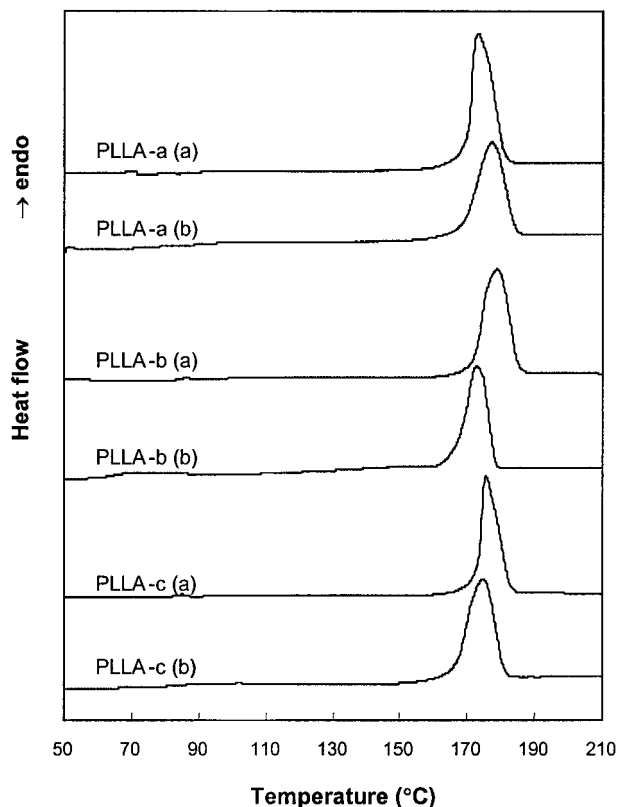


Figure 3 DSC thermograms of the PLLA fibers (a) after and (b) before 35 weeks of *in vitro* degradation.

Thermal Behavior and Crystallinity

The thermal behavior and crystallinities of the PLLA fibers before and after degradation for a certain period were studied by DSC analysis. The DSC thermograms are shown in Figure 3. The thermograms exhibited no recrystallization peaks because the fibers apparently had high crystallinities already.²³ The melting temperatures of the PLLA-a fibers decreased along the degradation period, but the T_m values of the PLLA-b and PLLA-c fibers tended to increase slightly (Fig. 4). The crystallinities of the PLLA fibers obtained by this method were noted to increase following the degradation as shown in Figure 5. The PLLA-a fibers increased their crystallinities from 61.9 to 69.2% at the end of 45 weeks of degradation, and the crystallinities of the PLLA-b and PLLA-c fibers were increased from 60.4 to 65.0 and 61.0 to 62.6%, respectively, after 35 weeks of degradation.

Generally, semicrystalline polymers consisted of the crystalline and amorphous regions. The

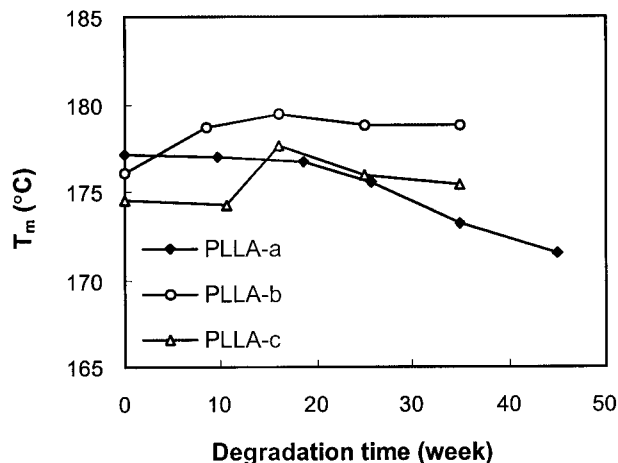


Figure 4 The changes in the melting temperatures of the PLLA fibers after different periods of *in vitro* degradation.

segments of the macromolecules were arranged more regularly and packed more tightly in the crystalline region than in the amorphous one. Therefore, small molecules like water attacked the segments in the amorphous regions easily and the degradation hydrolysis began naturally from the amorphous region. The breakage of the PLLA segments in the amorphous regions apparently resulted in a decrease of molecular entanglements and an increase of mobility of the macromolecular chains. Thus, the molecular chains could reorganize themselves in a more orderly manner and the crystallinity of the PLLA fibers after degradation apparently increased with the

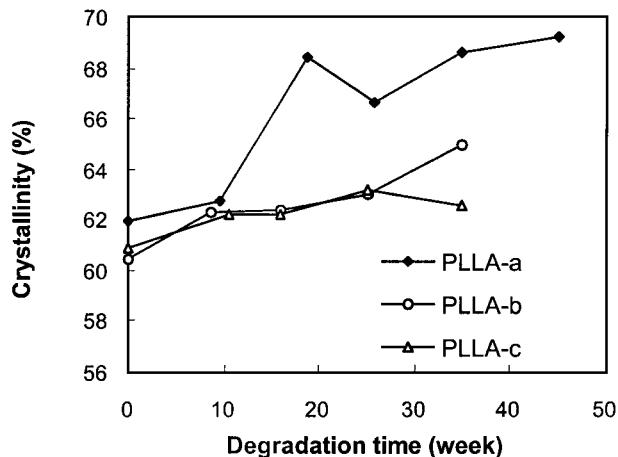


Figure 5 The changes in the crystallinities of the PLLA fibers after different periods of *in vitro* degradation.

degradation time.²⁶ The gradual increase of the crystallinity with the degradation time was probably caused by the gradual increase of the molecular orderliness as a result of the above process. The extent of the increase in the crystallinity of the PLLA-a fibers was higher than those of the PLLA-b and PLLA-c fibers. This might also suggest that PLLA-a fibers with smaller diameters degraded faster than PLLA-b and PLLA-c fibers with bigger diameters.

The enhanced mobility of the remaining segments might apparently increase the thickness of the crystallites and lead to a small increase of the melting temperatures of PLLA-b and PLLA-c fibers. A similar phenomenon was also found in a previous degradation study during the beginning period of PLLA degradation when the tensile strength of the film specimens showed no decrease.⁶ However, PLLA-a fibers did not show notable decreases in their melting temperatures. This might be due to the faster degradation rate of PLLA-a fibers that offered the crystallites in PLLA-a fibers little chance to grow.

Morphology

SEM micrographs of the PLLA fibers before and after degradation are shown in Figures 6 and 7. From the pictures of the PLLA fibers before degradation [Figs. 6(a), 7(a,c)], these fibers did not show any obvious defects on their surfaces at the beginning. However, after 40 weeks of degradation, microcracks obviously appeared on parts of the surface of the PLLA-a fiber [Fig. 6(b)]. The microcracks are clearly shown in a bigger magnification in Figure 6(c). After degradation the PLLA fibers seemed to have lost their initial surface smoothness. There were a few small spotty defects on the surfaces of the PLLA-b and PLLA-c fibers after 35 weeks of degradation [Fig. 7(b,d)] and on the surfaces of the degraded PLLA-a fibers [Fig. 6(b)].

The PLLA fibers were produced by a two-step melt-spinning process (i.e., melt extrusion and hot drawing).²³ The macromolecules could be oriented along the longitudinal direction of the fibers and the crystallites tended to pack along this direction by hot drawing.²⁷ The amorphous regions were located between these crystallites along the fibers. Some segments of PLLA in the amorphous regions could be hydrolyzed and removed by the medium. The amount of removed segments was enough to generate microcracks on the fiber surface. Such microcracks were also

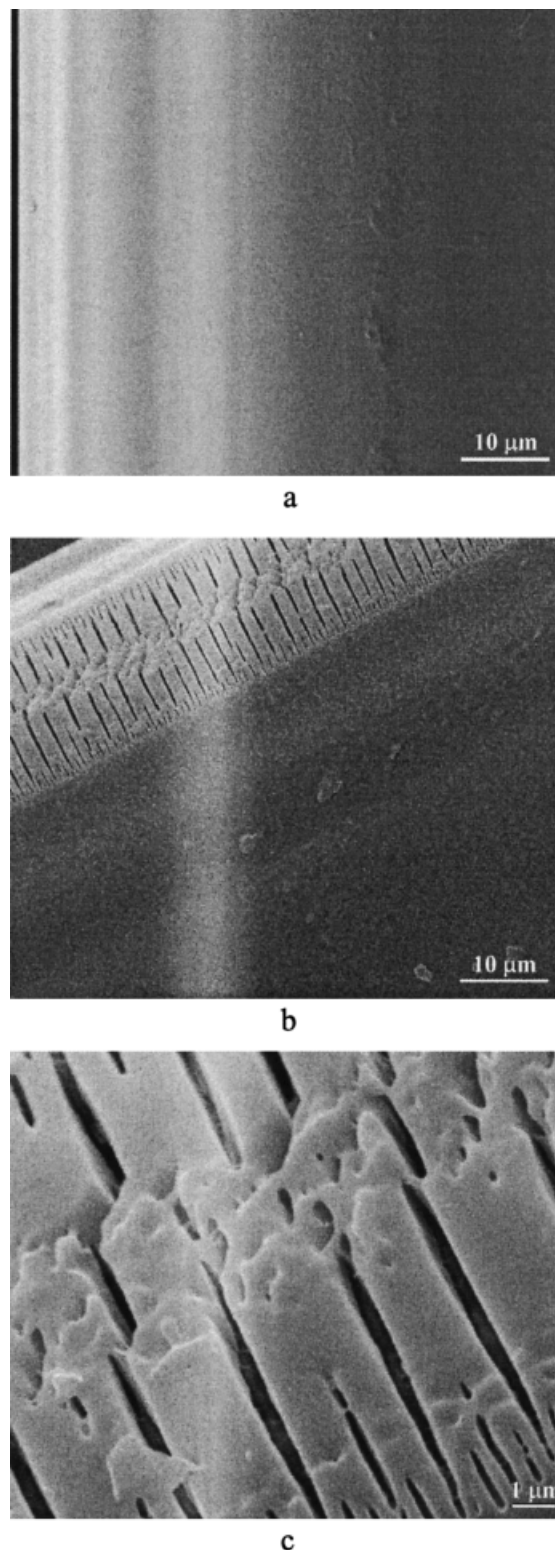


Figure 6 SEM micrographs of the PLLA-a fibers (a) before and (b,c) after 40 weeks of *in vitro* degradation. Original magnifications (a) $\times 3000$, (b) $\times 2000$, and (c) $\times 15,000$.

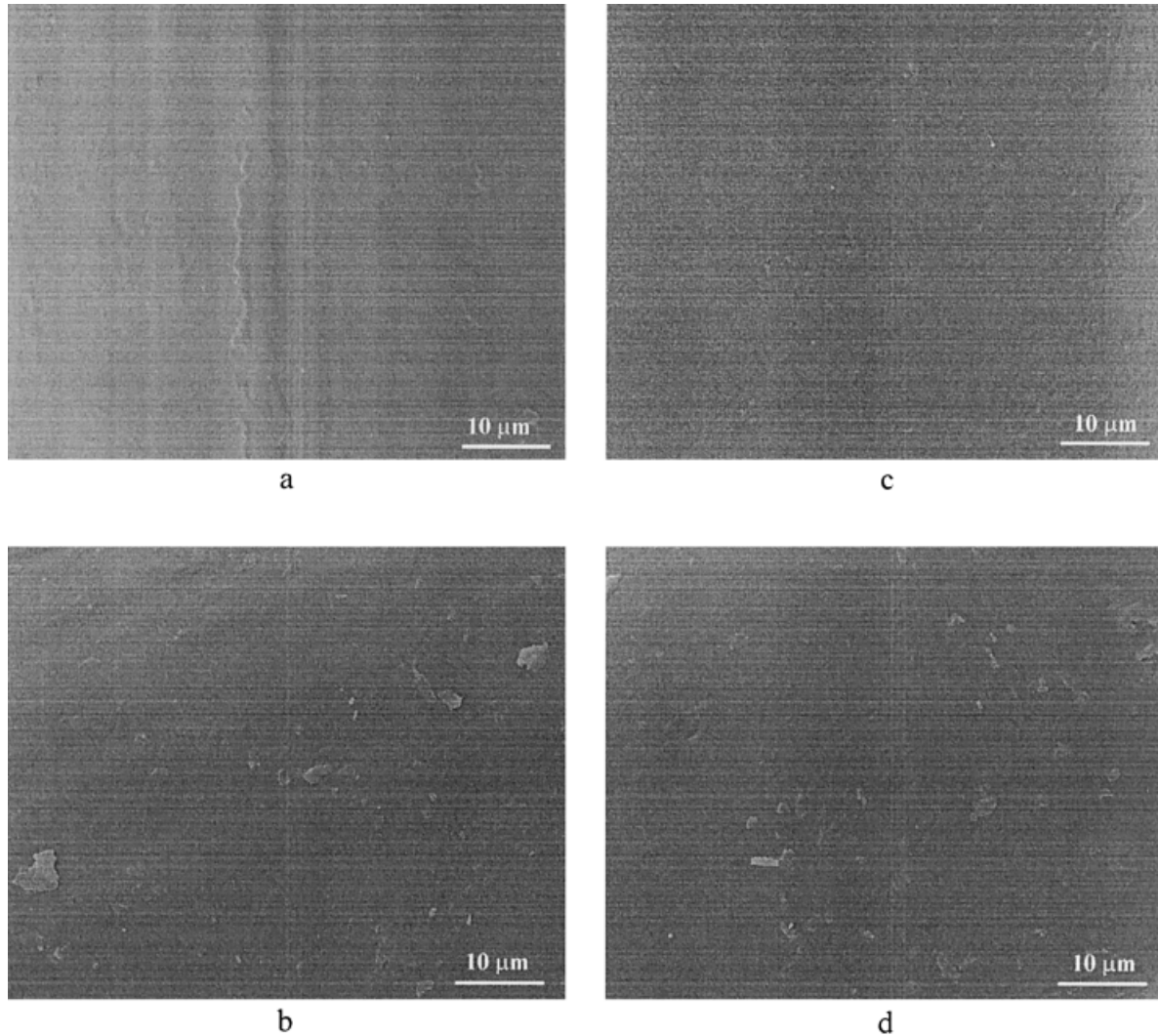


Figure 7 SEM micrographs of the (a,b) PLLA-b and (c,d) PLLA-c fibers (a,c) before and (b,d) after 35 weeks of *in vitro* degradation. Original magnification $\times 3000$.

found in the PLLA fibers after 20 h of hydrolysis in PBS at 100°C and poly(glycolic acid) suture fibers (Dexon®) after 40 days of degradation in PBS at 37°C.^{19,28} The degradation of the PLLA fibers had not reached a sufficient degradation extent so that those microcracks only appeared on parts of the fiber surface where the fiber might have relatively lower local crystallinity along the fiber direction due to its preparation process. It was supposed that the microcracks could further develop and cover the whole fiber surface if degradation was allowed to go further. The spotty defects appearing on the surfaces of these PLLA fibers were probably because of the elimination of molecular segments.

Tensile Properties

The changes in the tensile moduli, tensile strengths, and elongations of the PLLA fibers are shown in Figures 8–10, respectively. These figures showed that the tensile properties of the PLLA fibers did not change significantly after 35–45 weeks of *in vitro* degradation, except for a small decrease in the ultimate strength of the PLLA-a fibers. The ultimate strengths of the PLLA-a fibers after 35 weeks of degradation became significantly lower than their initial value ($p < 0.03$). These fibers showed a drop in their ultimate strength by 20% after 45 weeks of degradation with respect to their initial value. How-

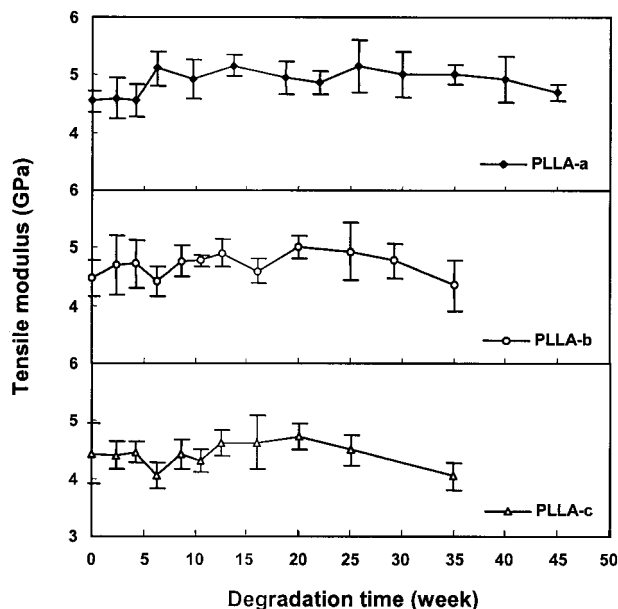


Figure 8 The changes in the tensile moduli of the PLLA fibers after different periods of *in vitro* degradation.

ever, the ultimate strengths of the PLLA-b and PLLA-c fibers exhibited no significantly decrease ($p > 0.05$). The ultimate strengths of PLLA-c fibers showed no significant differences with the exception of the lower value at 25 weeks of degradation in comparison with the initial value.

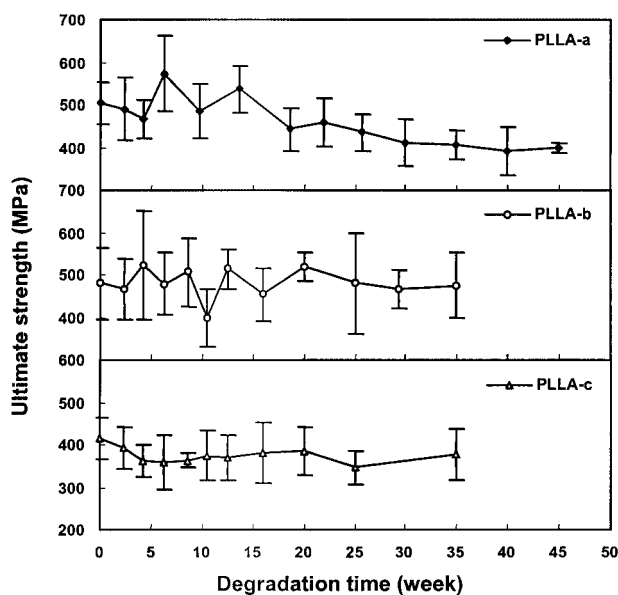


Figure 9 The changes in the tensile strengths of the PLLA fibers after different periods of *in vitro* degradation.

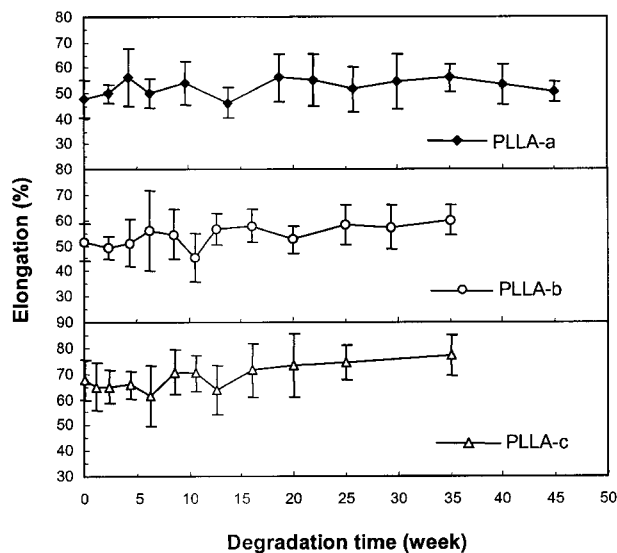


Figure 10 The changes in the elongations of the PLLA fibers after different periods of *in vitro* degradation.

This suggested that the PLLA fibers were mechanically stable during 35 weeks of *in vitro* degradation.

The mechanical stability of the PLLA fibers during the length of *in vitro* degradation in this study might be closely related to the slow degradation rate of the fibers. The decrease in the viscosity-average molecular weights and the defects on the surfaces of the fibers apparently did not affect their tensile properties significantly. The tensile strengths of the PLLA-a fibers decreased after 35 weeks of degradation with microcracks appearing on part of their surfaces. It was supposed that the PLLA fibers would lose their mechanical strengths quickly after the microcracks developed over the whole area of the fibers.¹⁹

CONCLUSIONS

PLLA fibers produced by melt spinning with different molecular weights showed a gradual decrease in the viscosity-average molecular weight along the *in vitro* degradation in PBS at pH 7.4 and 37°C for 35–45 weeks. The crystallinities of the PLLA fibers apparently increased slightly. The surface of the PLLA fibers gave rise to microcracks and spotty defects as a result of degradation. The tensile properties of the PLLA fibers did not exhibit any concomitant changes at the end of 35 weeks of degradation. However, the thinner

PLLA fibers showed a significant decrease in the ultimate strengths after 35–45 weeks of degradation.

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