Poly(L-lactide): V. Effects of Storage in Swelling Solvents on Physical Properties and Structure of Poly(L-lactide)

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ABSTRACT: The effects of storage at 25°C in swelling solvents having different solubility parameter (δ_s) values of 16.8–26.0 $J^{0.5}$ $cm^{-1.5}$ on the physical properties and structure of as-cast poly(L-lactide) (PLLA) films was investigated by the degree of swelling (DS), differential scanning calorimetry (DSC), and tensile tests. It was found that PLLA film shows durabity to swelling solvents having δ_s values much lower or higher than the value range of 19–20.5 $J^{0.5}$ $cm^{-1.5}$ and that the polymer solubility parameter (δ_p) for PLLA is in the value range of 19–20.5 $J^{0.5}$ $cm^{-1.5}$. The decrease in the glass transition temperature (T_g) and tensile properties and the increase in melting temperature (T_m) and crystallinity (x_c) were larger for PLLA films swollen in solvents having a high DS at 7 days (DS_{7days}). The slight increase in T_m and x_c for PLLA films after swelling in solvents with high DS_{7days} values was due to the crystallization of PLLA that occurred during swelling, while the small increase in T_g and elongation at break (ε_B) for PLLA films after immersion in the solvents having low DS_{7days} values was ascribed to stabilized chain packing in the amorphous region. The T_g, ε_B, and Young's modulus of the PLLA films after swelling in the solvents varied in the ranges of 47–57°C, 4–8%, and 55–77 kg/mm^2, depending on their DS_{7days} or δ_s values. © 2000 John Wiley & Sons, Inc. J Appl Polym Sci 79: 1582–1589, 2001

Key words: poly(lactide); poly(lactic acid); swelling; durability; solubility parameter; physical properties

INTRODUCTION

Poly(L-lactide) (PLLA) has been commercially produced for medical and pharmaceutical application as well as for environmental protection.[1–7] Annealing and thermal drawing of PLLA under various conditions have been performed to alter its initial physical properties[7–12] and biodegradability.[7,8,13–26] It was reported that the initial me-

chanical strength, Young's modulus, elongation at break, and hydrolytic behavior of PLLA can be changed to a certain extent by varying the structural parameters such as the crystallinity,[7,12] crystalline size,[12] and molecular orientation.[7–11] Shogren studied the effects of the highly ordered structure of PLLA on water-vapor permeability.[27] Water-vapor permeability is an important factor when PLLA is used in food packages, containers, bottles, and so on. The water-vapor transmission rate of an amorphous PLLA film (172 g mm^{-2} day^{-1} at 25°C) was higher than that of a crystallized PLLA film (82 g mm^{-2} day^{-1} at 25°C).

Pitt and Gu studied the degradation behavior of PLLA, poly(L-lactide-*co*-glycolide) (PLLA–GA),

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Table I   Characteristics of As-cast PLLA Film Before Swelling

M_w ($\times 10^5$)	M_w/M_n	T_g (°C)	T_m (°C)	x_c[a] (%)	σ_B[b] (kg/mm^2)	E[c] (kg/mm^2)	ε_B[d] (%)
3.3	1.7	55	172	40	4.4	81.2	6.8

[a] Crystallinity.
[b] Tensile strength.
[c] Young's modulus.
[d] Elongation at break.

and poly(ε-caprolactone) (PCL) films at 37°C in water, alcohols, and acidic and basic reagents.[28] They found significant effects of the nature of degradation mediums on the degradation rates of PLLA–GA and PCL but no such effects for the PLLA degradation when their degradation was estimated by molecular weight. Additionally, crystallization of an initially amorphous PLLA occurred during degradation in ethanol. The stability or durability of PLLA to liquids such as alcohol is crucial when used in containers, bottles, and similar vessels. The changes in physical properties and size of PLLA by contact with organic liquids are important to estimate its durability and structural change. However, such basic information has not been reported so far.

The purpose of this present work was to investigate the change in physical properties of PLLA as well as in its volume and structure in the crystalline and amorphous region in contact with different swelling solvents at 25°C. For this purpose, the degree of swelling (DS) and thermal and mechanical properties were estimated for an as-cast PLLA film after immersion in the selected swelling solvents having different solubility parameter (δ_s) values of 16.8–26.0 J$^{0.5}$ cm$^{-1.5}$.[29] The selected swelling solvents—cyclohexane, ethyl acetate, acetone, and ethanol—were neutral to exclude the effects of degradation or hydrolysis of PLLA during storage in them.

EXPERIMENTAL

Materials

PLLA (LACTY 5001) was kindly supplied by Shimadzu and utilized after purification by precipitation using chloroform and methanol as the solvent and nonsolvent, respectively, and drying *in vacuo* for 1 week. The films, 100 μm thick, used for the swelling experiments were prepared by the method described in a previous article.[12]

Briefly, a solution of PLLA was prepared to have a polymer concentration of 1.0 g/dL using methylene chloride as a solvent. The solution was cast onto a Petri dish, followed by solvent evaporation at 25°C for approximately 1 day. The resulting PLLA films were dried *in vacuo* for another week and stored in a desiccator at room temperature for more than 1 month to allow equilibrium of the amorphous region to be attained. The molecular characteristics and physical properties of the as-cast PLLA film are summarized in Table I.

Swelling

Swelling of the PLLA films (30 $\times$ 3 $\times$ 0.1 mm^3) was performed at 25°C up to 7 days (10,080 min) by immersing them in the swelling solvents: cyclohexane, ethyl acetate, acetone, and ethanol. The molecular weight, dipole moment (μ),[30] and δ_s[29] of these swelling solvents are given in Table II, together with those of good solvents of PLLA such as methylene chloride, chloroform, and dioxane. The DS of the PLLA films was evaluated by the following equation under the assumption that swelling of the PLLA film occurred isotropically:

$$\text{DS (\%)} = 100 \times [(L_{\text{after}}/L_{\text{before}})^3 - 1] \qquad (1)$$

where L_{after} and L_{before} are the length of a maximum side of the PLLA film before and after immersion in the swelling solvents. After swelling, the PLLA films were dried under reduced pressure for at least 2 weeks before the following measurements were taken:

Measurements

The glass transition and melting temperatures (T_g and T_m, respectively) and the enthalpy of melting and cold crystallization (ΔH_m and ΔH_c, respectively) of the PLLA films were determined by a Shimadzu DT-50 differential scanning calorimeter (DSC). The films (sample weight of ca. 3

Table II   Characteristics of Solvents and DS and Weight Loss of PLLA Films at 7 Days

Solvents	Molecular Weight (g/mol)	μ^a (D)	δ_s^b ($J^{0.5}$ $cm^{-1.5}$)	DS_{7days}^c (%)	Weight Loss (%)
Cyclohexane	84.16	0	16.8	1.5	0.6
Ethyl acetate	88.11	1.78	18.6	47.1	0.0
Chloroform	119.38	1.04	19.0	∞^c	100[d]
Methylene chloride	84.93	1.60	19.9	∞^c	100[d]
Dioxane	88.11	0	20.5	∞^c	100[d]
Acetone	58.08	2.88	20.5	36.4	4.2
Ethanol	46.07	1.69	26.0	2.5	2.0

[a] Values from ref. 30.
[b] Values from ref. 29.
[c] DS at 7 days.
[d] PLLA is soluble to these solvents.

mg) were heated at a rate of 10°C/min under a nitrogen gas flow of 50 mL/min. DSC results were calibrated using benzophenone, indium, and tin as standards. The crystallinity of the PLLA films (x_c) was calculated by the following equation[12,24–26]:

$$x_c \, (\%) = 100 \times (\Delta H_m + \Delta H_c)/93 \qquad (2)$$

where 93 J/g is the ΔH_m of PLLA crystals having the infinite crystal thickness reported by Fischer et al.[31] By definition, ΔH_m and ΔH_c are positive and negative, respectively.

The tensile properties of the PLLA films were measured at 25°C and 50% relative humidity using a Shimadzu tensile tester (EZ-Test) at a crosshead speed of 100%/min. The initial gauge length was always kept at 20 mm. The weight- and number-average molecular weights (M_w and M_n, respectively) of the PLLA films before and after swelling were evaluated by a Tosoh GPC system with TSK gel columns ($GMH_{XL} \times 2$) using polystyrene as a standard.

RESULTS

Swelling Behavior

The DS of the PLLA films immersed in the different swelling solvents is plotted in Figure 1 as a function of the immersion time. The DS reached a plateau after 20 min of immersion. Table II gives the DS at 7 days (DS_{7days}). Evident from this table, DS_{7days} depends on the δ_s of the solvents but not on their molecular weight or dipole moment (μ).

The reciprocal of DS_{7days} is plotted in Figure 2 against the δ_s of the swelling solvents. The data of the good solvents—chloroform, methylene chloride, and dioxane (Table II)—are also plotted in Figure 2. As seen, the DS_{7days}^{-1} of the PLLA film increases as the δ_s deviates from 19 to 20.5 $J^{0.5}$ $cm^{-1.5}$ of the good solvents of PLLA. The difference in the DS_{7days} between the PLLA films immersed in the acetone and dioxane both having the same δ_s value 20.5 $J^{0.5}$ $cm^{-1.5}$ may be due to the difference in the dipole moment (μ) values as shown in Table II.
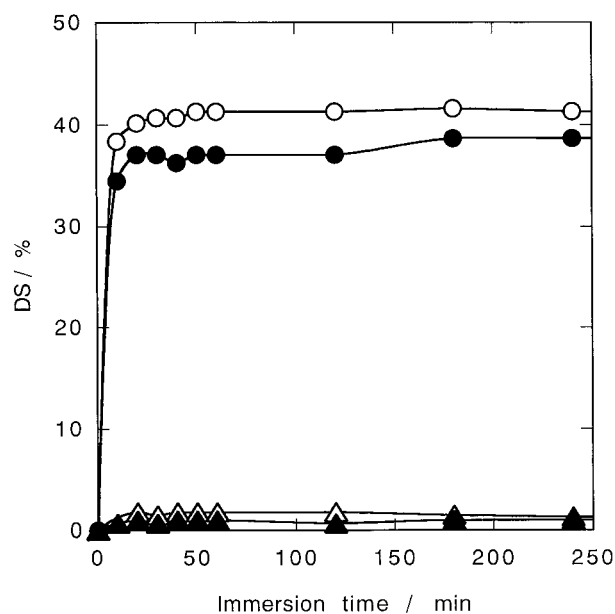

Figure 1   DS of PLLA films immersed in (△) cyclohexane, (○) ethyl acetate, (●) acetone, and (▲) ethanol as a function of immersion time.
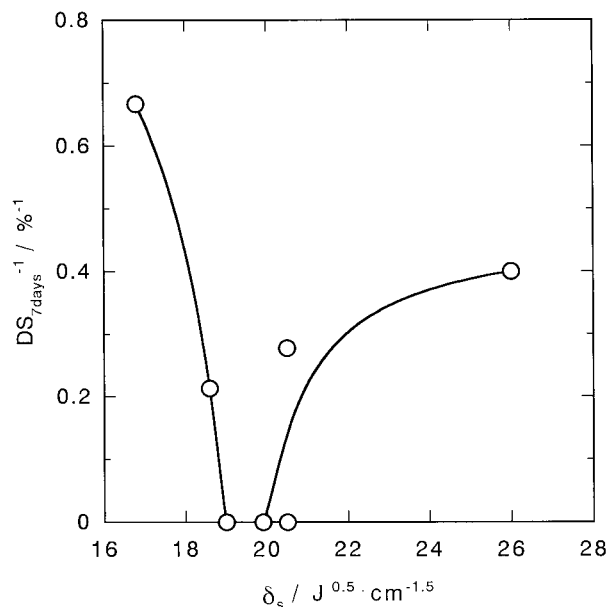
Figure 2 Reciprocal of DS of PLLA films at 7 days (DS_{7days}^{-1}) as a function of solubility parameter of solvents (δ_s) .

Swelling of a polymeric material is caused by diffusion or absorption of solvent molecules into the amorphous region of the polymeric material and the amount of the absorbed solvent or the DS value increases with an increase in its affinity for the polymer. Therefore, DS_{7days} values can be used as affinity indexes of the solvents for PLLA. In the following sections, DS_{7days} values will be used as the affinity indexes of the solvents for PLLA.

Weight Loss and Molecular Weight Change

Table II also shows the weight loss of the PLLA films after swelling in different solvents for 7 days. Significant weight loss was noticed for some PLLA films after swelling for 7 days, implying that a part of PLLA chains and/or the solvent and nonsolvent molecules used for purification were extracted from the mother PLLA film during immersion in the swelling solvents. No significant change in the M_w and M_n of PLLA occurred after swelling for 7 days, irrespective of the kind of the swelling solvents used (data not shown).

Thermal Properties

Figure 3 illustrates DSC thermograms of the PLLA films before and after immersion in different swelling solvents for 7 days. Significant

changes in the peak position of glass transition of the PLLA films occurred after 7 days of swelling while no significant change was noticed for the melting peak, irrespective of the kind of swelling solvents used.

The glass transition temperature (T_g), melting temperature (T_m), and crystallinity (x_c) of the PLLA films after immersion in different swelling solvents for 1 and 7 days are plotted in Figure 4 as a function of DS_{7days}. The T_g of the PLLA film increased and decreased for swelling solvents having DS_{7days} values lower and higher than 3%, respectively. It is interesting to note that the T_g of the PLLA film can be altered in the range between 47 and 57°C by immersion in swelling solvents having different DS_{7days} or δ_s values. The increase in T_g for the PLLA films immersed in the swelling solvents having relatively low DS_{7days} values (2–3°C) is comparable with that for the PLLA films hydrolyzed in a phosphate-buffered
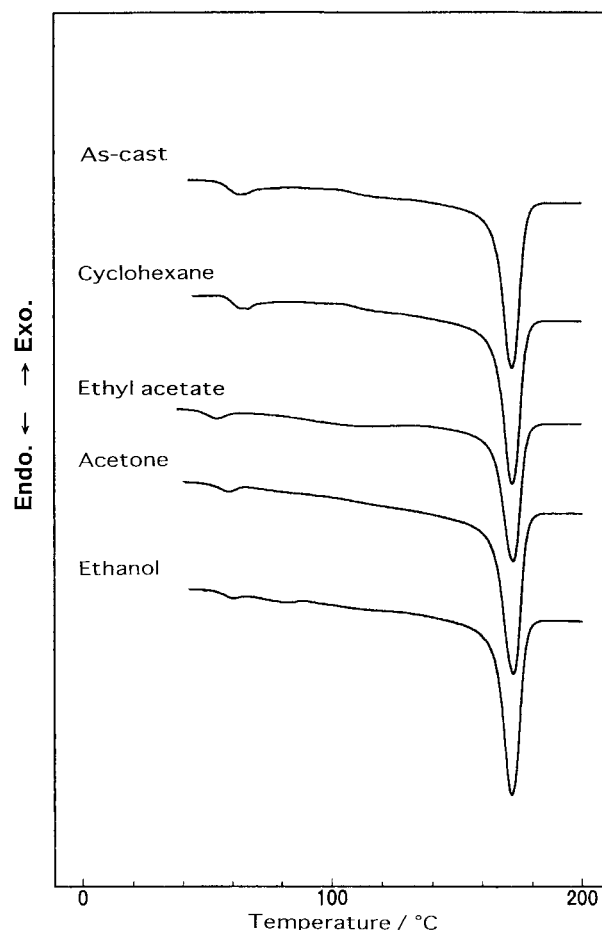

Figure 3 DSC thermograms of PLLA films before and after swelling in different solvents for 7 days.
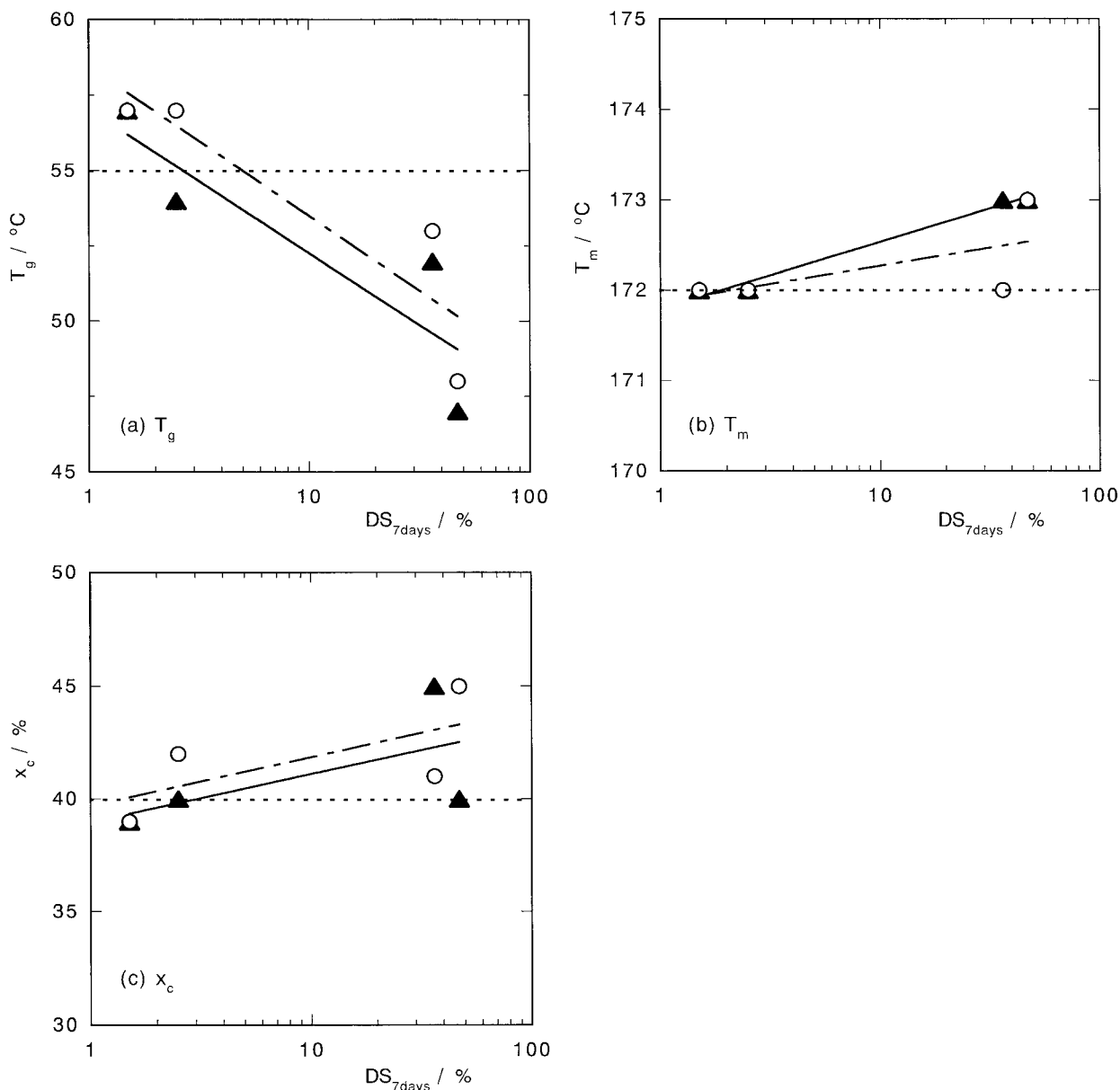
Figure 4 (a) T_g, (b) T_m, and (c) x_c of PLLA films (- - - -) before and after swelling for (○, - · - ·) 1 and (▲, —) 7 days as a function of DS_{7days}.

solution for 1 year at 37°C and pH 7.4.[25,26] On the other hand, the very small increase in T_m and x_c was noticed for the PLLA films immersed in the swelling solvents with relatively high DS_{7days} values or high affinity for PLLA.

Tensile Properties

Figure 5 demonstrates the tensile strength (σ_B), Young's modulus (E), and elongation at break (ε_B) of the PLLA films after immersion in different swelling solvents for 1 and 7 days as a function of DS_{7days}. The σ_B of the PLLA films remained unchanged after immersion in the solvents with relatively low DS_{7days} values, while a large reduction in σ_B was noticed for the PLLA films immersed in the solvents having large DS_{7days} values. On the other hand, the E of the PLLA films became lower after immersion in the swelling solvents, irrespective of the kind of swelling solvents used. The E of the PLLA films after swelling decreased from 77 to 55 kg/mm^2 with an increase in DS_{7days}. The ε_B of the PLLA films increased and decreased for the
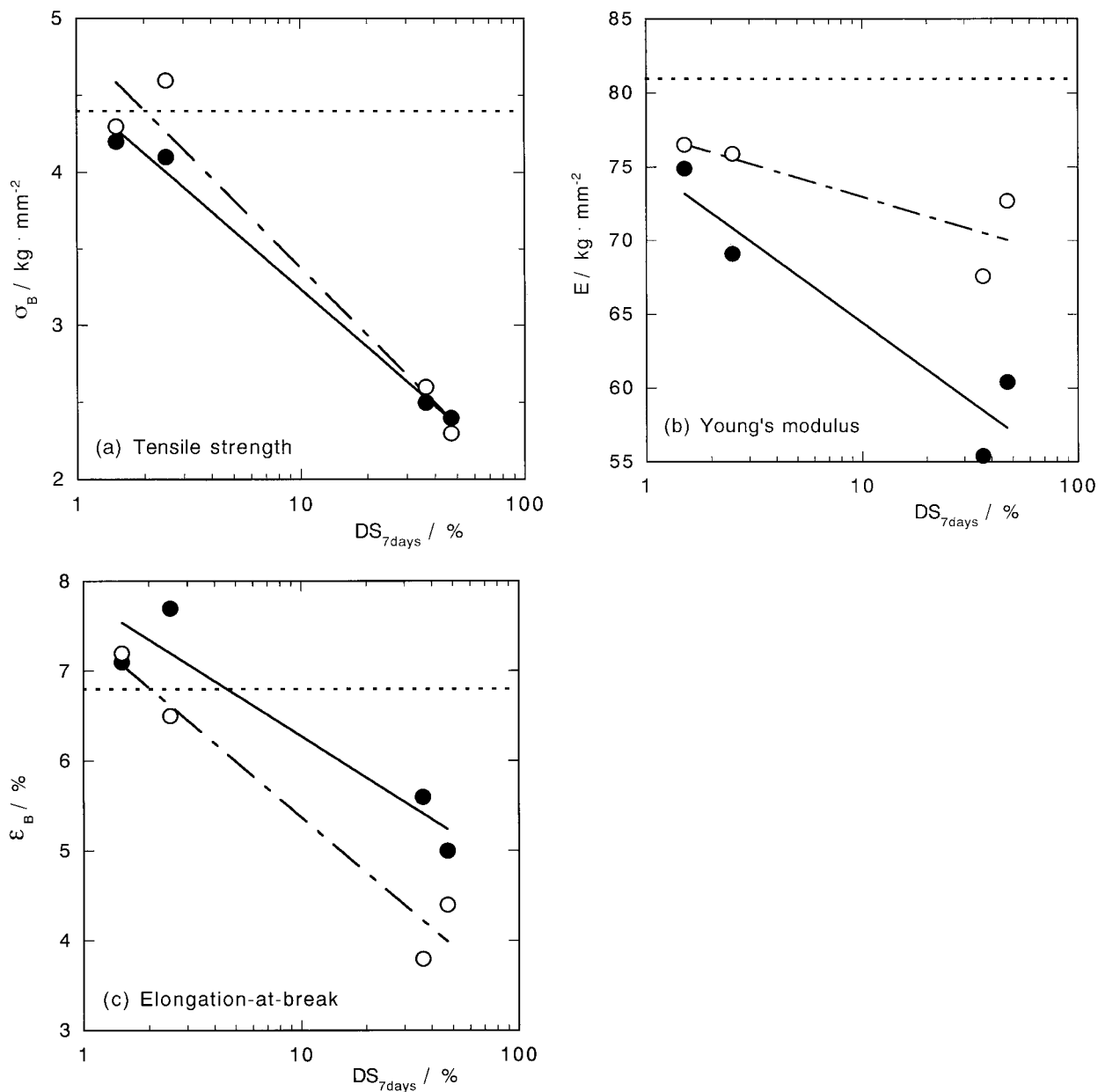
Figure 5 (a) Tensile strength (σ_B), (b) Young's modulus (E), and (c) elongation at break (ε_B) of PLLA films (- - - -) before and after swelling for ($\bigcirc$, - · - ·) 1 and ($\bullet$, —) 7 days as a function of DS_{7days}.

swelling solvents having DS_{7days} values lower and higher than 3%, respectively. The ε_B of the PLLA films after swelling decreased from 8 to 4% with an increase in DS_{7days}.

DISCUSSION

The results of DS, DSC, and tensile properties measurements revealed that PLLA is durable to

the swelling solvents having δ_s values much lower or higher than 19–20.5 $J^{0.5}$ $cm^{-1.5}$ of the good solvents for PLLA. The dependence of DS^{-1} on δ_s (Fig. 2) implies that the polymer solubility parameter (δ_p) for PLLA is in the range between 19 and 20.5 $J^{0.5}$ $cm^{-1.5}$. This δ_p value range agrees well with $\delta_p = 20.5$ $J^{0.5}$ $cm^{-1.5}$ estimated for poly(DL-lactide) (PDLLA) using high-precision density measurements[32] but is rather lower than the $\delta_p = 22.7$ $J^{0.5}$ $cm^{-1.5}$ calculated for PLLA using the

group-contribution method.[28,33] Even the δ_p value of 20.5 $J^{0.5}$ $cm^{-1.5}$ estimated for PDLLA is the highest among the δ_p value range for PLLA. The tacticity difference between PLLA and PDLLA having isotactic and rather random sequences, respectively, may have caused a small difference in their δ_p values. More detailed investigations should be necessary for accurate estimation of the δ_p value for PLLA.

The increase in x_c and T_m of the PLLA films after swelling in the solvents having high DS_{7days} values or high affinity for PLLA [Figs. 4(b) and (c)] is ascribed to the crystallization of PLLA chains or thickening of PLLA crystallites during immersion in the swelling solvents which will enhance the molecular mobility of the PLLA chains. Pitt and Gu reported that a melt-quenched amorphous PLLA film having a relatively low viscosity-average molecular weight (M_v) of 1000 crystallized during swelling in ethanol.[28] This was evidenced by the disappearance of the cold-crystallization peak in a DSC thermogram for the PLLA film after swelling for 21 days. Without the presence of any swelling solvents, crystallization of a blocky poly(L-lactide-co-ε-caprolactone) with a T_g below room temperature was reported to occur during storage at room temperature because of its high molecular mobility at this temperature.[34–36]

The increase in T_g for the PLLA films immersed in the solvents with low DS_{7days} values [Fig. 4(a)] may be due to stabilized chain packing in the amorphous region by low-temperature annealing in the presence of the swelling solvent molecules. In the case of PLLA films hydrolyzed in a phosphate-buffered solution,[25,26] chain stabilization in the amorphous region will probably be accelerated by the enhanced chain mobility resulting from its reduced molecular weight, in addition to the plasticizer effect of water molecules. When the PLLA films are immersed in swelling solvents having high DS_{7days} values or high affinity for PLLA, the PLLA chains will be surrounded by a large amount of solvent molecules, resulting in weak interaction between the PLLA chains. Removing the solvent molecules from these films by drying will leave the loosely packed unstable chains in the amorphous region, resulting in the reduced T_g.

The difference in σ_B and ε_B between the PLLA films after immersion in the different swelling solvents is ascribed mainly to their T_g difference after swelling. As mentioned above, higher T_g means that the PLLA chains in the amorphous
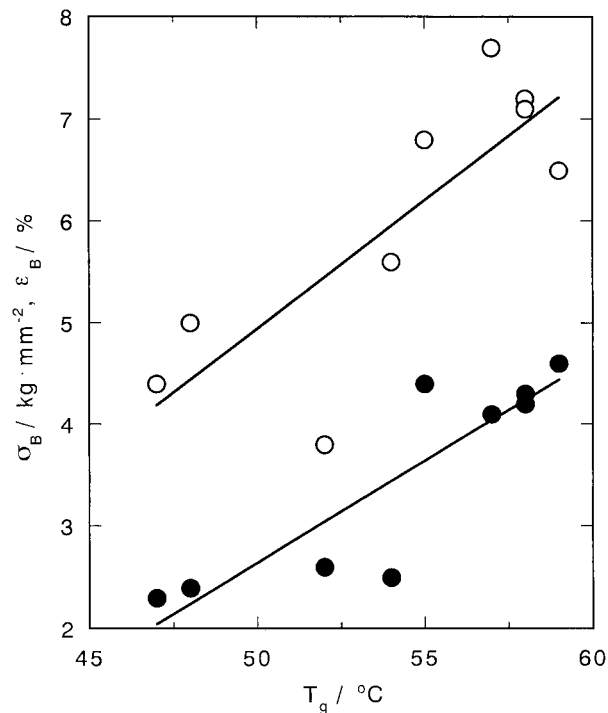

Figure 6 (●) Tensile strength (σ_B) and (○) elongation at break (ε_B) of PLLA films after swelling for 1 and 7 days as a function of T_g.

region are stabilized. The stabilized chains in the amorphous region will increase the σ_B and ε_B of the PLLA films even if their T_g was higher than the temperature for the tensile tests (room temperature). To confirm this assumption, the σ_B and ε_B of the PLLA films after swelling for 1 and 7 days are plotted in Figure 6 as a function of T_g. Evidently, both σ_B and ε_B increase linearly with the T_g, confirming the above-mentioned assumption. Although we cannot explain why the E of the PLLA films decreased in spite of their increased x_c values after swelling and why the PLLA films swollen for 7 days had an ε_B higher than those swollen for 1 day in spite of their lowered T_g at 7 days, this study revealed that the E and ε_B of the PLLA films can be altered from 55 to 77 kg/mm^2 and from 4 to 8%, respectively, by immersing them in swelling solvents having different δ_s or DS_{7days} values without any thermal treatments[12] which will cause thermal degradation of PLLA.

CONCLUSIONS

It may be concluded from this study that the PLLA film is durable to the swelling solvents

having δ_s values much lower or higher than 19–20.5 $J^{0.5}$ cm$^{-1.5}$ and that the δ_p of PLLA is in the range of 19–20.5 $J^{0.5}$ cm$^{-1.5}$. The slight increase in T_m and x_c for the PLLA films after swelling in the solvents with high DS$_{7days}$ values was due to the crystallization of PLLA that occurred during swelling, while the small increase in T_g and ε_B for the PLLA films after immersion in the solvents having low DS$_{7days}$ values was ascribed to stabilized chain packing in the amorphous region. This study also revealed that the physical properties of PLLA materials can be altered by swelling in the solvents having different DS or δ_s values without any thermal treatments as shown in the previous study.[12]

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