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Preparation and properties of biodegradable network poly(ester-carbonate) elastomers

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Abstract

Biodegradable elastomeric network poly(ester-carbonate)s were prepared from multifunctional aliphatic carboxylic acids such as tricarballylic acid (Y_t) or trimesic acid (Y) and polycarbonate diols (PCD) with molecular weights of 1000 and 2000 g/mol. Prepolymers prepared by a melt polycondensation were cast from dimethylformamide solution and postpolymerized at 270 °C for 40–80 min to form a network. The resultant films were transparent, flexible and insoluble in organic solvents. WAXS exhibited the crystalline peaks due to polycarbonate segments for the network films from PCD_{2000}, while those from PCD_{1000} were amorphous. The tensile properties were determined for these network films at the temperatures 22, 30, 40 and 50 °C. These films showed elastomeric properties at all temperatures measured. The elongation at break was much higher for the films from PCD_{2000} (208–434%) than those from PCD_{1000} (40–120%), and decreased with increasing temperatures. The weight losses of the network films degraded in the buffer solution of *Rhizopus delemar* lipase at 37 °C increased with time, suggesting that these network films are biodegradable. The degradation rate of the network films from Y_t is faster than that from Y. The GPC curves showed that the lipase hydrolyzed both the ester linkages between Y or Y_t and PCD as well as polycarbonate moiety in the network polymer.

Keywords: Network poly(ester-carbonate)s; Enzymatic degradation; Elastomers

1. Introduction

Recently the biodegradable elastomers have received much attention for their potential biomaterial uses including scaffolds for regenerating soft tissue and drug delivery. Though a number of biodegradable polymers have been developed, comparatively less attention has been paid to biodegradable elastomers [1]. There are two classes of elastomers: thermoplastic and thermosets. Thermoplastic elastomers are rather easily fabricated, but their semicrystalline nature would often cause a heterogenous degradation, leading to the rapid loss of mechanical properties as the material degrades [2]. In contrast, the advantages of thermosets are that they often offer a homogenous degradation and retain good dimensional stability during degradation, which would be favorable in the application of medical devices.

The thermoset biodegradable elastomers have been prepared by the cross-linking of prepolymers such as vinyl-end group functionalized poly(trimethylene carbonate-*co*-DL-lactide) [3] and star-shaped poly(ε-caprolactone-*co*-DL-lactide) [2,4,5]. The biodegradable network elastomers have also been prepared *via* polycondensation of multifunctional monomers. Yang et al. synthesized poly(diol citrate) biodegradable elastomers [6], and Wang et al. prepared a tough biodegradable elastomer using glycerol and sebacic acid [7].

We have previously reported the novel biodegradable elastomers with a regular network structure from aliphatic or aromatic multifunctional carboxylic acids and the macrodiols such as poly(ε-caprolactone) diols [8,9] and poly(ethylene

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glycol)s [10], which showed the interesting mechanical and degradation properties depending on the structures of macrodiols. Our recent interests have continued on the investigation of this type of elastomers, that is, the regular network elastomeric polymers from the biodegradable macrodiols. The work herein describes the synthesis and evaluation of the novel biodegradable network elastomeric poly(ester-carbonate)s from tricarballylic acid (Y_t) and trimesic acid (Y) with polycarbonate diols (PCD) of molecular weights (MW) of 1000 and 2000 g/mol. Aliphatic poly(ester-carbonate)s are reported to be biodegradable [11] and are more water resistant than biodegradable aliphatic polyesters such as poly(L-lactic acid) and poly(butylene succinate). The effects of MWs of PCD and testing temperature of the network films on the elastomeric properties of these network polymers are examined in detail in this work. The enzymatic degradation of these poly(ester-carbonate)s is also reported.

2. Experimental

2.1. Materials

Trimesic acid (Y) and tricarballylic acid (Y_t) were obtained from Tokyo Kasei Kogyo Co. Ltd. and New Japan Chemical Co. Ltd, respectively, and used without further purification. Polycarbonate diols (PCD) with an average molecular weight (MW) of 1000 (PCD_{1000}, $n = 6.1$) and 2000 g/mol (PCD_{2000}, $n = 13.1$) supplied by Asahi Kasei Co. Ltd were used as-received. Chemical formula of PCD is as follows: $H[-O(CH_2)_6OCO-]_nO(CH_2)_6OH$.

2.2. Preparation of prepolymers

The prepolymers were prepared from Y and PCD or Y_t and PCD by a melt polycondensation according to the similar procedure given earlier [8]; a mixture of Y or Y_t and PCD_{1000} or PCD_{2000} (total amount: 4 g, molar ratio of Y or Y_t/PCD: 2/3) was heated in a stream of nitrogen at 260 °C for 20–40 min for $YPCD_{1000}$ and Y_tPCD_{1000}, and for 90–180 min for $YPCD_{2000}$ and Y_tPCD_{2000}, respectively. Further heating caused the gelation of the prepolymers.

2.3. Film preparation and postpolymerization

The prepolymer obtained was cast on an aluminum plate using a 17 wt.% dimethylformamide solution at 80 °C. The cast film was heated at 270 °C for 40–80 min period of time in a nitrogen atmosphere. The postpolymerized film was peeled off an aluminum substrate, and stored in a desiccator over silica gel prior to use. The thickness of the films was about 200 μm. The chemical structure of network polymer is shown in Fig. 1.

2.4. Characterization

The Fourier transform infrared (FTIR) spectra were recorded on a Perkin–Elmer model FTIR spectrophotometer using thin films. Wide angle X-ray scattering (WAXS) was performed with a Bruker MX-Labo X-ray diffractometer with nickel-filtered Cu Kα radiation. Differential scanning calorimetry (DSC) was made on a TA Instruments DSC 2920 differential scanning calorimeter with a heating rate of 10 °C/min in a nitrogen atmosphere. In order to provide the same thermal history, each sample was preheated from room temperature to 100 °C and rapidly cooled down to −100 °C. Then the DSC scan was recorded by heating from −100 to 100 °C. The density of the film was measured using a sink and float method in potassium iodide aqueous solution at 30 °C. Water absorption was measured by immersing the film in water at 37 °C for 24 h, and then the specimens were taken out for weighing. Samples were gently blotted with filter paper to remove surplus surface water and dried to a constant weight. The water absorption was calculated as the differences between the dry weight and the wet weight.

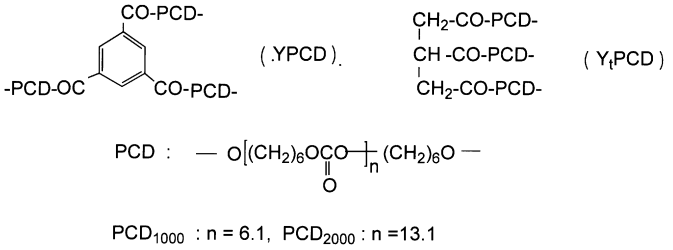

Fig. 1. Chemical structure of network polymers.

The tensile tests were performed on a Shimadzu AG-1 autograph with a thermo chamber and temperature controller at a strain rate of 20 mm/min. The tensile strength, elongation, and Young's modulus were measured, and the averaged value of 5–10 film specimens was employed.

2.5. Enzymatic degradation

The enzymes used in this study were lipases from *Rhizopus delemar* (specific activity of 715 unit/mg from Seikagaku Kogyo Co., Ltd.). The film specimen (20 × 20 mm, about 200 μm thickness) was placed in a small bottle containing 10 ml of 1/15 mol phosphate buffer solution (pH 7.2) with and without 600 unit/ml of the above-mentioned lipase. The vial was incubated at 37 °C for various periods of time. After incubation the film was washed with water thoroughly, and dried at room temperature *in vacuo* to constant weight. The degree of degradation was calculated as the differences between the dry weight after degradation and the initial weight.

3. Results and discussion

3.1. Degree of reaction (D_R)

The degree of reaction (D_R) was estimated by the procedures reported previously [6,7]. After casting the prepolymer, it was postpolymerized to form a network. As expected, the network film was insoluble in organic solvents such as dichloromethane and *N*,*N*-dimethylformamide. The network

Table 1
D_R values, densities and water absorptions of the network films postpolymerized at 270 °C

Polymer code	Prepolymerization time (min)	Postpolymerization time (min)	D_R (%)	Density (g/cm^3)	Water absorption (%)
$YPCD_{1000}$	40	40	73	1.149	2.3
Y_tPCD_{1000}	20	40	77	1.136	1.1
$YPCD_{2000}$	180	80	78	1.265	0.7
Y_tPCD_{2000}	90	80	79	1.268	0.4

polymers showed infrared absorptions due to hydroxyl group at 3460 cm^{-1} and methylene groups at 2940 cm^{-1}. The absorption at 3460 cm^{-1} decreased with increasing postpolymerization time, while the absorption at 2940 cm^{-1} remained unchanged. Since the postpolymerization proceeds through the reactions between the carboxyl group of multifunctional aliphatic carboxylic acid and hydroxyl group of PCD, the change in absorption intensity ratio between −OH and $>CH_2$, A_{OH}/A_{CH_2}, is a measure of the degree of reaction. For $YPCD_{1000}$, at the beginning of reaction, the ratio of hydroxyl and methylene groups in a monomeric unit, [OH]/[CH_2], was 2/42 and varied with the progress of reaction to become (2−2)/42 when the network structure of film was completely developed.

Thus, the following equation is defined:

$$[OH]/[CH_2] = (2 - y)/42$$

and

$$y = 2 - (42[OH]/[CH_2])$$

Here y is the number of reacted hydroxyl groups. The degree of reaction (D_R) is calculated by:

$$D_R = (y/2) \times 100\ (\%)$$

To obtain the quantitative [OH]/[CH_2] ratio in network films, the calibration curve between A_{OH}/A_{CH_2} made by the known diols and alcohols [12].

D_R values of the network films increased with postpolymerization time and approximately leveled off after 40−80 min, depending on the molecular weight of PCD. D_R values of network films postpolymerized for 40−80 min are summarized in Table 1. They are higher than 70%, demonstrating that a network structure is formed.

3.2. Structure and thermal properties of postpolymerized films

Fig. 2 shows WAXS intensity curves of various network films. Two diffraction peaks are appeared at around $2\theta = 20°$ and 23° for the network films from PCD_{2000}, whereas those from PCD_{1000} show only amorphous halos. These diffraction peaks are due to the crystallization of PCD_{2000} component. The Y_tPCD_{2000} film exhibits sharper diffraction peak intensity than that of $YPCD_{2000}$, showing that the aromatic tricarboxylic acid more disturbs the crystallization of PCD_{2000} segment.

The densities and water absorption of various network films are given in Table 1. Higher densities and lower water absorption of the films from PCD_{2000} are responsible for the higher intermolecular cohesive energy (more closely packed).

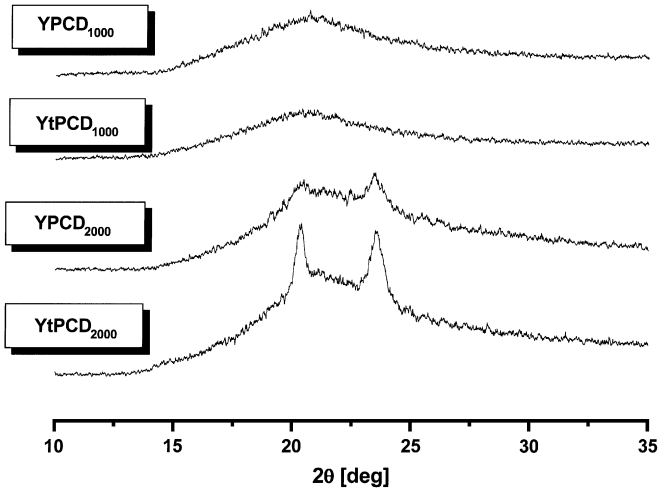

Fig. 2. WAXS patterns of the various network films.

Fig. 3 shows typical DSC heating scans of various network films. Endothermic changes due to glass transition (T_g) are observed for all films. T_gs are in the range of −51 to −41 °C. T_g's of the network films from PCD_{2000} are lower than those from the corresponding PCD_{1000}, suggesting that the mobility of the molecular chains in network films is increased due to the lower cross-linking density. Melting peaks due to the crystallization of PCD components appear at 29 °C for $YPCD_{2000}$ and 24 °C for Y_tPCD_{2000}, corresponding to the diffraction peaks observed in WAXS curves as shown in Fig. 1. In addition, Y_tPCD_{2000} showed a cold crystallization temperature (T_{cc}) at 0 °C.

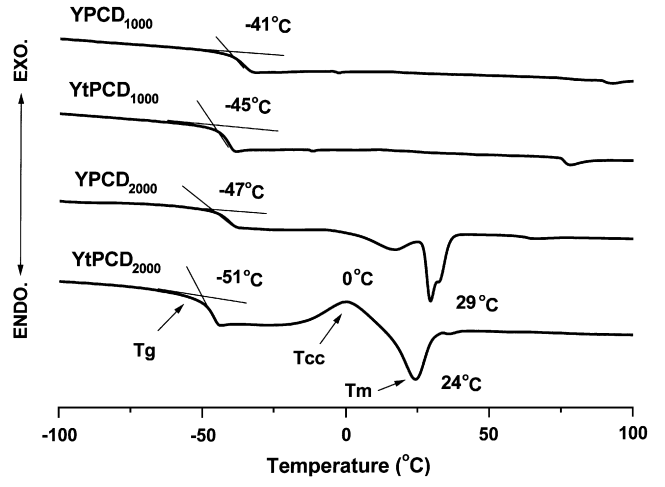

Fig. 3. DSC heating curves of the various network films.

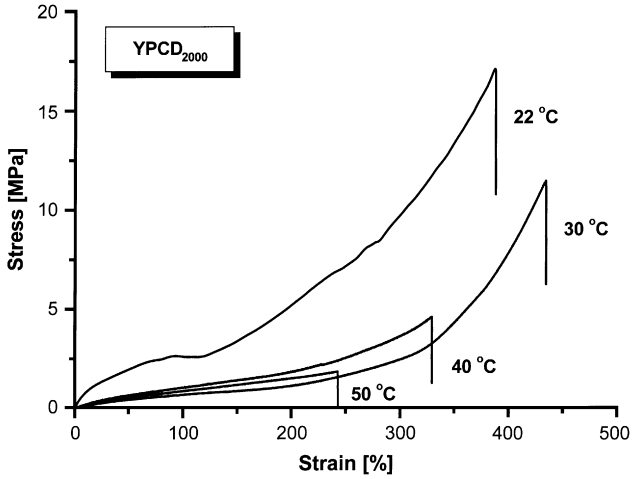

Fig. 4. Typical stress–strain curves of Y_tPCD_{2000} films at the various temperatures.

3.3. Mechanical properties of postpolymerized films

Fig. 4 shows typical shapes of the stress–strain curves of the $YPCD_{2000}$ network film at several temperatures (22, 30, 40 and 50 °C). Table 2 summarizes the results of stress–strain data such as tensile strength at break, Young's modulus and elongation at break. All network films showed the elastomeric properties at 22–50 °C: full recovery of the sample dimensions after tensile testing was observed except for the films from PCD_{2000} measured at the lowest temperature (22 °C). At this temperature, the films from PCD_{2000} did not recover to the initial state completely after tensile testing, which would be ascribed to the increased crystallinity of these films allowing the higher tensile strength at break (9.4–13.5 MPa) and Young's modulus (15.1–20.4 MPa). The elongation at break of the network films from PCD_{1000} is 40–120% and much lower than that from PCD_{2000} having an elongation of 208–434%, which would be ascribed to the higher cross-linking density of the former films that disturbs the extension of the network films. For the network films from PCD_{1000}, the elongation gradually decreases with increasing temperature from 22 to 50 °C; while to the ones from PCD_{2000}, the elongation first increases and then decreased. The melting temperatures of network films from PCD_{2000} are in the range of 24 and 29 °C, thus the crystalline region of these films melts at testing temperatures of 30 °C, leading to the first increase in the elongation. The tensile strength at break and Young's modulus of the films from PCD_{2000} are much lower at temperatures higher than 30 °C, which would be ascribed to the melting of their crystalline regions. The elongation of the network films decreases gradually with increasing temperatures, suggesting that the intermolecular cohesive energy decreases with an increase of temperature.

Table 2
Tensile properties of network films at various temperatures

Polymer code	Temperature (°C)	Tensile strength at break (MPa)	Young's modulus (MPa)	Elongation at break (%)
$YPCD_{1000}$	22	1.3 ± 0.2	1.8 ± 0.1	120 ± 16
	30	0.9 ± 0.1	1.3 ± 0.1	101 ± 5
	40	0.8 ± 0.1	1.2 ± 0.1	75 ± 2
	50	0.4 ± 0.0	0.8 ± 0.1	74 ± 4
Y_tPCD_{1000}	22	1.5 ± 0.1	2.4 ± 0.1	108 ± 3
	30	0.8 ± 0.1	2.1 ± 0.1	71 ± 2
	40	0.9 ± 0.1	2.4 ± 0.1	50 ± 4
	50	0.8 ± 0.1	2.4 ± 0.1	40 ± 3
$YPCD_{2000}$	22	20.4 ± 1.2	13.5 ± 1.4	367 ± 6
	30	11.4 ± 0.5	1.4 ± 0.1	434 ± 0.5
	40	5.1 ± 0.7	1.5 ± 0.1	332 ± 16
	50	2.0 ± 0.2	1.6 ± 0.1	236 ± 10
Y_tPCD_{2000}	22	15.1 ± 0.4	9.4 ± 1.1	340 ± 6
	30	13.7 ± 1.1	2.1 ± 0.1	355 ± 4
	40	6.6 ± 0.6	1.6 ± 0.1	340 ± 12
	50	2.3 ± 0.3	1.7 ± 0.1	208 ± 16

In order to check the material's elastomeric properties in detail, hysteresis cycle was performed at several temperatures (22, 30, 40,50 °C) on all films. As a typical example, hysteresis cycle of Y_tPCD_{2000} film after the 10th elongation is shown in Fig. 5: 250% elongation and back at 30 °C (a) and 200% elongation and back at 50 °C (b). These materials show an excellent recovery, with a set at 100% at both temperatures after the 10th elongation. At 30 °C, a loss of energy as heat is appeared, but no loss of energy at 50 °C. The network films

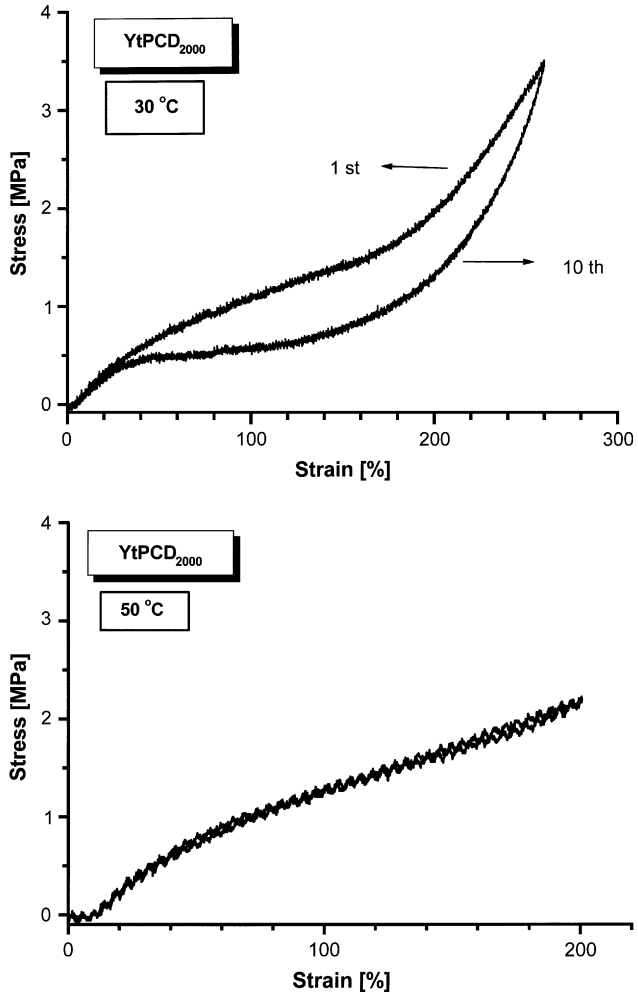

Fig. 5. Typical hysteresis curves of Y_tPCD_{2000} films at 30 (a) and 50 °C (b).

from PCD_{1000} hardly exhibited loss of energy at every temperatures measured, while those from PCD_{2000} did loss energy and it became smaller with increasing temperature. This could be attributed to the difference of intermolecular cohesive energy between PCD components (PCD_{2000} is larger than PCD_{1000} [13]). The network films representing no loss of energy such as all films from PCD_{1000} and the films from PCD_{2000} measured at 50 °C recover rapidly to the initial size.

3.4. Enzymatic degradation of postpolymerized films

Fig. 6 shows the weight loss of various network films *versus* degradation time in a phosphate buffer solution with *Rh. delemar* lipase at 37 °C. The weight loss increases almost linearly with time. In contrast, no significant weight loss was observed in the absence of the lipase, demonstrating that these network poly(ester-carbonate) films are enzymatically degradable. The rate of degradation is much slower than that of the analogous network polyesters ($YPCL_{2000}$) prepared from Y and poly(ε-caprolactone diol) of MW = 2000 g/mol, whose weight loss was 100% after a 20 h degradation under the similar degradation conditions [8]. This shows that aliphatic carbonate linkage is much more reluctant to enzymatic degradation than aliphatic ester linkage. Moreover the linear weight loss against degradation time indicates that *Rh. delemar* lipase hydrolyzes the PCL chains in the surface layer of the film, and the polymer erosion proceeds *via* surface dissolution. The surface erosion by lipase enzyme has been reported for various degradable polyesters [14]. The films from Y_t degrade much faster than the corresponding films from Y, indicating that aromatic ester linkages are reluctant to enzymatic hydrolysis. The degradation rate of the network films from PCD_{1000} is higher than those from PCD_{2000}, which could be ascribed to the enhanced water absorption and/or higher concentration of ester linkage per weight.

The hydrolysis products by *Rh. delemar* lipase were identified by GPC in order to examine the degradation mechanism. After degradation, the solution was freeze-dried and the residue was dissolved in tetrahyrofuran and filtered, then subjected to GPC analysis. Fig. 7 shows a typical GPC curve of degraded Y_tPCD_{2000}. The oligomeric Y_tPCD_{2000} as well as Y_t and 1,6-hexanediol are detected, suggesting that *Rh. delemar* lipase hydrolyzes ester linkages between Y or Y_t and PCD as well as the carbonate linkage in polycarbonate segment.

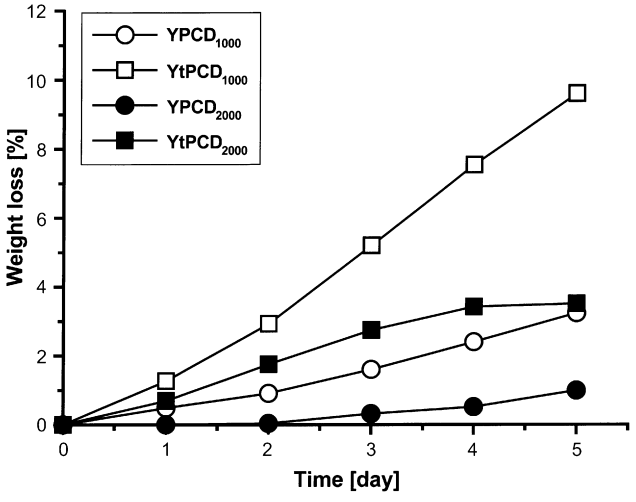

Fig. 6. Weight loss of the various network films against degradation time in a phosphate buffer solution with *Rh. delemar* lipase at 37 °C.

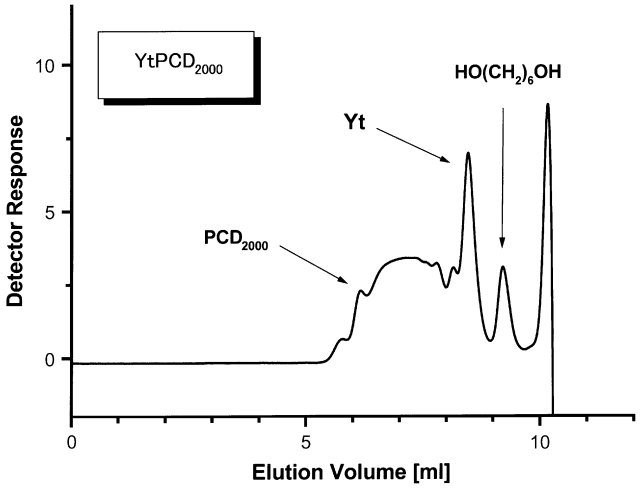

Fig. 7. GPC curves of degraded Y_tPCD_{2000} in the phosphate buffer solution with *Rh. delemar* lipase at 37 °C.

4. Conclusions

Biodegradable elastomeric network poly(ester-carbonate)s were prepared from tricarballylic acid (Y_t) or trimesic acid (Y) and polycarbonate diols (PCD) of molecular weight of 1000 and 2000 g/mol. These network films showed elastomeric properties at the temperature range of 22–50 °C. $YPCD_{2000}$ and Y_tPCD_{2000} films exhibited the excellent elastomeric property of 208–236% extension even at higher temperature (50 °C), which recovered to the initial state rapidly. The network films were degraded in the buffer solution of *Rh. delemar* lipase at 37 °C, suggesting that these network films are biodegradable. This lipase hydrolyzed both the ester linkages between Y or Y_t and PCD as well as polycarbonate moiety in the network polymer. The network poly(ester-carbonate) films may have the potential applications in biomedical and environmental fields because they could show the excellent elastomeric properties at the higher temperatures (around 50 °C) as well as biodegradable properties.

References

[1] Mallapragada SK, Narasimhan B, editors. Handbook of biodegradable polymeric materials and their application. New York: American Scientific Publishers; 2005. p. 191.
[2] Amsden B, Misra G, Gu F, Younes HM. Biomacromolecules 2004; 5:2479.
[3] Storey RF, Warren S, Allison CJ, Puckett AD. Polymer 1997;38:6295.
[4] Helminen A, Korhonen H, Seppala JV. Macromol Chem Phys 2002;203: 2630.
[5] Amsden B, Wang S, Wyss U. Biomacromolecules 2004;5:1399.
[6] Yang J, Webb AR, Pickerill SM, Hageman G, Ameer GA. Biomaterials 2006;27:1889.

[7] Wang Y, Ameer GA, Sheppard BJ, Langer R. Nat Biotechnol 2002;20: 602.
[8] Nagata M, Kanechika M, Sakai W, Tsutsumi N. J Polym Sci Part A Polym Chem 2002;40:4523.
[9] Nagata M, Kato K, Sakai W, Tsutsumi N. Macromol Biosci 2006;6:333.
[10] Nagata M, Sugiura R, Sakai W, Tsutsumi N. J Appl Polym Sci 2007; 106:2885.
[11] Okada M, Yokoe M, Aoi K. J Appl Polym Sci 2002;86:872.
[12] Kiyotsukuri T, Tsutsumi N, Chen Y. Polymer 1990;28:1197.
[13] The cohesive energy of network polymer was estimated from the values of group contribution to molar attraction constant. For instance, $YPCD_{2000}$, 1020 kJ/mol/unit; $YPCD_{1000}$, 560 kJ/mol/unit. Van Krevelen DW. Properties of polymers. Amsterdam: Elsevier; 1990. p. 189–225 [chapter 7].
[14] For example Kumagai Y, Kanesawa Y, Doi Y. Makromol Chem 1992; 193:53.