Ring-opening Polymerization of L-Lactide with Silica Supported Titanium Alkoxide Catalysts

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Abstract: $TiCl(O\text{-}i\text{-}Pr)_3/SiO_2$ and $Ti(O\text{-}i\text{-}Pr)_4/SiO_2$ were prepared by immobilizing chlorotitanium (IV) isopropoxide ($TiCl(O\text{-}i\text{-}Pr)_3$) and titanium (IV) isopropoxide ($Ti(O\text{-}i\text{-}Pr)_4$), to pretreated silica. The effect of the polymerization reaction conditions on the catalytic activity and characteristics of the resulting PLA were investigated. The catalytic conversion, molecular weight and polydispersity index (PDI) of the PLA produced on the titanium alkoxide supported catalysts increased proportionally with the reaction temperature. When the PLA was synthesized in bulk polymerization, the PLA produced with the supported catalysts had higher molecular weight than those with homogeneous catalysts. The melting temperature of the polymer produced with silica supported alkoxide catalysts was approximately 170-180 °C.

Keywords: titanium alkoxide catalyst, silica support, polylactide, biodegradable polymer.

Introduction

Polylactide (PLA), a biodegradable aliphatic polyester produced from lactic acid derived from renewable sources such as starch and molasses, is the first product to be commercialized in the plastic industry.[1-4] In general, PLA breaks down into low molecular weight oligomers upon exposure to heat and water and is decomposed into water and carbon dioxide by the action of microorganisms commonly existing in the natural environment.[5] PLA can be synthesized by polycondensation of lactic acid or ring-opening polymerization of lactide, which is a dimer of lactic acid. Lactic acid exists as three stereoisomers; L- , D- and *meso*-lactic acid. The L- and D-lactic acids have high crystallinity and the resulting polymer has a high melting temperature and good physical properties.[6] PLA has been used for surgical and pharmaceutical applications, such as suture threads, bone fixation, and materials for drug delivery systems. It also has potential uses in environmentally friendly packaging and consumer goods due to the excellent mechanical properties, transparency, biosafety, compatibility and biodegradability.[7-10] A large variety of new catalytic systems based on tin, aluminum, zinc, magnesium, iron, lanthanide, and lithium organometallic complexes containing initiating groups such as amides, carboxylates, and alkoxides have been reported as effective single-site initiators for the ring-opening polymerization (ROP) of L-lactide to isotactic PLA and *rac*-lactide to atactic PLA.[11-17] In recent years, the research focus on PLA has been directed toward the introduction of stereoregularity such as heterotacticity and stereoblock to develop a new polymer system. Among various metal complexes that are known to produce stereoregular PLA,[18-21] chiral aluminum catalysts in particular draw attention since they can transform *meso*- and *rac*-lactide into heterotactic and isotactic stereoblock PLA, respectively, revealing that the catalyst's chirality might be an important stereocontrol factor of the polymerization. In this work, enantiomerically pure L-lactide which mostly produces isotactic PLA was used as a monomer.[12] Recently, titanium alkoxides have been investigated as potential homogeneous catalysts for ring-opening polymerization of lactide.[22-24] From a practical point of view, it would be desirable for these catalysts to be heterogeneous to allow for better control of the polymerization process and easier separation of the catalysts from the polymer product.[25,26] In this work, silica supported catalysts were prepared by reacting $TiCl(O\text{-}i\text{-}Pr)_3$ and $Ti(O\text{-}i\text{-}Pr)_4$ with pretreated silica. Lactide polymerizations were performed with the silica supported catalysts to compare the catalytic activity and characteristics of the resulting PLA under various polymerization conditions. The propagation rate constants of the reaction were also calculated as a preliminary kinetic study in the heterogeneous catalytic system.

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Experimental

Materials. L-Lactide (PURASORB L, PURAC) was recrystallized with toluene three times prior to use. Toluene was purified by distillation over sodium metal in a nitrogen atmosphere to remove residual traces of moisture and was stored with 4 Å molecular sieves. Silica (Sylopol 948, Grace Davison) was used as a support to immobilize the catalysts. Titanium (IV) isopropoxide (Ti(O-i-Pr)$_4$, Sigma, 97%) and chlorotitanium (IV) isopropoxide (TiCl(O-i-Pr)$_3$, Sigma, 95%) were used as received, without further purification. All procedures for monomer purification and catalyst preparation were performed under a dry nitrogen atmosphere.

Characterization. Inductively coupled plasma spectroscopy (JY Horiva, JY Activa) was used to determine the titanium content of the supported catalyst. Specific surface area measurements were performed using the BET method (Micromeritics, ASAP 2020) at 78 K using nitrogen as an adsorption gas. Before the measurement, the samples were degassed at 423 K for 4 h to reach a final pressure of 10^{-4} torr. Scanning electron microscopy (JEOL, JSM-6500F) was used to observe the morphology of the supported catalyst. The number average and weight average molecular weight (M_n and M_w respectively) and polydispersity index (PDI, M_w/M_n) of the resulting PLA were determined by gel permeation chromatography (Polymer Laboratory, PL-GPC 120) using CHCl$_3$ as a solvent. The melting temperature of PLA was determined using differential scanning calorimetry (TA instrument, Q20) with a second heating cycle at a heating rate of 10 °C/min.

Preparation of Supported Catalysts. A silica support was calcined at 400 °C under a 100 cc/min stream of N$_2$ for 10 h to remove residual traces of moisture and hydroxyl groups before reacting with catalysts. Four grams of calcined silica was suspended in 100 mL of dry toluene and a predetermined amount of titanium alkoxide was added. The mixture was stirred for 3 h at 50 °C and the resulting catalyst was filtered and washed three times with 100 mL of toluene. Finally, the slurry was dried for 12 h under vacuum and stored in a glove box.
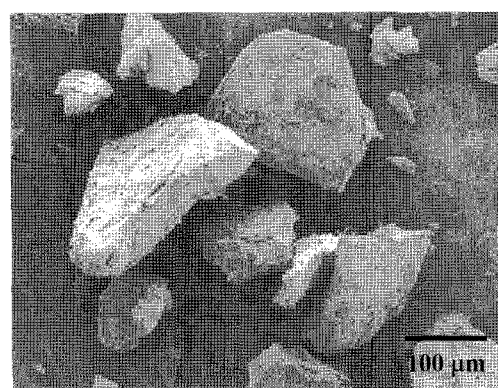
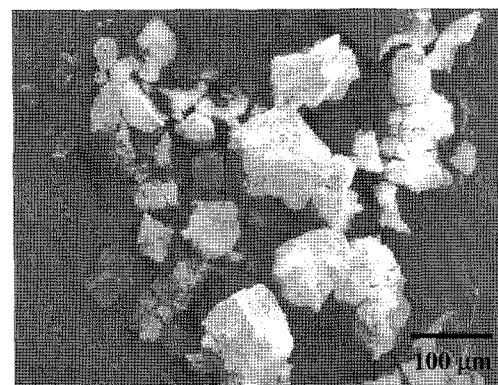**Solution Polymerization of L-Lactide.** Solution polymerization of L-lactide was performed using a flask equipped with a magnetic stirrer. Predetermined amounts of purified L-lactide, dried toluene and homogeneous or a supported catalyst were charged in succession into a flask under an argon atmosphere. The polymerization was performed at 70 °C for 2, 6, 12 and 24 h. The reaction was terminated by addition of 5 mL of methanol and the polymer was precipitated in an excess amount of methanol. The obtained polymer was washed with methanol and dried at 50 °C under vacuum for 12 h.

Bulk Polymerization of L-Lactide. Bulk polymerization of L-lactide was performed using a vial equipped with a

magnetic stirrer. Predetermined amounts of purified L-lactide, dried toluene and homogeneous or supported catalyst were charged in succession into a vial under an argon atmosphere. The polymerization was performed at 130 °C for 5, 15, 30 and 120 min. The reaction was terminated by addition of 5 mL of methanol. The precipitated polymer was dissolved in 5 mL of methylene chloride at low temperature and was precipitated again in an excess amount of methanol. The obtained polymer was washed with methanol and dried at 50 °C under vacuum for 12 h.

Results and Discussion

Characteristics of Polymerization with Supported Catalysts. Silica supported catalysts were prepared by reacting TiCl(O-i-Pr)$_3$ or Ti(O-i-Pr)$_4$ with silica which was calcined at 400 °C for 10 h. It was found that the specific surface area of the catalysts slightly decreased during immobilization of the titanium alkoxide on the silica surface. Specifically, the silica support has a specific surface area of 260 m^2/g, while the specific surface areas of the resulting TiCl(O-i-Pr)$_3$/SiO$_2$ and Ti(O-i-Pr)$_4$/SiO$_2$ catalysts were 246.1 and 229.6 m^2/g, respectively. From the ICP

(a)

(b)

Figure 1. SEM photographs of the PLA produced from (a) TiCl(O-i-Pr)$_3$ and (b) TiCl(O-i-Pr)$_3$/SiO$_2$.

analyses, the titanium content of the TiCl(O-*i*-Pr)$_3$/SiO$_2$ and Ti(O-*i*-Pr)$_4$/SiO$_2$ catalysts were 3.02 and 3.22 wt%, respectively.

Solution polymerization of L-lactide was performed at 70 °C with TiCl(O-*i*-Pr)$_3$/SiO$_2$ or Ti(O-*i*-Pr)$_4$/SiO$_2$ at a L-lactide/catalyst molar ratio of 100. Figure 1 shows SEM photographs of the PLA produced with TiCl(O-*i*-Pr)$_3$ and TiCl(O-*i*-Pr)$_3$/SiO$_2$. The morphologies of the PLA produced with TiCl(O-*i*-Pr)$_3$ and TiCl(O-*i*-Pr)$_3$/SiO$_2$ were irregular. There was no "replication phenomena" that is generally observed in the heterogeneous catalytic olefin polymerization. When the lactide polymerization was conducted with titanium alkoxide catalysts, the removal of metal residues in the polymer chain would be possible by adding a small amount of water, acetic acid or methanol after polymerization.[27] Therefore, a pure metal-free polymer product for more valuable applications with those heterogeneous catalyst systems may have been prepared. As shown in Figure 1, the produced PLA was separated from the silica supported catalysts.

Solution Polymerization with Supported Catalysts. A series of solution polymerizations of L-lactide were performed at various temperatures with TiCl(O-*i*-Pr)$_3$/SiO$_2$ or Ti(O-*i*-Pr)$_4$/SiO$_2$ at a L-lactide/catalyst molar ratio of 100 to observe characteristics of the supported catalyst and the resulting polymer. As shown in Figures 2 and 3, the polymerization with both TiCl(O-*i*-Pr)$_3$/SiO$_2$ and Ti(O-*i*-Pr)$_4$/SiO$_2$ showed similar reaction behaviors with respect to the reaction temperature. It was observed that the catalytic conversion of both TiCl(O-*i*-Pr)$_3$/SiO$_2$ and Ti(O-*i*-Pr)$_4$/SiO$_2$ rapidly increased with increasing reaction temperature. The catalyst activity at 90 °C sharply increased in the initial stage of the reaction, but rapidly decreased with time in the stream. Alternatively, the catalyst activity at 50 °C was very low in the beginning of the reaction, but it slowly increased through the entire period of the polymerization. It is notable that the conversion at 90 °C was reversed by the conversion at 70 °C in 24 h for both the supported catalysts, even though the rate of polymerization at 90 °C was considerably higher than that at 70 °C. It is thought that a fast polymeriza-
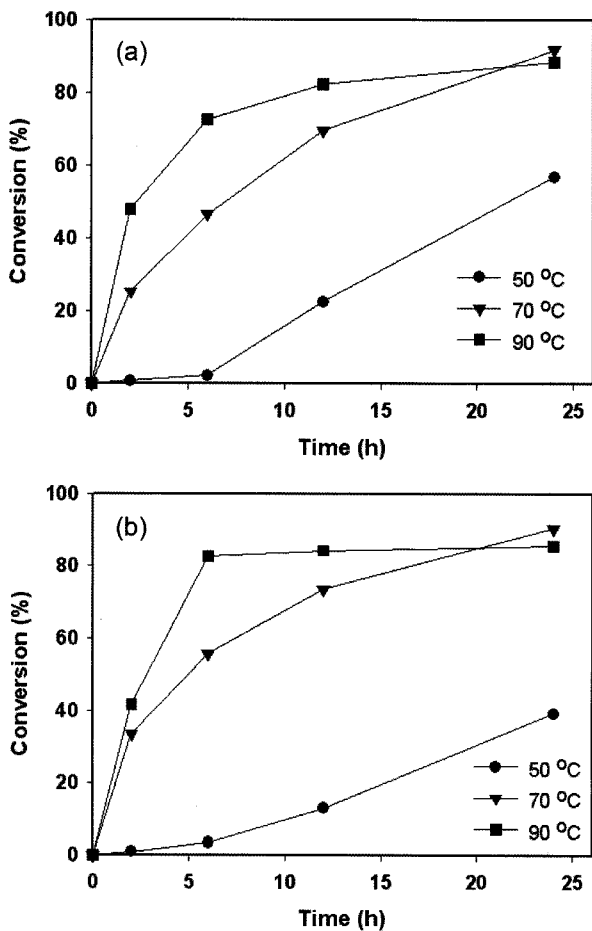
Figure 2. L-Lactide conversion with reaction time with (a) TiCl (O-*i*-Pr)$_3$/SiO$_2$ and (b) Ti(O-*i*-Pr)$_4$/SiO$_2$ at variable temperatures in solution polymerization. Polymerization conditions; L-lactide/ Ti=100, 20 mL toluene, temperature=70 °C.
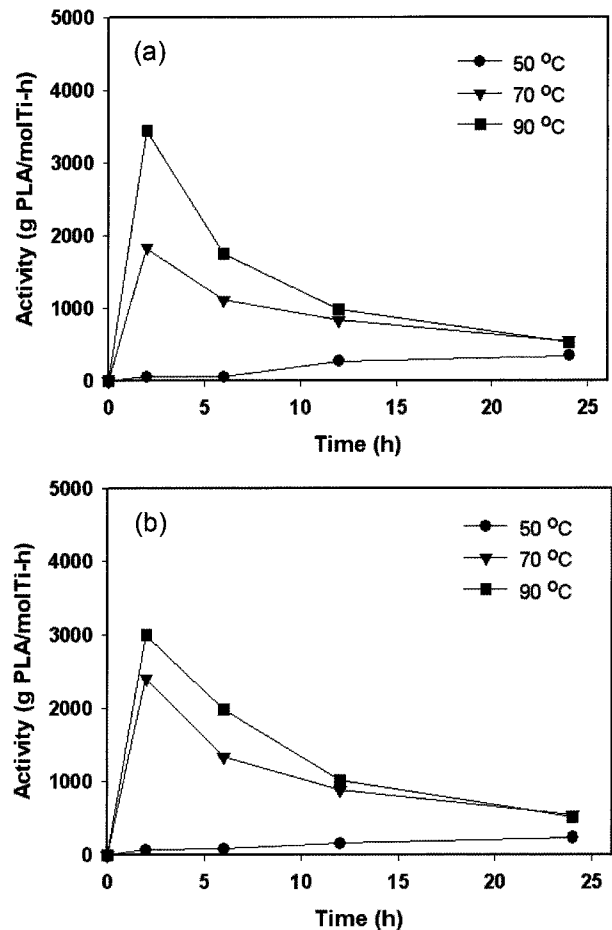
Figure 3. Activity profiles of (a) TiCl(O-*i*-Pr)$_3$/SiO$_2$ and (b) Ti (O-*i*-Pr)$_4$/SiO$_2$ at variable temperatures in solution polymerization. Polymerization conditions; L-lactide/Ti=100, 20 mL toluene, temperature=70 °C.

Table I. Characteristics of Produced PLA by Solution Polymerization with Supported Titanium Alkoxide Catalysts at Variable Temperatures
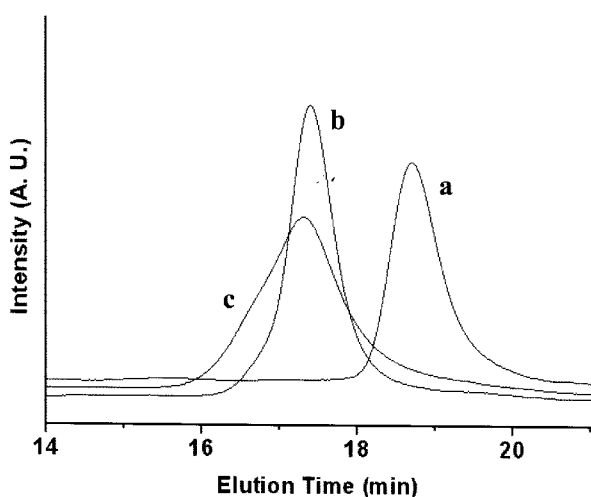
Catalyst	Reaction Temp. (°C)	Conversion(%)	Conversion[a](%)	M_n (g/mol)	M_w (g/mol)	PDI	T_m (°C)
TiCl(O-i-Pr)₃/SiO₂	50	23	57	10,800	12,000	1.11	-
	70	70	92	29,500	36,200	1.23	166.2
	90	82	89	29,000	41,900	1.44	164.2
Ti(O-i-Pr)₄/SiO₂	50	13	39	n.d.[b]	n.d.	n.d.	-
	70	74	91	30,300	36,300	1.20	165.6
	90	84	86	n.d.	n.d.	n.d.	164.8

Polymerization conditions: L-lactide/Ti = 100, 20 mL, temperature = 70 °C, time = 12 h. [a]Time = 24 h. [b]n.d.: Not determined.

tion rate in the beginning of the reaction is unfavorable for high conversion.

Table I shows the characteristics of the PLA produced from solution polymerization with TiCl(O-i-Pr)₃/SiO₂ and Ti(O-i-Pr)₄/SiO₂ at various temperatures. The molecular weight and PDI of the PLA were measured for the polymer samples from 12 h at 50, 70 and 90 °C. The molecular weight and PDI of the PLA with TiCl(O-i-Pr)₃/SiO₂ catalyst increased with increasing reaction temperature. The GPC chromatograms of the PLA produced with both TiCl(O-i-Pr)₃/SiO₂ and Ti(O-i-Pr)₄/SiO₂ showed similar shape and as shown in Figure 4, all the GPC chromatograms of the PLA produced with TiCl(O-i-Pr)₃/SiO₂ at various temperature showed monomodal distributions. The melting temperature of the produced polymers was observed at approximately 165 °C, regardless of the reaction temperature. For PLA conversions less than 40%, the DSC thermographs of the resulting PLA were too broad to determine the melting temperature.

The apparent propagation rate constant (k_p) was calculated to compare the characteristics of polymerization over

two supported catalysts.[28] If the polymerization rate (mol L⁻¹ h⁻¹) is 1st order reaction of monomer and catalyst concentration, the polymerization rate will be represented by the following equation:

$$R_p = -\frac{d[M]}{dt} = k_p[C^*][M] \tag{1}$$

where $[M]$ is the monomer concentration and $[C^*]$ is the active catalyst concentration.

On the other hand, if we assume that the catalyst deactivation effect is negligible, eq. (1) can be integrated to

$$-\frac{\ln(1-x)}{[C^*]_0} = k_p t \tag{2}$$

where $[C^*]_0$ is the initial catalyst concentration. Therefore, k_p is determined from the conversion with time on stream. Table II shows the calculated k_p based on the results of lactide polymerization with the supported titanium alkoxide catalysts. As expected, the propagation rate constants of reactions with TiCl(O-i-Pr)₃/SiO₂ and Ti(O-i-Pr)₄/SiO₂ catalysts significantly increased with increasing reaction temperature. It was observed that the conversions of lactide were similar, despite the fact that the k_p values of TiCl(O-i-Pr)₃/SiO₂ catalyst were greater than those of the Ti(O-i-Pr)₄/SiO₂ catalyst. Note that the apparent propagation rate constants were calculated based on the initial rate of reaction. The k_p values at 90 °C were nearly two times greater than those at
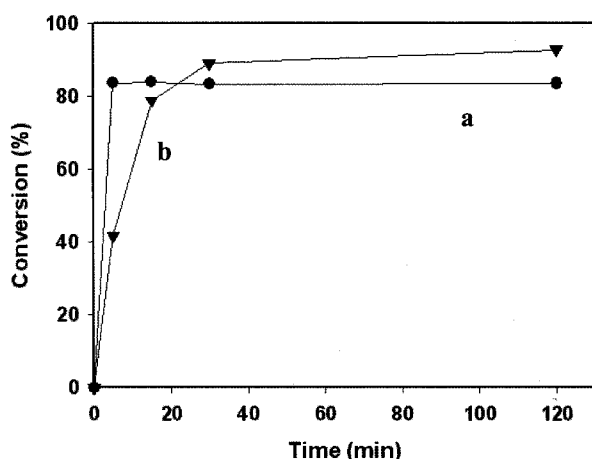

Figure 4. GPC traces of the PLA produced by solution polymerization with TiCl(O-i-Pr)₃/SiO₂ at (a) 50 °C, (b) 70 °C and (c) 90 °C.

Table II. Calculated k_p Values Using an Arrhenius Plot

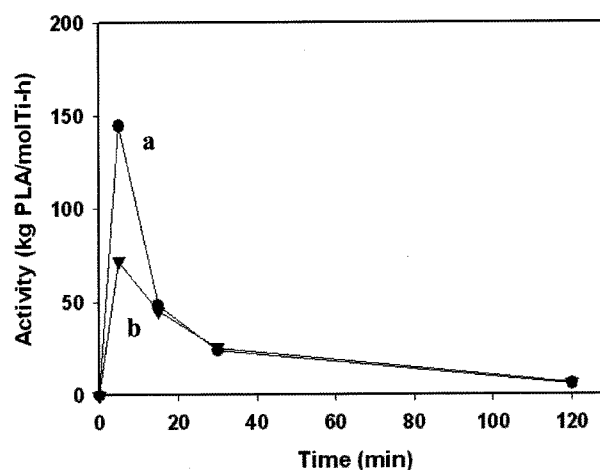| Catalyst	Temperature (°C)	k_p (L/mol·h)
TiCl(O-i-Pr)₃/SiO₂	50	8.9
	70	42.2
	90	93.8
Ti(O-i-Pr)₄/SiO₂	50	5.5
	70	58.7
	90	77.7

70 °C.

Bulk Polymerization with Supported Catalysts. Bulk polymerization of L-lactide was performed at 130 °C with homogeneous and supported TiCl(O-*i*-Pr)₃ or Ti(O-*i*-Pr)₄ catalysts at a L-lactide/catalyst molar ratio of 100. It was observed that a coarse and tangled polymer was obtained in bulk polymerization, while a thin plate-shaped polymer was obtained in solution polymerization.

A plot of the conversion to PLA versus time in the bulk polymerization of L-lactide with TiCl(O-*i*-Pr)₃ and TiCl (O-*i*-Pr)₃/SiO₂ is shown in Figure 5. The catalytic conversion of both TiCl(O-*i*-Pr)₃ and TiCl(O-*i*-Pr)₃/SiO₂ increased with reaction time and the conversion reached approximately 80% within a few minutes. The conversion with homogeneous TiCl(O-*i*-Pr)₃ catalyst remained at approximately 84% after 5 min of reaction. In contrast, the conversion with TiCl(O-*i*-Pr)₃/SiO₂ increased gradually and was 10% greater than the homogeneous TiCl(O-*i*-Pr)₃ catalyst. Note that the catalytic activity of TiCl(O-*i*-Pr)₃ was much greater than that of TiCl(O-*i*-Pr)₃/SiO₂ at the beginning of the reaction, but it rapidly decreased with time on stream in bulk polymerization (Figure 6). The maximum catalytic activity of TiCl(O-*i*-Pr)₃/SiO₂ was 72,133 g PLA/(mol Ti - h) and the activity decreased slowly with time on stream. The

Figure 6. Activity profiles of (a) TiCl(O-*i*-Pr)₃ and (b) TiCl(O-*i*-Pr)₃/SiO₂ in bulk polymerization. Polymerization conditions; L-lactide/Ti=100, temperature=130 °C.

activity profiles of homogeneous and heterogeneous catalysts in bulk polymerization are similar to those in solution polymerization. However, the maximum catalytic activity of TiCl (O-*i*-Pr)₃/SiO₂ in bulk polymerization was 40 times greater than that in solution polymerization due to the higher molar concentration of monomer in the bulk polymerization than in the solution polymerization.

Table III shows the characteristics of PLA produced by bulk polymerization with homogeneous and supported catalysts. It is interesting to observe that the molecular weights of PLA produced with supported catalysts were considerably higher than those with homogeneous catalysts. For supported catalysts, it is thought that not all the active sites of the catalyst particles were used for polymerization. Alternatively, the PLA produced with Ti(O-*i*-Pr)₄/SiO₂ catalyst showed a higher molecular weight and a broader molecular weight distribution than that with the TiCl(O-*i*-Pr)₃/SiO₂ catalyst as shown in Figure 7. The T_m of the polymers produced by the supported catalysts was near 175 °C, which were ca. 15 °C higher than those produced by the homogeneous catalyst. In addition, the T_m of the polymer produced with Ti(O-*i*-Pr)₄/SiO₂ catalyst was higher than that with TiCl(O-*i*-Pr)₃/SiO₂. The higher molecular weight of the

Figure 5. L-Lactide conversion as a function of reaction time for (a) TiCl(O-*i*-Pr)₃ and (b) TiCl(O-*i*-Pr)₃/SiO₂ in bulk polymerization. Polymerization conditions; L-lactide/Ti=100, temperature =130 °C.

Table III. Characteristics of Produced PLA by Bulk Polymerization with Homogeneous and Heterogeneous Titanium Alkoxide Catalysts

Catalyst	Conversion (%)	M_n (g/mol)	M_w (g/mol)	PDI	T_m (°C)
TiCl(O-*i*-Pr)₃	84	11,900	18,800	1.58	160.7
TiCl(O-*i*-Pr)₃/SiO₂	93	31,400	39,200	1.25	173.1
Ti(O-*i*-Pr)₄	68	11,800	21,300	1.81	160.9
Ti(O-*i*-Pr)₄/SiO₂	92	38,800	70,900	1.83	175.6

Polymerization conditions: L-lactide/Ti = 100, temperature = 130 °C, time = 2 h.
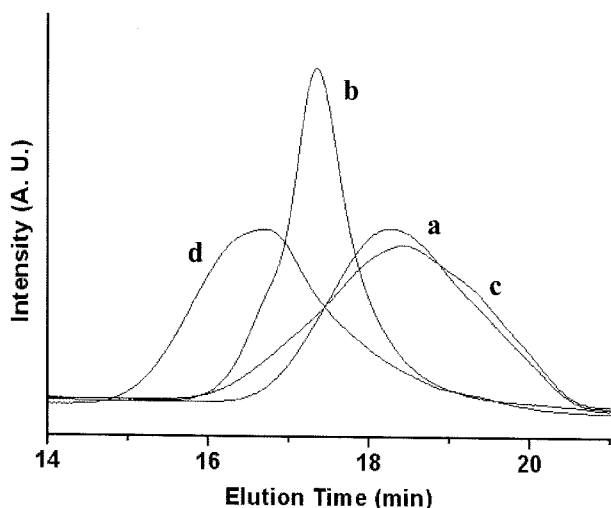
Figure 7. GPC traces of the PLA produced by bulk polymerization with (a) TiCl(O-i-Pr)₃, (b) TiCl(O-i-Pr)₃/SiO₂, (c) Ti(O-i-Pr)₄, and (d) Ti(O-i-Pr)₄/SiO₂.

polymer produced with Ti(O-i-Pr)₄/SiO₂ may explain the differences in the melting temperature.

Conclusions

Silica supported catalysts were prepared by reacting TiCl(O-i-Pr)₃ and Ti(O-i-Pr)₄ with pretreated silica. A series of solution and bulk polymerizations of L-lactide were conducted with the silica supported titanium alkoxide catalysts to compare the catalytic activity and characteristics of resulting PLA under various polymerization conditions. The polymerization with both the supported catalysts showed similar reaction behaviors with respect to the reaction temperature and the catalytic conversion rapidly increased with increasing reaction temperature. When the PLA was synthesized in bulk polymerization, the resulting PLA with supported catalysts had higher molecular weights. Furthermore, the melting temperatures of the PLAs from both TiCl(O-i-Pr)₃/SiO₂ and Ti(O-i-Pr)₄/SiO₂ catalysts were observed 170-180 °C, which is the typical melting temperature range of commercial PLA.

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