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Syntheses of High Molecular Weight Poly(L-phenyllactic acid)s by a Direct Polycondensation in the Presence of Stable Lewis Acids

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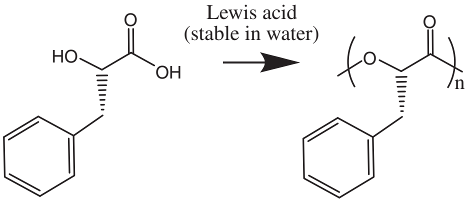
Poly(L-phenyllactic acid)s (PLPhLAs) with high molecular weight were prepared by a direct polycondensation of L-phenyllactic acid in the presence of stable Lewis acids such as $HfCl_4 \cdot 2THF$ under various reaction conditions. As a result, PLPhLAs with a number-average molecular weight (M_n) more than 100000 g mol^{-1} were obtained and showed specific optical rotation $[\alpha]_D^{25}$ of −46° and the glass-transition temperature (T_g) of 55 °C whose absolute values were higher than the reported values and was comparable with T_g of poly(L-lactic acid).

Poly(L-lactic acid)s (PLAs), a biocompatible and biodegradable polyester, have drawn much attention in the chemical industry. PLAs have been majorly applied in medical tools, pharmaceutics, and agrochemistry.[1] However, the application ranges of PLA-based polymers are limited because of the difficulty in controlling the hydrolysis rate, poor hydrophobicity, and brittleness. To overcome those problems, a series of lactic acid derivatives, where the hydrogen in a methyl group were substituted, were polymerized to give poly(butylglycolide), poly(hexylglycolide), and poly(ethylglycolide).[2] L-Phenyllactic acid (LPhLA) is a lactic acid bioderivative produced by *Lactobacillus plantarum*.[3] The incorporation of a bulk aromatic group into lactic acid should be effective to increase the glass-transition temperature, T_g, of the corresponding biobase plastics.[4] The bulky aromatic side group, however, brought about difficulty in solution polymerization; steric hindrance of the benzyl group could lower the polymerization rate.[5] Although direct polymerization of LPhLA[6] and ring-opening polymerization (ROP) of LPhLA[5] have been made, T_g values of poly(L-phenyllactic acid) (PLPhLA) were reported to be lower than the T_g of PLA (55 °C), which might be attributed to low molecular weight less than 20000 g mol^{-1}.

In recent years, stable Lewis acids have been proven to overcome troubles of direct polycondensation of hydroxy acid. These catalysts are rare-earth metal triflate salts[7] and some other metals such as hafnium and vanadium. Stable Lewis acid catalysts have a resistance against inactivation by the water condensed in polymerization of hydroxy acids. The salts of hafnium(IV) were reported to give a higher yield of conversion in direct polycondensation of diacids and diols than conventional catalysts and did not catalyze the transesterification at all.[8] Scandium trifluoromethanesulfonate and scandium trifluoromethanesulfonimide were also reported to have high activity in polycondensation of several diacids and diols even at room temperature.[9]

Here we conduct a one-step polymerization by a direct melt polycondensation of PhLA in the presence of the stable Lewis acids and obtain the T_g of PLPhLA (Scheme 1).



Scheme 1. Poly(L-phenyllactic acid) synthesis by a condensation of L-phenyllactic acid under Lewis acid stable in water.

Table 1. Results of poly(L-phenyllactic acid) syntheses in the presence of various stable Lewis acid

Catalyst	M_w	M_n	M_w/M_n	Yield/%	T_g/°C
$HfCl_4 \cdot 2THF$	183000	58700	3.12	81	55
$Sc(OTf)_3$	129000	76300	1.69	86	47
$Hf(OTf)_4$	214000	104000	2.06	85	55
$Yb(OTf)_3$	195000	95600	2.04	85	45
$VCl_3 \cdot 3THF$	51000	26300	1.94	30	38

In order to find the Lewis acid most suitable for the polymerization of LPhLA, PLPhLA was synthesized in the presence of various stable Lewis acids such as $Sc(OTf)_3$, $Yb(OTf)_3$, $VCl_3 \cdot 3THF$ (THF: tetrahydrofuran), and $Hf(OTf)_4$ in the concentration of 0.5 wt %. The mixtures were stepwise heated at 130 and 150 °C for 3 h each with agitation under nitrogen gas flow and then at 180 °C for 6 h agitation under reduced pressure of 14 kPa. At the last stage, the pressure was reduced to 20 Pa while maintaining the temperature, and the mixture was further agitated for 60 h. Since the polymerization did not proceed at room temperature, it was found that the heating was indispensable in this system. However, a sudden temperature jump to 180 °C induced rapid evaporation of the monomer, which reduced the yield of polymer products. On the other hand, the stepwise heating well restricted the monomer evaporation because of the stable oligomer formation through the initial lower-temperature treatment. The obtained polymers were insoluble in water but soluble in various organic solvents (Table S1[11]). We confirmed the formation of the aimed structure of poly(L-phenyllactic acid) from ^1H NMR spectrum (Figure S1,[11] solvent: DMSO-d_6) The weight- (M_w) and number-average molecular weight (M_n) of the purified polymers were then analyzed and summarized in Table 1 which indicates that all the catalysts used here were effective, and the yields were high except for vanadium chloride. $VCl_3 \cdot 3THF$ had the least activity but ytterbium and hafnium salts had sufficient activity to increase M_n to more than 50000 g mol^{-1}. Especially for the polymerization in the presence of $Hf(OTf)_4$, M_n exceeded 100000 g mol^{-1}. Figure 1 shows the time course of molecular

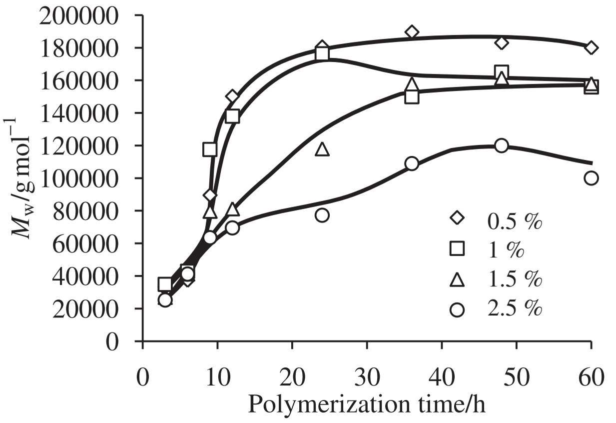


Figure 1. Time course of molecular weights of poly(L-phenyllactic acid) prepared under various amounts of $HfCl_4$.

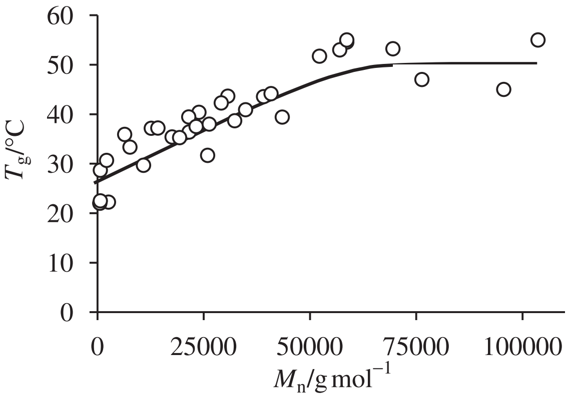


Figure 2. Molecular weight dependence of glass-transition temperature of poly(L-phenyllactic acid)s.

weights of PLPhLA prepared under various amounts of $HfCl_4 \cdot 2THF$. Molecular weights increased and almost saturated at around 40 h. If the polymerization was made for a longer time than 40 h, the molecular weight of the resulting polymers decreased a bit. The reason for the molecular weight decrease may be due to negative effects of Lewis acid, which will be discussed later. The content of Lewis acid still effectively on controlled the molecular weights; while the polymerization speed in the initial 6 h was almost independent of the catalyst content, the polymerization rates under 0.5 and 1 wt % Lewis acid at 6–10 h were higher than those under 1.5 and 2.5 wt %. Excess catalyst was not good for polymerization. This may be similar to the above-mentioned long-time polymerization. The reason is discussed below. The polymerizing liquid became viscous at long reaction times, and condensed water was entrapped in the polymerization liquid. A small ratio of $HfCl_4$ may react with water vapor at over 130 °C for a long producing hydrochloride despite the catalyst being reported to be stable to water. Hydrochloride sometimes promotes the hydrolysis of PLPhLA chains, which may be the main reason for the lower molecular weight of PLPhLA prepared at higher $HfCl_4$ loading or at long reaction times.

Figure 2 shows the glass-transition temperature, T_g, of PLPhLA under various polymerization conditions, where T_g was measured by differential scanning calorimetry (DSC). No melting peak was detected, but a flexion point typical of T_g appeared (Figure S2[11]). A representative DSC curve is shown in Figure S2,[11] and T_g increased with an increase in M_n, which is not unexpected[10] However, the T_g leveled to show a maximum value of 55 °C which was higher than the T_g values of PLPhLA polymers reported in the literature (35–50 °C).[5,6] The higher T_g of PLPhLA in the present study may be attributed to the high molecular weight, which was attained using special Lewis acid stable in water. However, the T_g of PLPhLA was comparable with that of poly(lactic acid) in spite of the presence of a bulky pendant group. The pendant phenyl group may hinder the main chain rotation but widen the interchain gap to weaken the interchain interaction. These opposite effects on the molecular mobility of PLPhLA chains can compete to result in little effect on T_g.

In order to check the racemization, we measured specific optical rotation $[\alpha]_D^{25}$ and obtained negative values from −32 and to −46° increasing with an M_w increase as shown in Table S2. The minimum value is lower than that reported[6b] ($[\alpha]_D^{25} = -38°$), indicating that the higher molecular weight increased the absolute values of $[\alpha]_D^{25}$. Furthermore, we can emphasize thermal racemization was restricted even in a high-temperature condition at 180 °C for 6 h.

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References and Notes

1 A. P. Gupta, V. Kumar, *Eur. Polym. J.* **2007**, *43*, 4053.
2 D. E. Henton, P. Gruber, J. Lunt, J. Randall, in *Natural Fibers, Biopolymers, and Biocomposites*, ed. by A. K. Mohanty, M. Misra, L. T. Drzal, CRC Press, **2005**, p. 543.
3 Y. Kimura, *Polym. J.* **2009**, *41*, 797.
4 T. Kaneko, T. H. Thi, D. J. Shi, M. Akashi, *Nat. Mater.* **2006**, *5*, 966.
5 T. L. Simmons, G. L. Baker, *Biomacromolecules* **2001**, *2*, 658.
6 a) H. Fukuzaki, M. Yoshida, M. Asano, M. Kumakura, K. Imasaka, T. Nagai, T. Mashimo, H. Yuasa, K. Imai, H. Yamanaka, *Eur. Polym. J.* **1990**, *26*, 1273. b) H. Tsuji, H. Matsuoka, S. Itsuno, *J. Appl. Polym. Sci.* **2008**, *110*, 3954.
7 S. Kobayashi, K. Manabe, *Pure Appl. Chem.* **2000**, *72*, 1373.
8 K. Ishihara, S. Ohara, H. Yamamoto, *Science* **2000**, *290*, 1140.
9 A. Takasu, Y. Iio, Y. Oishi, Y. Narukawa, T. Hirabayashi, *Macromolecules* **2005**, *38*, 1048.
10 J. Zhang, Y. Liang, J. Yan, J. Lou, *Polymer* **2007**, *48*, 4900.
11 Supporting Information is available electronically on the CSJ-Journal Web site, http://www.csj.jp/journals/chem-lett/index.html.