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Use of pyrazoles as ligands greatly enhances the catalytic activity of titanium iso-propoxide for the ring-opening polymerization of L-lactide: a cooperation effect⁺

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Using TiOⁱPr₄ with a pyrazole ligand for one-pot LA polymerization improved catalytic activity compared with using TiOⁱPr₄ only. At 60 °C, TiOⁱPr₄ with ^{fur}Pz exhibited a higher catalytic activity (approximately 3fold) than TiOⁱPr₄. At room temperature, TiOⁱPr₄ with ^{Bu}Pz exhibited a higher catalytic activity (approximately 17-fold) than TiOⁱPr₄. High molecular mass PLA ($M_{\text{Depc}} = 51\,100$, and D = 1.10) could be produced by using TiOⁱPr₄ with ^{fur}Pz in melt polymerization ([TiOⁱPr₄] : [^{fur}Pz] = 1000 : 1 : 1 at 100 °C, 240 min). The crystal structure of ${}^{Me}Pz_2Ti_2O^iPr_7$ revealed the cooperative activation between two Ti atoms during LA polymerization.

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Introduction 1.

Petrochemical plastics are extensively used in modern society; however, widely discarded plastic waste pollutes the environment continually1-4 because bacteria cannot decompose it naturally within a short period. To accelerate the environmental degradation of polymers, biodegradable polylactide (PLA)5-7 has been developed for creating a sustainable society. PLA-based biomaterials are used in various fields⁸⁻¹⁸ because of their biocompatible^{19,20} and permeable²¹ physical properties. One of the methods of PLA synthesis is the Lewis acidic metal-catalyzed ring-opening polymerization (ROP) of cyclic esters.²²⁻³¹

For biomaterials, metal residuals present in resulting PLA are a serious problem, and using catalysts with non-cytotoxic metals is a straightforward approach to solving this problem. Because of the non-cytotoxic property and strong Lewis acidity of titanium, Ti

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complexes^{22,23,30-33} are commonly used catalysts in LA ROP. Numerous Ti complexes bearing various ligands such as calix[4] arene,^{33,34} Schiff base,³⁵⁻³⁹ salen,⁴⁰⁻⁴² salan,⁴³⁻⁴⁶ phenolate,⁴⁷⁻⁵⁰ aminophenolate,^{51,52} benzotriazole phenolate,⁵³⁻⁵⁵ phosphinophenolate,⁵⁶ thiophenolate,^{57,58} bis-phenolate-N-heterocyclic carbene,⁴⁵ pyridonate,59,60 and pyrrolide61 have been reported to exhibit considerable catalytic activity or controllability, which is contributed by ligands. However, for most studies, focusing on materials is inconvenient, because the synthesis and purification of Ti catalysts are time-consuming processes. An efficient method of fabricating PLA without time-consuming Ti catalyst-base synthesis and purification is necessary. Herein, commercially available Ti alkoxides was also used catalysts for cyclic esters polymerization.62-65 Recently, dinuclear Ti complexes38 bearing hydrazinebridging Schiff base ligands (Fig. 1) were reported to exhibit



Fig. 1 Strategy of dinuclear Ti complexes in LA polymerization inspired by the literature.

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a high catalytic activity of LA polymerization because of the cooperation between two Ti atoms. Based on this study, if pyrazole is added to LA polymerization with titanium iso-propoxide $(TiO^{i}Pr_{4})$ as a catalyst, bringing two Ti atoms close together to enable dinuclear cooperation is possible. Following this strategy, several pyrazole derivatives (Fig. 2) were added to LA polymerization with a $TiO^{i}Pr_{4}$ catalyst to investigate dinuclear cooperation relative to the mixture of $TiO^{i}Pr_{4}$ and pyrazole.

2. Experimental section

2.1 Chemicals

Standard Schlenk techniques and a N₂-filled glovebox were used all over the isolation and treatment of all the compounds. Solvents, ₁₋ lactide (LA), and deuterated solvents were purified prior to use. LA, ^HPz, ^{Me}Pz, ^{Bu}Pz, ^{Ph}Pz, ^{fur}Pz, ^{thio}Pz, Tz, ^{py}Pz, and ^{MeO}Pz were purchased from Aldrich. ClPz⁶⁶ were prepared following literature procedures. ¹H and ¹³C NMR spectra were recorded on a Varian Gemini 2000-200 (200 MHz for ¹H and 50 MHz for ¹³C) spectrometer. Chemical shifts (in ppm) of ¹H NMR spectra were referenced to tetramethylsilane ($\delta = 0$ ppm) in CDCl₃ as an internal standard, and chemical shifts of ¹³C NMR spectra were reported in ppm referenced to the center line of a triplet at 77.0 ppm of CDCl₃. Microanalyses were performed using a Heraeus CHN-O-RAPID instrument. The gel permeation chromatography (GPC) measurements were performed on a Jasco PU-2080 PLUS HPLC pump system equipped with a differential Jasco RI-2031 PLUS refractive index detector using THF (HPLC grade) as an eluent (flow rate 1.0 mL min⁻¹, at 40 °C). The chromatographic column was JORDI Gel DVB 10⁻³ Å, and the calibration curve was made by primary polystyrene standards to calculate molar masses of PLA. Values of $M_{n_{GPC}}$ were obtained through gel permeation chromatography (GPC) times 0.58.

2.2 Synthesis of MePz₂Ti₂OⁱPr₇

A mixture of ^{Me}Pz (0.96 g, 10 mmol) and TiOⁱPr₄ (2.84 g, 10 mmol) in toluene (20 mL), was stirred at room temperature for 24 h. Volatile materials were removed under vacuum to give light yellow mud, and then hexane was transferred to be the suspension. The light-yellow powder was obtained after filtering, and was recrystallized in toluene to form the crystal. Yield: 1.15 g (33%). ¹H NMR spectrum (CDCl₃, 200 MHz, Fig. S1†) was complex, but it could be assigned that two β -Hs were at 5.59 and 5.43 ppm, and the methine protons of

Table 1 \perp -Lactide polymerization with the mixture of TiOⁱPr₄ and pyrazole derivatives as catalysts in toluene^{*a*}

Entry	Ligand $(TiO^iPr_4:L)$	Time (min)	$\operatorname{Conv.}^{b}(\%)$	$M_{n_{\rm GPC}}^{c}$ (g mol ⁻¹)	$M_{n_{_{NMR}}}^{b}$ (g mol ⁻¹)	D^{c}	$k_{ m obs}~({ m min}^{-1})$
1^d	$^{\text{thio}}$ Pz (1:0.5)	50	85	3900	3300	1.30	0.035
2^d	$^{\text{thio}}$ Pz (1:1)	45	86	4700	4600	1.51	0.036
3^d	$^{\text{thio}}$ Pz (1:2)	125	84	7000	6000	2.10	0.008
4^d	(1:4)	220	99	7400	6500	2.02	0.013
5	$^{\text{thio}}$ Pz (1:1)	10	87	2300	2200	1.27	0.232
6	L free	22	92	2100	1600	1.75	0.161
7	$^{\rm H}$ Pz (1 : 1)	8	88	2600	2100	1.31	0.285
8	$^{Me}Pz(1:1)$	13	94	7100	4400	1.68	0.233
9	$^{Cl}Pz(1:1)$	14	89	1900	1800	1.13	0.166
10	$^{Bu}Pz(1:1)$	9	95	2100	1700	1.23	0.394
11	$^{Ph}Pz(1:1)$	10	94	2500	2000	1.25	0.334
12	$^{\mathrm{fur}}\mathrm{Pz}\ (1:1)$	5	86	2200	2100	1.23	0.418
13	$^{\mathrm{py}}\mathrm{Pz}\ (1:1)$	15	88	2000	2200	1.18	0.152
14	MeO Pz (1 : 1)	10	92	6500	3000	1.38	0.288
15	Tz(1:1)	20	87	1900	1800	1.12	0.120
16^e	^{Me}Pz (1 : 1)	16	88	1800	1700	1.10	—
17 ^f	^{Me}Pz (1 : 1)	25	89	3900	3600	1.27	_
18^g	^{Me}Pz (1 : 1)	24	80	5500	5200	1.27	_
19^h	^{Me}Pz (1 : 1)	45	87	8500	7900	1.32	—
20^i	$^{Me}Pz(1:1)$	95	90	13 100	12 500	1.49	_
21^j	L ^H -TiOPr ₆ ³⁸	50	89	3100	_	1.25	0.065

^{*a*} In general, the reaction was carried out in 5 mL toluene with [LA] = 2 M at 60 °C for LA polymerization ($[LA] : [TiO^{i}Pr_{4}] = 50 : 1$). ^{*b*} The data were determined using ¹H NMR analysis. ^{*c*} Values of $M_{n_{GPC}}$ were corrected considering Mark–Houwink factor (0.58) from polystyrene standards in THF. ^{*d*} [LA] = 1 M, in 5 mL toluene, $[LA] : [TiO^{i}Pr_{4}] = 100 : 1$. ^{*e*} $[LA] : [TiO^{i}Pr_{4}] : [M^{e}Pz] = 50 : 1 : 1$, $[TiO^{i}Pr_{4}] = 13.4 \text{ mM}$ in toluene 15 mL. ^{*f*} $[LA] : [TiO^{i}Pr_{4}] : [M^{e}Pz] = 100 : 1 : 1$, $[TiO^{i}Pr_{4}] = 13.4 \text{ mM}$ in toluene 15 mL. ^{*g*} $[LA] : [TiO^{i}Pr_{4}] : [M^{e}Pz] = 150 : 1 : 1$, $[TiO^{i}Pr_{4}] = 13.4 \text{ mM}$ in toluene 15 mL. ^{*f*} $[LA] : [TiO^{i}Pr_{4}] : [M^{e}Pz] = 200 : 1 : 1$, $[TiO^{i}Pr_{4}] = 13.4 \text{ mM}$ in toluene 15 mL. ^{*i*} $[LA] : [TiO^{i}Pr_{4}] : [M^{e}Pz] = 300 : 1 : 1$, $[TiO^{i}Pr_{4}] = 13.4 \text{ mM}$ in toluene 15 mL. ^{*i*} $[LA] : [TiO^{i}Pr_{4}] : [M^{e}Pz] = 300 : 1 : 1$, $[TiO^{i}Pr_{4}] = 13.4 \text{ mM}$ in toluene 15 mL. ^{*i*} $[LA] : [TiO^{i}Pr_{4}] : [M^{e}Pz] = 300 : 1 : 1$, $[TiO^{i}Pr_{4}] = 13.4 \text{ mM}$ in toluene 15 mL. ^{*i*} $[LA] : [TiO^{i}Pr_{4}] : [M^{e}Pz] = 300 : 1 : 1$, $[TiO^{i}Pr_{4}] = 13.4 \text{ mM}$ in toluene 15 mL. ^{*i*} $[LA] : [TiO^{i}Pr_{4}] : [M^{e}Pz] = 300 : 1 : 1$, $[TiO^{i}Pr_{4}] = 13.4 \text{ mM}$ in toluene 15 mL. ^{*i*} $[LA] : [TiO^{i}Pr_{4}] : [M^{e}Pz] = 300 : 1 : 1$, $[TiO^{i}Pr_{4}] = 13.4 \text{ mM}$ in toluene 15 mL. ^{*i*} $[LA] : [TiO^{i}Pr_{4}] = 100 : 1 : 1$, $[TiO^{i}Pr_{4}] =$



Fig. 3 Linear plot of various $M_{n_{cal.}}$ with the supposed initiators and $M_{n_{cal.}}$ against [LA]₀ × conv./[TiOⁱPr₄] (Table 1, entries 16–20).

isopropyl oxide were at 4.92–4.28 ppm, and dimethyl groups of ^{Me}Pz were at 2.39 and 2.14 ppm.

3. Results and discussion

3.1 Polymerization of LA

Table 1 presents the conditions for optimizing LA polymerization by using a mixture of $TiO^{i}Pr_{4}$ and ^{thio}Pz as the catalyst. Entries 1–5 in Table 1 reveal that the 1 : 1 ratio of $TiO^{i}Pr_{4}$ and

^{thio}Pz ([LA] = 1 M, $[TiO^{i}Pr_{4}] = 10$ mM) exhibited the fastest polymerization rate. When [LA] was increased to 2 M with 40 mM of [TiOⁱPr₄], after 10 min, the conversion became 87%. Under this condition ([LA] = 2 M, [LA]: $[TiO^{i}Pr_{4}]$: $[^{thio}Pz]$ = 50:1:1 in 5 mL toluene), various pyrazole derivatives were used to analyze LA polymerization, and all pyrazole derivatives improved the catalytic activity of TiOⁱPr₄, except ^{py}Pz and Tz in the following order: ${}^{\text{fur}}\text{Pz} > {}^{\text{Bu}}\text{Pz} > {}^{\text{Ph}}\text{Pz} > {}^{\text{MeO}}\text{Pz} > {}^{\text{H}}\text{Pz} > {}^{\text{Me}}\text{Pz} = {}^{\text{thio}}\text{Pz} >$ ^{Cl}Pz > ^{py}Pz > Tz. Although ^{Me}Pz improved the catalytic activity of $TiO^{i}Pr_{4}$, it provided low controllability (dispersity, D = 1.68). To solve this problem, the TiOⁱPr₄ concentration was decreased from 20 to 13.4 mM, and the D value was decreased to 1.10. LA polymerization using TiOⁱPr₄ (13.4 mM) as a catalyst with ^{Me}Pz was systematically investigated with the [LA]/[TiOⁱPr₄] ratio ranging from 50 to 300 (entries 16-20). The results revealed that LA polymerization was controllable, confirmed by the linear relationship between $[LA]_0/[TiO^iPr_4]$ and $M_{n_{GPC}}$ (Fig. 3). However, the controllability in the [LA]/[TiOⁱPr₄] ratio of 300 (D = 1.49, entry 20 in Table 1) was low, and it may be ascribed to transesterification67 because of the long polymerization time at 60 °C. Fig. 3 revealed that four isopropoxides of TiOⁱPr₄ could be initiators to initiate LA. TiOⁱPr₄ with thioPz exhibited a higher catalytic activity (3.5 folds) in LA polymerization than L^H-TiOPr₆ (entry 21)³⁸ did.

A survey of LA ROP using Ti complexes as catalysts revealed that few Ti catalysts could polymerize LA at room temperature. Therefore, LA polymerization was conducted at room temperature (Table

$\mathcal{D}^{b}(\mathrm{g} \mathrm{mol}^{-1}) \qquad \mathcal{D}^{c} \qquad k_{\mathrm{o}}$	$_{\rm bs} imes 10^3 ({ m min}^{-1})$
1.25 0.1	3
1.12 3.0	0
1.08 0.4	9
1.08 2.0	0
1.07 5.0	0
1.12 1.0	0
1.08 4.0	0
1.08 2.0	0
1.08 2.4	4
1.08 2.0	0
1.11 0.	7
1.08 —	-
1.09 —	-
1.11	
1.27	
1.13 —	-
1.09 —	-
1.16 —	-
1.14 —	-
1.10	
1.26	
	1.14 - 1.10 - 1.26

Table 2 \perp -Lactide polymerization with the mixture of TiOⁱPr₄ and pyrazole derivatives as catalysts in CH₂Cl₂ at room temperature^a

^{*a*} In general, the reaction was carried out in 2.5 mL CH₂Cl₂ with [LA] = 2 M at room temperature for LA polymerization ($[LA] : [TiOⁱPr_4] = 25 : 1$). ^{*b*} The data were determined using ¹H NMR analysis. ^{*c*} Values of $M_{n_{crc}}$ were corrected considering Mark-Houwink factor (0.58) from polystyrene standards in THF. ^{*d*} $[LA] : [TiOⁱPr_4] : [^{fur}Pz] = 37.5 : 1 : 1$, $[TiOⁱPr_4] = 0.08$ M in 2.5 mL CH₂Cl₂. ^{*e*} $[LA] : [TiOⁱPr_4] : [^{fur}Pz] = 43.75 : 1 : 1$, $[TiOⁱPr_4] = 0.08$ M in 2.5 mL CH₂Cl₂. ^{*e*} $[LA] : [TiOⁱPr_4] : [^{fur}Pz] = 62.5 : 1 : 1$, $[TiOⁱPr_4] = 0.08$ M in 2.5 mL CH₂Cl₂. ^{*f*} $[LA] : [TiOⁱPr_4] : [^{fur}Pz] = 62.5 : 1 : 1$, $[TiOⁱPr_4] = 0.08$ M in 2.5 mL CH₂Cl₂. ^{*f*} $[LA] : [TiOⁱPr_4] : [^{fur}Pz] = 62.5 : 1 : 1$, $[TiOⁱPr_4] = 0.08$ M in 2.5 mL CH₂Cl₂. ^{*f*} $[LA] : [TiOⁱPr_4] : [^{fur}Pz] = 62.5 : 1 : 1$, $[TiOⁱPr_4] = 0.08$ M in 2.5 mL CH₂Cl₂. ^{*f*} $[LA] : [TiOⁱPr_4] : [^{fur}Pz] = 62.5 : 1 : 1$, $[TiOⁱPr_4] = 0.08$ M in 2.5 mL CH₂Cl₂. ^{*f*} $[LA] : [TiOⁱPr_4] : [^{fur}Pz] = 62.5 : 1 : 1$, $[TiOⁱPr_4] = 0.08$ M in 2.5 mL CH₂Cl₂. ^{*f*} $[LA] : [TiOⁱPr_4] : [^{fur}Pz] = 62.5 : 1 : 1$, $[TiOⁱPr_4] = 0.08$ M in 2.5 mL CH₂Cl₂. ^{*f*} $[LA] : [TiOⁱPr_4] : [^{fur}Pz] = 62.5 : 1 : 1$, $[TiOⁱPr_4] = 0.08$ M in 2.5 mL CH₂Cl₂. ^{*f*} $[LA] : [TiOⁱPr_4] : [^{fur}Pz] = 62.5 : 1 : 1$, $[TiOⁱPr_4] = 0.08$ M in 2.5 mL CH₂Cl₂. ^{*f*} [LA] : [^{fur}Pz] = 62.5 : 1 : 1, $[TiOⁱPr_4] = 0.08$ M in 2.5 mL CH₂Cl₂. ^{*f*} [LA] : [^{fur}Pz] = 62.5 : 1 : 1, $[TiOⁱPr_4] = 0.08$ M in 2.5 mL CH₂Cl₂. ^{*f*} [LA] : [^{fur}Pz] = 62.5 : 1 : 1, $[TiOⁱPr_4] = 0.08$ M in 2.5 mL CH₂Cl₃. ^{*i*} [Iar + 1c] = 0.003, $[LA] : [TiOⁱPr_4] = 0.08$ M in 2.5 mL CH₂Cl₃. ^{*fur* [Tar + 1] = 0.003 M in 2.5 mL CH₂Cl₃. ^{*fur* [Tar + 1] = 0.003 M in 2.5 mL CH₂Cl₃. ^{*fur* [Tar + 1] = 0.003 M in 2.5 mL CH₂Cl₃. ^{*fur* [Tar + 1] = 0.003 M in 2.5 mL CH₂Cl₃. ^{*fur* [Tar + 1] = 0.003 M in 2.5 mL}}}}}

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Fig. 4 Linear plots of $M_{n_{GPC}}$ versus ([LA]₀ × conv.)/[TiOⁱPr₄]. Blue solid dots indicate Ds.



Fig. 5 ¹H NMR spectrum of PLA (entry 13 in Table 2).

All pyrazole derivatives improved the catalytic activity of $TiO^{i}Pr_{4}$ in the following order: $^{Bu}Pz > ^{fur}Pz > ^{H}Pz > ^{Py}Pz > ^{Cl}Pz =$ $^{\text{thio}}Pz = {}^{\text{MeO}}Pz > {}^{\text{Ph}}Pz > {}^{\text{Me}}Pz > Tz$ (Table 2). In the CH₂Cl₂ solution, the pyrazole ligand provided the benefit of considerable improvement of the catalytic reaction. For example, k_{obs} of TiOⁱPr₄ with ^{Bu}Pz was 17 times higher than that of TiOⁱPr₄, and $k_{\rm obs}$ of TiOⁱPr₄ with ^{fur}Pz was 13 times higher than that of TiOⁱPr₄. In addition, the controllability of TiOⁱPr₄ with all pyrazole derivatives was improved (D = 1.07-1.12). Although TiOⁱPr₄ with ^{Bu}Pz revealed the highest polymerization rate, ^{Bu}Pz is overly expensive. Therefore, ^{fur}Pz was used as a ligand with TiOⁱPr₄ as a catalyst to polymerize LA with various ratios of [LA]/ [TiOⁱPr₄] (entries 12–19, Table 2). The [LA]/[TiOⁱPr₄] ratio from 37.5 to 62.5 was investigated, and the molecular mass $(M_{n_{opc}})$ of PLA increased from 1400 to 2100. According to the solubility of LA in CH_2Cl_2 , the limit of the $[LA]/[TiO^iPr_4]$ ratio is 62.5 (1.80 g of LA in 2.5 mL CH₂Cl₂), and PLA with high molecular mass PLA cannot be synthesized by increasing the [LA]/[TiOⁱPr₄] ratio.

To investigate the living property^{68,69} of TiOⁱPr₄ with the pyrazole ligand in LA polymerization, first, LA was polymerizated ($[LA] : [TiOⁱPr_4] : [^{fur}Pz] = 100 : 4 : 4 in CDCl₃, entry 16 in$ Table 2). After 390 min, the conversion was 84%, and 100 equivalents of LA were reloaded into the solution (entry 17 in Table 2). However, the polymerization time increased to 895 min with a 92% conversion. Subsequently, 100 equivalents of LA were reloaded into the solution (entry 18 in Table 2), and the polymerization rate decreased. After 1495 min, the conversion was 83%, and 100 equivalents of LA were reloaded into the solution (entry 19 in Table 2). The solution could not be stirred after 2000 min with a 72% conversion. The slower LA polymerization rate can be ascribed to the higher viscosity of the polymerizated solution. On the basis of the linear relationship between $M_{n_{GPC}}$ and ([LA]₀ × conv.)/[TiOⁱPr₄] (entries 7, and 12–19 in Table 2 and Fig. 4), TiOⁱPr₄ with the pyrazole ligand demonstrated a high controllability with narrow D for LA polymerization. To confirm that PLA with high molecular mass can be synthesized using TiOⁱPr₄ with the pyrazole ligand, LA was polymerizated using TiOⁱPr₄ with ^{fur}Pz ([LA] : [TiOⁱPr₄] : [^{fur}Pz] = 1000:1:1 at 100 °C without solvent, entry 20 in Table 2). After 240 min, the conversion was 93%, and PLA ($M_{n_{GPC}}$ =



Fig. 6 MALDI-TOF spectrum of PLA (entry 13 in Table 2).



Fig. 7 Molecular plot of ^{Me}Pz₂Ti₂OⁱPr₇ with 20% probability ellipsoids (all hydrogen atoms were omitted for clarity).

51 100, and D = 1.10) was obtained. Compared with LA polymerization using TiOⁱPr₄ without ^{fur}Pz (240 min, conv. = 52%, $M_{n_{GPC}} = 31\ 600$, D = 1.26, entry 21 in Table 2), adding ^{fur}Pz to LA polymerization improved the polymerization rate and enhanced the controllability for producing PLA.

The ¹H nuclear magnetic resonance (NMR) spectrum of PLA (entry 2 in Table 2 and Fig. 5) confirmed the presence of one isopropyl oxide group (peak a) and a hydroxyl chain end (peak c'), suggesting that initiation occurred through insertion of an isopropyl oxide into LA. The matrix-assisted laser desorption/ ionization time-of-flight (MALDI-TOF) mass spectrum of PLA (entry 5 in Table 2 and Fig. 6) revealed the presence of isopropyl oxide group at the end of the PLA chain.

3.2 Synthesis and characterization of MePz₂Ti₂OⁱPr₇

To determine what was the real catalysis mechanism in the polymerization process, the reaction of ${}^{Me}Pz$ and $TiO^{i}Pr_{4}(1:1)$ in toluene was investigated. Fig. 7 illustrates the crystal of $^{Me}Pz_2Ti_2O^{i}Pr_7$ (CCDC 1568213, Table S4[†]). However, the ¹H NMR spectrum (Fig. S3†) revealed that ${}^{Me}Pz_{2}Ti_{2}O^{i}Pr_{7}$ was impure. The crystal data of MePz2Ti2OiPr7 indicated that the Ti-Ti distance was 3.2322(14) Å, which is slightly shorter than that of L^{Bu}-TiOPr₆³⁸ distance (3.242 Å), and it implied the cooperative activation can occur in this system. To prove that ^{Me}Pz₂Ti₂OⁱPr₇ is the real catalyst in LA polymerization, the crystal of impure ${}^{Me}Pz_{2}Ti_{2}O^{i}Pr_{7}$ was used as a catalyst in LA polymerization with the polymerization condition of entry 17 of Table 1 $([LA] : [{}^{Me}Pz_2Ti_2O^{i}Pr_7] = 100 : 0.5, [{}^{Me}Pz_2Ti_2O^{i}Pr_7] = 6.7 \text{ mM at}$ 60 °C in 15 mL toluene). After 16 min, the conversion was 95% with $M_{n_{GPC}} = 4900$, D = 1.56, and $k_{obs} = 0.203 \text{ (min}^{-1}\text{)}$, and the results were similar to the results of entry 17 of Table 1 (conversion was 89% after 25 min).

4. Conclusions

Our strategy of using TiOⁱPr₄ with pyrazole ligand for one-pot LA polymerization successfully improved the catalytic activity

compared with using TiOⁱPr₄ only. The crystal structure of ${}^{Me}Pz_2Ti_2O^iPr_7$ revealed cooperative activation between two Ti atoms during LA polymerization. These results can provide a straightforward approach to synthesize PLA by using TiOⁱPr₄ as a catalyst. In future, we intend to investigate the mechanism of LA polymerization.

Conflicts of interest

There are no conflicts to declare.

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