D_015_PF: SYNTHESIS OF HIGH MOLECULAR WEIGHT POLY(ε-CAPROLACTONE) USING TITANIUM(IV) n-BUTOXIDE AS EFFECTIVE INITIATOR

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Abstract: In this work, high molecular weight poly(ε-caprolactone) (PCL) was synthesized from the ring–opening polymerization (ROP) of ε-caprolactone (ε-CL) initiated by titanium(IV) n-butoxide (Ti(OnBu)$_4$). The polymerizations of ε-CL with different concentrations of Ti(OnBu)$_4$ initiator (0.025 – 0.200 mol%) were carried out under bulk condition (solvent free process) at 150 °C for 24 h. The molecular weights of the synthesized PCL were determined from the conventional gel permeation chromatography (GPC) technique. From bulk polymerization, Ti(OnBu)$_4$ could control the polymerization of ε-CL and molecular weight of PCL. The physical appearances of the purified PCL were varied from white powder to white fiber. The number average molecular weights (M_n) of the synthesized PCL were in the range of 2.01×10^4 – 4.62×10^4 g/mol with molecular weight distribution (MWD) of 1.80 – 1.93. Furthermore, the values of %yield for the synthesized PCLs were in the range of 90 – 93%. The polymerization mechanism of ε-CL with Ti(OnBu)$_4$ was proposed through the coordination–insertion mechanism. The condition used in this work could effectively improve the molecular weight of PCL obtained from the ROP of ε-CL with Ti(OnBu)$_4$ reported in literature.

Introduction: Biodegradable aliphatic polyesters have considered as important material that can be used to replace the petroleum based polymer in the future. Polylactides and polylactones are the well known biodegradable polyester which can be utilized in many applications [1]. Traditionally, they are synthesized from the ring–opening polymerization (ROP) of cyclic esters through the coordination–insertion mechanism [2]. In this mechanism, many organometallic compounds especially covalent metal alkoxides (MOR) and metal carboxylates (MCOOR) have been used as initiating system. Among these, tin(II) octoate (Sn(Oct)$_2$) is the most frequently and widely used in the ROP of cyclic esters [3]. However, Sn(Oct)$_2$ is not a true initiator because it reacts with hydroxyl containing compounds to form tin(II) alkoxide before initiates polymerization [4]. The direct synthesis of tin(II) alkoxide seems to be an effective route for control of polymerization of cyclic esters and molecular weight of polymers [5]. Other metal alkoxides with different metal centers such as Al(III) [6] Sn(IV) [7] and Ti(IV) [8] were also studied and developed for control synthesis of biodegradable polyesters. Titanium(IV) alkoxide (Ti(OR)$_4$) catches our attention due to its high solubility in monomer, commercially available and high reaction rate.

Li *et al.* [8] reported the kinetics of the ROP of ε-caprolactone (ε-CL) with the novel double bond containing titanium(IV) alkoxide initiator (Ti[O(CH$_2$)$_4$OCH=CH$_2$]$_4$). Differential scanning calorimetry (DSC) was employed to investigate the dependency of polymerization rate with initiator concentration. The number average molecular weight (M_n) and molecular weight distribution (MWD) of PCLs were in the range of 9.40×10^3 – 2.37×10^4 g/mol and 1.76 – 2.36, respectively. Meelua *et al.* [9] also studied the steric interference of Ti(OR)$_4$ structure on the ROP of ε-CL by using non–isothermal DSC technique. Titanium(IV) n-propoxide, titanium(IV) n-butoxide, titanium(IV) *tert*-butoxide and titanium(IV) 2-ethylhexoxide were utilized as initiator in the ROP of ε-CL. They found that the activation energy (E_a) for the ROP of ε-CL initiated by titanium(IV) n-propoxide < titanium(IV)

n–butoxide ≈ titanium(IV) 2–ethylhexoxide < titanium(IV) *tert*–butoxide. Furthermore, they also synthesized PCL by using these Ti(OR)₄ initiators via bulk polymerization at 120 °C for 72 h. It was founds that the M_n of the synthesized PCLs were lower 1.88×10⁴ g/mol. Moreover, their synthesis process also gave board MWD values (> 3.0) of PCLs.

      Therefore, it is interesting that Ti(OR)₄ seems to be reactive initiator in the ROP of *ε*–CL but it produces low molecular weight of PCL. This indicates that the synthesis process reported in literatures is not suitable for Ti(OR)₄. This impacts our attention to develop the synthesis process that can produce higher molecular weight of PCL by using Ti(OR)₄ as initiator. The objective of this work is to synthesize high molecular weight PCL via bulk polymerization by using titanium(IV) *n*–butoxide as initiator. The molecular weight average and MWD of all synthesized PCLs are determined from gel permeation chromatography (GPC) technique. Furthermore, the polymerization mechanism of *ε*–CL with titanium(IV) *n*–butoxide is also described.

Methodology:

Materials preparation: *ε*–Caprolactone (Sigma–Aldrich, 99.0%) was purified by vacuum distillation and kept in round bottom flask under vacuum before used. Titanium(IV) *n*–butoxide (Sigma, 97.0%) was used as received. Methanol (Qrec, 99.0%) and chloroform (LabScan, 99.5%) were used without purification.

Synthesis of poly(ε-caprolactone) via bulk polymerization: *ε*–CL (4 g) with different concentrations of titanium(IV) *n*–butoxide (Ti(O*n*Bu)₄) were weighed in 10 mL dried round bottom flasks which were further closed by glass stopper under nitrogen atmosphere. The prepared reaction flasks were immersed into preheated silicone oil bath at 150 °C for 24 h. After complete 24 h, the flasks were cooled down at room temperature followed by ice bath. The obtained crude PCLs were dissolved in CHCl₃ and precipitated in cold methanol. The purified PCLs were dried in vacuum oven until constant weight was reached.

Polymer characterization: The molecular weight averages and molecular weight distribution (MWD) of purified PCLs were determined by gel permeation chromatography (GPC) technique (Waters e2695 GPC) at 35 °C using tetrahydrofuran (THF) as eluent.

Results and Discussion: The ring–opening polymerization (ROP) of cyclic esters with metal containing initiator can be investigated by many techniques such as gravimetry [10], spectroscopy [11] and calorimetry [6, 7, 9]. As reported by Meelua *et al.* [9], the ROP of *ε*–CL with different titanium(IV) alkoxides initiator (Ti(OR)₄) can be effectively investigated by differential scanning calorimetry (DSC) technique. In their work, the reactivity of four different Ti(OR)₄ initiators such as titanium(IV) *n*–propoxide, titanium(IV) *n*–butoxide, titanium(IV) *tert*–butoxide and titanium(IV) 2–ethylhexoxide has been compared and discussed. They found that the reactivity of Ti(OR)₄ in the ROP of *ε*–CL depended on the steric hindrance around Ti–O active center. The reactivity of Ti(OR)₄ in the ROP of *ε*–CL was determined in the following order: titanium(IV) *n*–propoxide > titanium(IV) *n*–butoxide ≈ titanium(IV) 2–ethylhexoxide > titanium(IV) *tert*–butoxide. From DSC analysis, the reactivity of titanium(IV) *n*–propoxide and titanium(IV) *n*–butoxide in the ROP of *ε*–CL is high because they initiate the polymerization of *ε*–CL at low temperature (150 °C). They seem to be more reactive than those of tributyltin(IV) alkoxides (Bu₃SnOR; R = Me, Eth, *n*Pr and *n*Bu) initiators that initiate polymerization of *ε*–CL at 180 °C [7]. Furthermore, the obtained DSC polymerization exotherms for the ROP of *ε*–CL initiated by Ti(OR)₄ are sharper and more symmetry than Bu₃SnOR initiators. The efficiency of all Ti(OR)₄ initiators in the synthesis of PCL is also investigated via bulk polymerization. Their results show that the molecular weight of PCL increases with decreasing of Ti(OR)₄ initiators. When compared the molecular weight of the PCL synthesized from the ROP of *ε*–CL with Ti(OR)₄ initiators at a similar concentration of 0.010 mol%, it is found

that titanium(IV) *n*-butoxide produces the highest molecular weight of PCL as shown in Table 1.

Table 1. GPC analysis for PCL obtained from bulk polymerization of ε-CL initiated by different Ti(OR)$_4$ initiators at 120 $^\circ$C for 72 h reported in literature [9].

Initiators	[Ti(OR)$_4$] (mol%)[a]	M_n (g/mol)[a]	MWD [a]	%Yield (%) [b]
Titanium(IV) *n*-propoxide		1.29×10^4	2.42	94
Titanium(IV) *n*-butoxide	0.010	1.85×10^4	3.13	93
Titanium(IV) *tert*-butoxide		1.57×10^4	3.21	92
Titanium(IV) 2-ethylhexoxide		1.51×10^4	3.64	93

[a] Determined from GPC technique by using THF as eluent.
[b] Calculated from the weight of PCL obtained after filtration.

It is interesting that the number average molecular weight of PCLs synthesized by the ROP of ε-CL using Ti(OR)$_4$ as initiator are low ($M_n < 1.88\times10^4$ g/mol) and MWD values are high (> 3.0). Broad MWD values (> 3.0) indicate that the transesterification reaction occurred that decreases the molecular weight of PCL. Moreover, the molecular weight of PCL does not correspond to the reactivity of Ti(OR)$_4$ initiators. In fact, high molecular weight PCL should be obtained from highly reactive initiators. The results clearly demonstrated that the synthesis condition used in their work seem to be unsuitable for the reactive Ti(OR)$_4$ initiators.

Therefore, we try to improve the effectiveness of Ti(OR)$_4$ in synthesizing high molecular PCL via bulk polymerization. Titanium(IV) *n*-butoxide is selected because it produces high reaction rate and molecular weight of polymer. Firstly, we increase the polymerization temperature from 120 to 150 $^\circ$C. From our previous work, the increasing of temperature can increase the molecular weight of PCL [6]. Moreover, we also decrease the polymerization time from 72 to 24 h to reduce the transesterification. From the results, it is found that titanium(IV) *n*-butoxide is rapidly and completely dissolved in ε-CL monomer resulting in an accurate initiator concentration. This synthesis condition is suitable for the reactive titanium(IV) *n*-butoxide initiator. The physical appearances of the synthesized PCL are depicted in Figure 1. From Figure 1, the synthesized PCLs are white powder to white fiber. The purified PCLs shown Figure 1 are further analyzed by GPC technique. The GPC analysis of those PCL samples is summarized in Table 2.
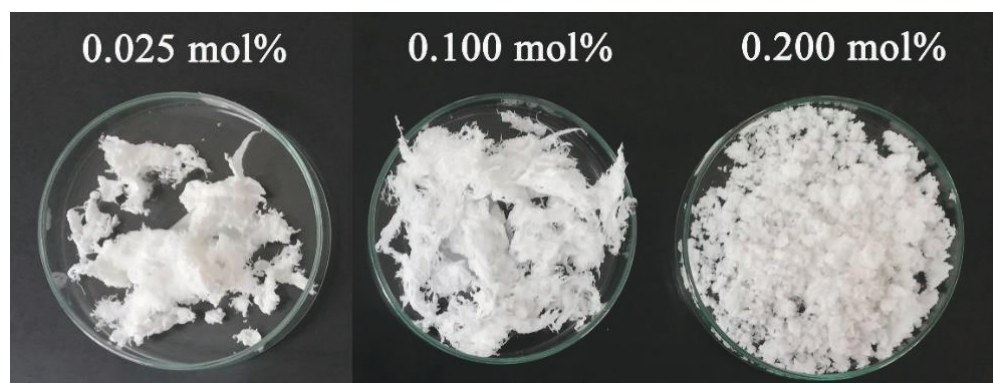

Figure 1. The physical appearances of purified PCL obtained from bulk polymerization of ε-CL initiated by different concentrations of titanium(IV) *n*-butoxide at 150 $^\circ$C for 24 h.

Table 2. GPC analysis for PCL obtained from bulk polymerization of ε-CL initiated by different concentrations of titanium(IV) n-butoxide at 150 °C for 24 h.

[Ti(OnBu)$_4$] (mol%)	M_n (g/mol)[a]	M_w (g/mol)[a]	MWD [a]	%Yield (%) [b]
0.025	4.62×10^4	8.32×10^4	1.80	91
0.100	3.14×10^4	5.84×10^4	1.86	93
0.200	2.01×10^4	4.00×10^4	1.93	90

[a] Determined from GPC technique by using THF as eluent.
[b] Calculated from the weight of PCL obtained after filtration.

From Table 2, it is found that the molecular weights of PCL are controlled by adjusting titanium(IV) n-butoxide concentration. The molecular weight of PCL increases with decreasing of titanium(IV) n-butoxide concentration similar to literatures [6, 9]. Furthermore, the molecular weights of PCL shown in Table 2 are higher than PCLs synthesized by the condition reported by Meelua et $al.$ [9]. The MWD values of the synthesized PCL are also lower than 1.93 suggesting the lower amount of transesterification reaction. The highest M_n for the synthesized PCL obtained from our synthesis condition is 4.62×10^4 g/mol with titanium(IV) n-butoxide concentration of 0.025 mol%. In addition, titanium(IV) n-butoxide also produces PCL with %yield > 90%. This synthesis condition clearly confirms that titanium(IV) n-butoxide acts as an effective initiator that can be used in very low concentration range. For mechanistic consideration, the ROP of ε-CL with titanium(IV) n-butoxide is proposed through the coordination–insertion mechanism as shown in Figure 2 [6, 7, 9].
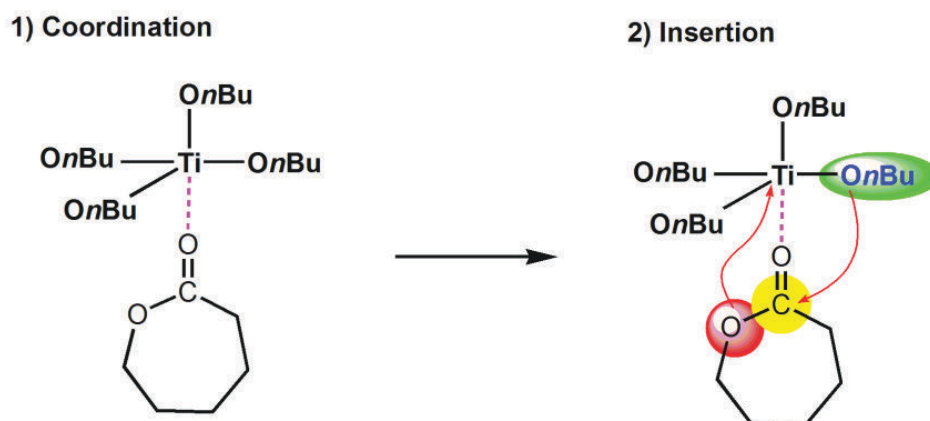

Figure 2. The coordination–insertion ROP of ε-CL with titanium(IV) n-butoxide initiator.

This mechanism starts by the coordination of ε-CL with reactive Ti–O bond of titanium(IV) n-butoxide. Then, n-butoxide group of titanium(IV) n-butoxide attacks the carbonyl carbon of ε-CL ring resulting in the cleavage of monomer ring. The opened ε-CL will insert into initiator molecule and convert to propagating specie. Another ε-CL molecule will insert into this propagating specie by the same mechanism to the first molecule yielding PCL. From the obtained results, titanium(IV) n-butoxide is considered as one of the powerful candidate initiator for synthesizing high molecular weight biodegradable polyesters.

Conclusion: The ring–opening polymerization of ε-CL initiated by titanium(IV) n-butoxide was successfully conducted via bulk polymerization at 150 °C for 24 h. Titanium(IV) n-butoxide was completely dissolved in monomer at all concentrations used in this work (0.025 – 0.200 mol%). From bulk polymerization, the molecular weight of PCL was controlled by titanium(IV) n-butoxide concentration. The highest molecular weights of PCLs (M_n = 4.62×10^4 g/mol) with 91% of yield was obtained at 0.025 mol% of titanium(IV) n-butoxide. The MWD values for all

synthesized PCLs were lower than 1.93 indicating the lower amount of transesterification. The results obtained from this work can be used as template for synthesizing other biodegradable polyesters. Furthermore, the scale up of the synthesis of biodegradable polymers using titanium(IV) *n*-butoxide as initiator is in our attention and still working in laboratory.

References:
1. Cabaret OD., Vaca BM., Bourissou D. Chem Rev. 2004; 101:6147–6176.
2. Stridsberg KM., Ryner M., Albertsson AC. Adv Polym Sci. 2002; 157:41–65.
3. Karidi K., Mantourlias T., Seretis A., Pladis P., Kiparissides C. Eur Polym J. 2015; 72: 114–128.
4. Storey RF., Mullen BD., Desai GS., Sherman JW., Tang CN. J Polym Sci: Part A: Polym Chem. 2002; 40:3434–3442.
5. Kowalski A., Libiszowski J., Duda A., Penczek S. Macromolecules. 2000;33:1964–1971.
6. Limwanich W., Punyodom W., Kungwan N., Meepowpan P. Int J Kinet. 2015; 47:734–743.
7. Limwanich W., Khunmanee S., Kungwan N., Punyodom W., Meepowpan P. Thermochim Acta. 2015; 599:1–7.
8. Li P., Zerroukhi A., Chen J., Chalamet Y., Jeanmaire T., Xia Z. J App Polym Sci. 2008; 110: 3990–3998.
9. Meelua W., Molloy R., Meepowpan P., Punyodom W. J Polym Res. 2012; 19:9799.
10. Purnama P., Jung Y., Hong CH., Han DS., Kim SH. Macromol Res. 2012; 5:515–519.
11. Limwanich W., Meepowpan P., Kungwan N., Punyodom W. Reac Kinet Mech Cat. 2016; 119:381–392.