CHAPTER 5

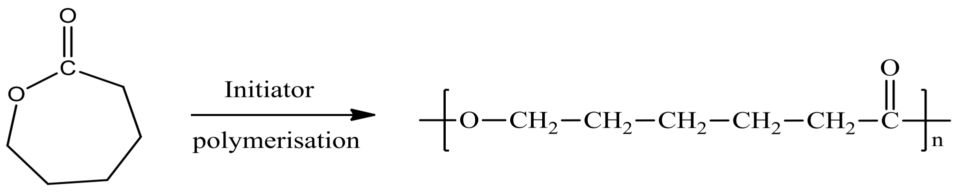
Synthesis and Characterisation of Polycaprolactone

In this chapter, the bulk ROP of ε-caprolactone (ε-CL) is described using the synthesised tin(II) alkoxide initiators (both solid and liquid initiators) to compare their reactivities and effectiveness. The ε-CL monomer was chosen for study not only because it is easy to polymerise but also because it is also one of the comonomers used for producing copolymer fibres used as absorbable surgical sutures.

PCL is a tough, flexible, and biocompatible plastic with a melting point of around 60 ^{o}C and a T_g well below room temperature (-60 ^{o}C). PCL is in its rubbery state (modulus = 0.4 GPa and extrusion = 300-400 %) at room temperature and exhibits a permeability to low molecular weight species at body temperature. These properties have made it a candidate for controlled drug release applications. The repeating unit of PCL consists of five non-polar methylene groups and a single relatively polar ester group. This structure gives PCL some unique properties. The mechanical properties are similar to polyolefins because of its high olefinic content, while the presence of the hydrolytically unstable aliphatic ester linkage causes the polymer to be biodegradable. PCL is degradable very slowly *in vivo* initiated by nonenzymatic ester hydrolysis of its backbone ester bonds to yield ε-hydroxycaproic acid which enters the citric acid cycle and is completely metabolized.

5.1 Synthesis and Purification of Poly(ε-caprolactone), PCL

PCL is synthesised from ε-CL monomer via ring-opening polymerisation with a suitable initiator as shown below.

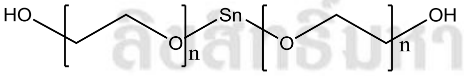
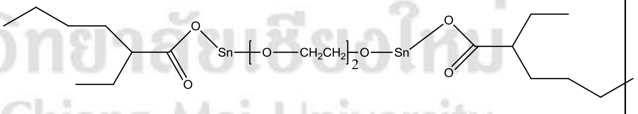
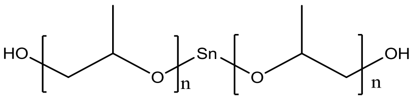
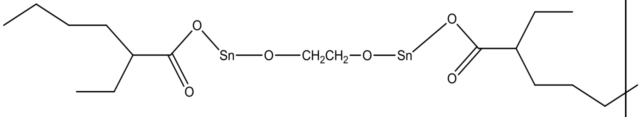
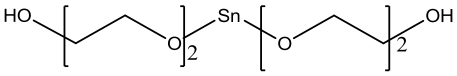


Ring-opening polymerisation (ROP) temperatures in bulk for PCL are usually in the range of 100-150 ^{o}C with the polymerisation being normally initiated by $Sn(Oct)_2$. Other initiators which have been used include various Lewis acids, metal alkyls, metal alkoxides and organic acids [109].

In principle, the ROP process is believed to occur via the previously described coordination-insertion mechanism, whereby the initiation proceeds by insertion of a monomer unit into the Sn-O bond with cleavage of the acyl-oxygen bond of the monomer. However, despite the huge amount of initiating systems for cyclic ester polymerisation, there is a paucity of structurally authenticated intermediate species [110], [111].

In this thesis, all ring-opening polymerisations (ROP) were carried out in bulk at 130°C for 48 hrs in a round-bottomed flask with ground-glass joints and a magnetic stirring. Both the solid and liquid tin(II) alkoxide initiators (their chemical structures are shown in Table 5.1) in 0.02, 0.10 and 0.20 mol % concentrations and ε-caprolactone (CL) were weighed and added to the reaction flask in a controlled atmosphere glove box under dry nitrogen at room temperature.

Table 5.1 Chemical structures of the tin(II) alkoxide initiators used for PCL synthesis.

Solid Initiators	**Liquid Initiators**
Tin(II) poly ethylene glycol, $Sn(PEG300)_2$  	Bis (tin(II) octoate) diethylene glycol, $[Sn(Oct)]_2DEG$ 
Tin(II) poly propylene glycol, $Sn(PPG400)_2$  	Bis (tin(II) octoate) ethylene glycol, $[Sn(Oct)]_2EG$ 
Tin(II) diethylene glycol, $Sn(DEG)_2$  	

After removing the flask from the glove box, it was immersed in a silicone oil bath at a constant temperature and for given period of time as shown in Figure 5.1. At the end of the polymerisation period, the flask was taken out from the silicone oil bath and left to cool down to room temperature (approximate 30°C). PCL was purified by dissolving in chloroform, and then reprecipitating in chilled methanol as shown in Figure 5.2. Then, the purified homopolymer products as white solids were dried in a vacuum oven at 40 °C to constant weight.

Figure 5.1 Apparatus used in the ring-opening bulk polymerisation of ε-CL.

Figure 5.2 Apparatus used for PCL purification by re-precipitation from solution.

The purified PCL were characterised (chemical structure, temperature transitions, thermal stability and molecular weight) by a combination of the following analytical techniques:

- Fourier-transform infrared spectroscopy (FT-IR)
- Nuclear magnetic resonance spectroscopy (NMR)
- Differential scanning calorimetry (DSC)
- Thermogravimetric analysis (TGA)
- Dilute-solution viscometry

5.2 Chemical Structure Analysis

5.2.1 Fourier Transform Infrared Spectroscopy (FT-IR)

The PCL samples used for the structural characterisation by FT-IR were prepared in the form of thin films cast from solution in chloroform. The spectra can be compared with the commercial (Sigma Aldrich) PCL in Figure 5.3. Major vibrational peaks in Figure 5.3 are listed in Table 5.2.

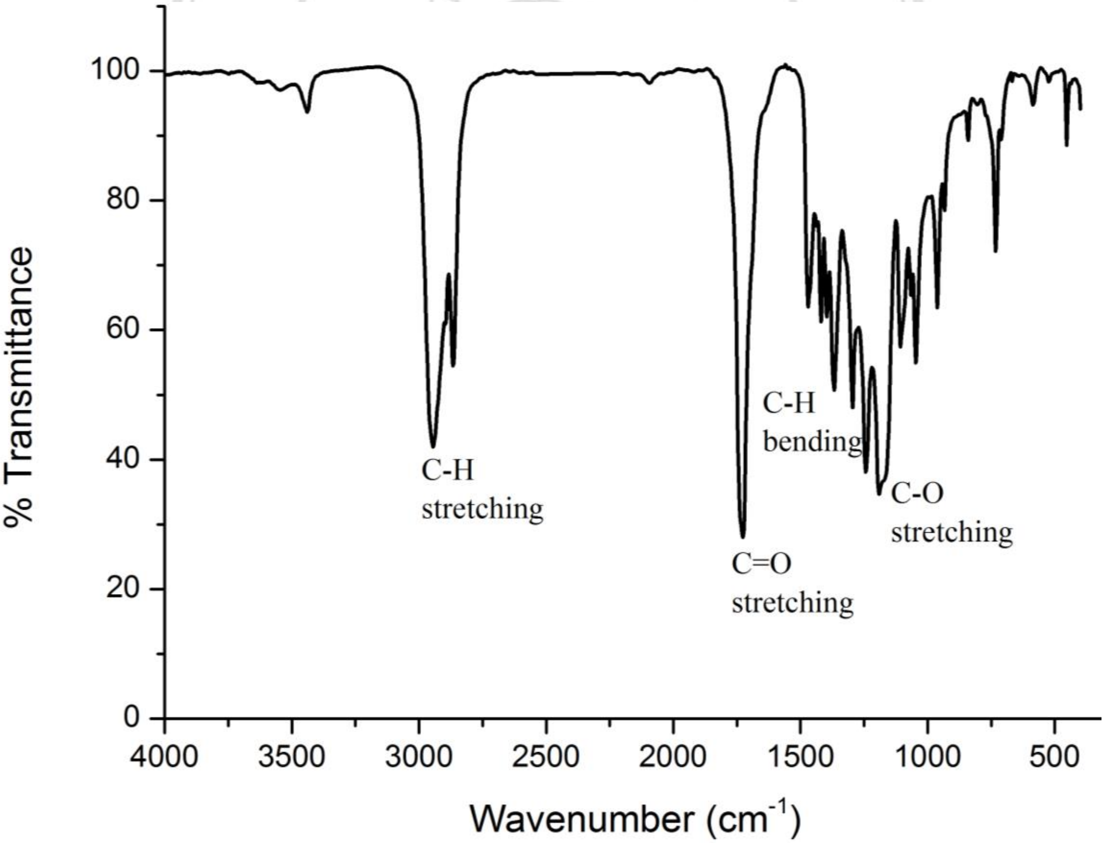


Figure 5.3 Infrared spectrum of commercial PCL.

Table 5.2 Main vibrational assignments in the FT-IR spectrum of the commercial PCL.

Type of vibration	Wavenumber (cm^{-1})
C-H stretching	3000-2800
C=O stretching	1729
C-H bending	1470-1360
C-O stretching	1300-1000

The FT-IR spectra of the purified poly(ε-caprolactone (PCL) products are shown in Figures 5.4 – 5.8. The major vibrational peak assignments are listed in Tables 5.3-5.4.

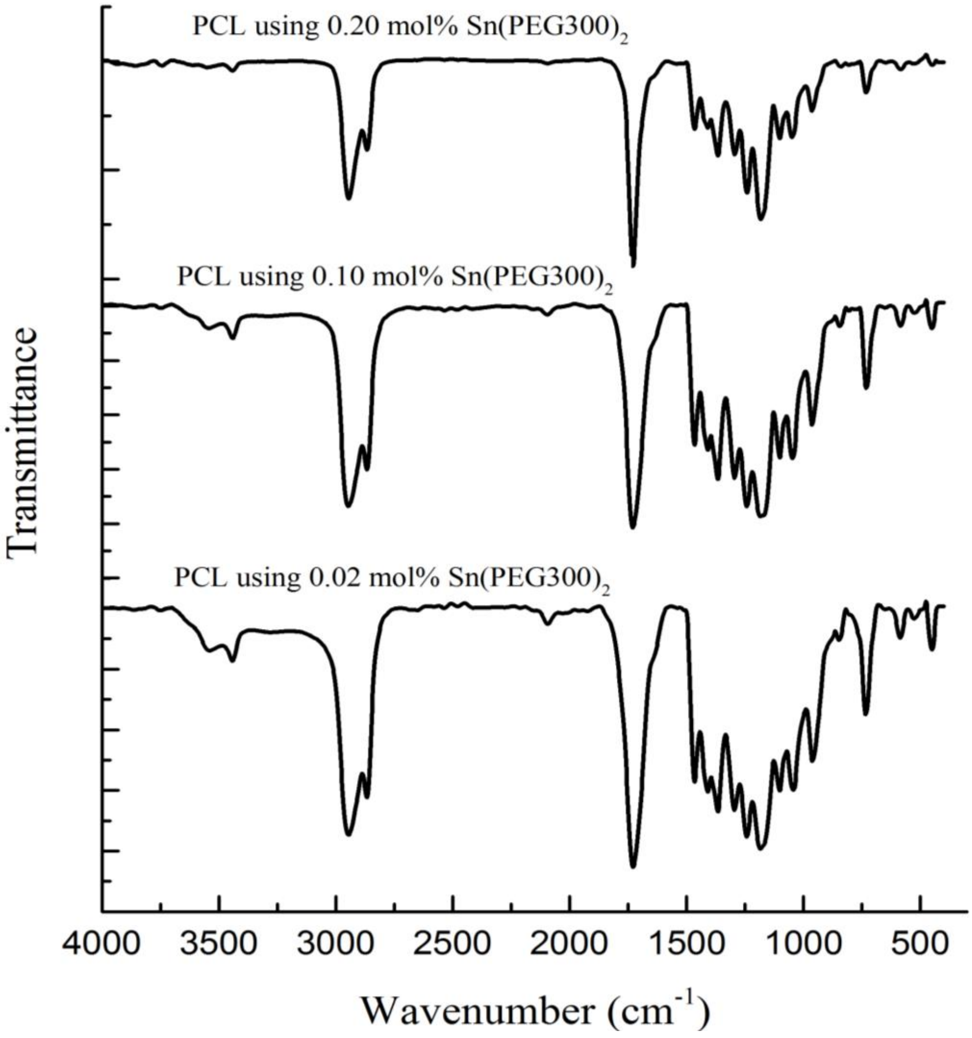


Figure 5.4 Infrared spectra of the purified PCL using the solid Sn(PEG300)$_2$ initiator.

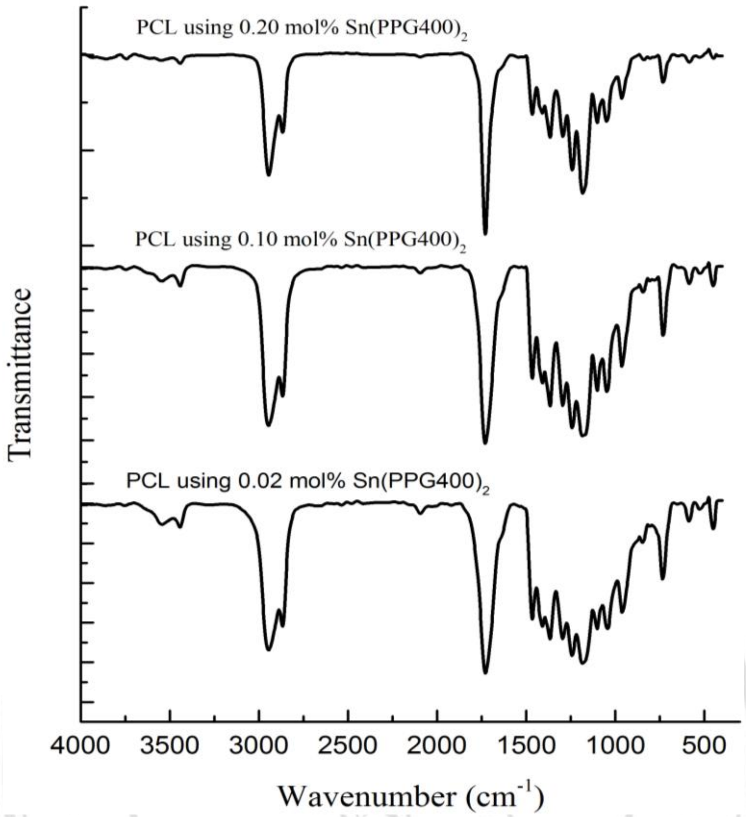


Figure 5.5 Infrared spectra of the purified PCL using the solid Sn(PPG400)$_2$ initiator.

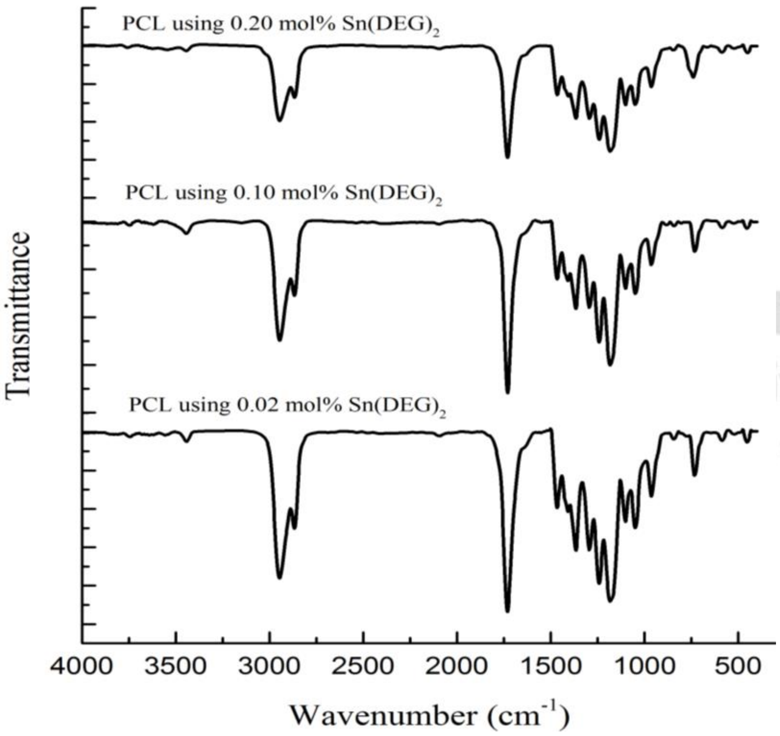


Figure 5.6 Infrared spectra of the purified PCL using the solid Sn(DEG)$_2$ initiator.

Table 5.3 Main vibrational assignments in the FT-IR spectra of the purified PCL products using 0.10 mol % the solid tin(II) alkoxides initiators.

Type of vibration		Wavenumber (cm^{-1})		
		$Sn(PEG300)_2$	$Sn(PPG400)_2$	$Sn(DEG)_2$
C-H	stretching	3000-2800	3000-2800	3000-2800
C=O	stretching	1723	1730	1727
C-H	bending	1470-1360	1470-1360	1470-1360
C-O	stretching	1300-1000	1300-1000	1300-1000

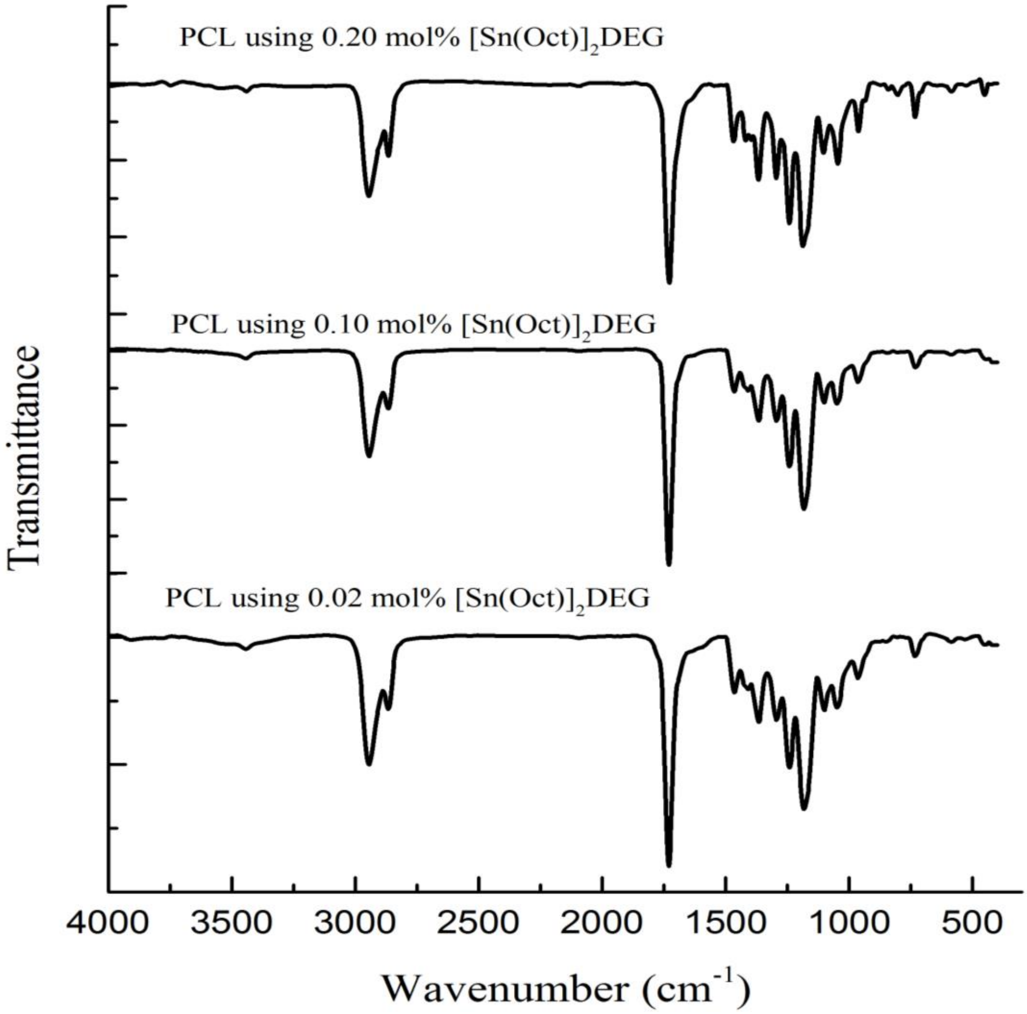


Figure 5.7 Infrared spectra of the purified PCL using the liquid $[Sn(Oct)]_2DEG$ initiator.

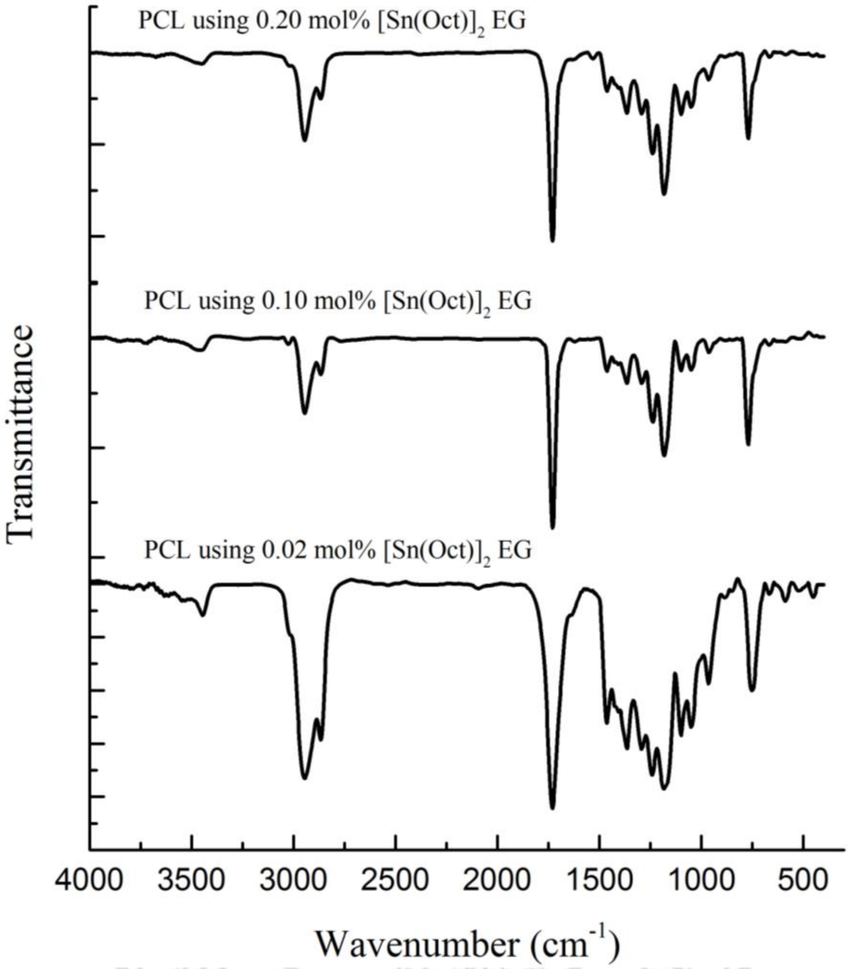


Figure 5.8 Infrared spectra of the purified PCL using the liquid $[Sn(Oct)]_2EG$ initiator.

Table 5.4 Main vibrational assignments in the FT-IR spectra of the purified PCL products using 0.10 mol % the liquid tin(II) alkoxide initiators.

Type of vibration		Wavenumber (cm^{-1})	
		$[Sn(Oct)]_2DEG$	$[Sn(Oct)]_2EG$
C-H	stretching	3000-2800	3000-2800
C=O	stretching	1728	1729
C-H	bending	1470-1360	1470-1360
C-O	stretching	1300-1000	1300-1000

From these results, it can be seen that the FT-IR spectra of the synthesised PCL products using different initiators were found to be consistent with that of the commercial PCL.

5.2.2 Proton Nuclear Magnetic Resonance Spectroscopy (^{1}H-NMR)

Proton nuclear magnetic resonance (^{1}H-NMR) was carried out to characterise the synthesised PCL. Peak assignments (a, b, c, d, e) are shown along with the corresponding chemical structure of the commercial PCL in Figure 5.9. Figures 5.10 – 5.11 show the ^{1}H-NMR spectra of the PCL products synthesised using the solid and liquid initiators. Table 5.5 compares the chemical shifts and the relative peak intensities of the ^{1}H-NMR spectra for Figures 5.9-5.11.

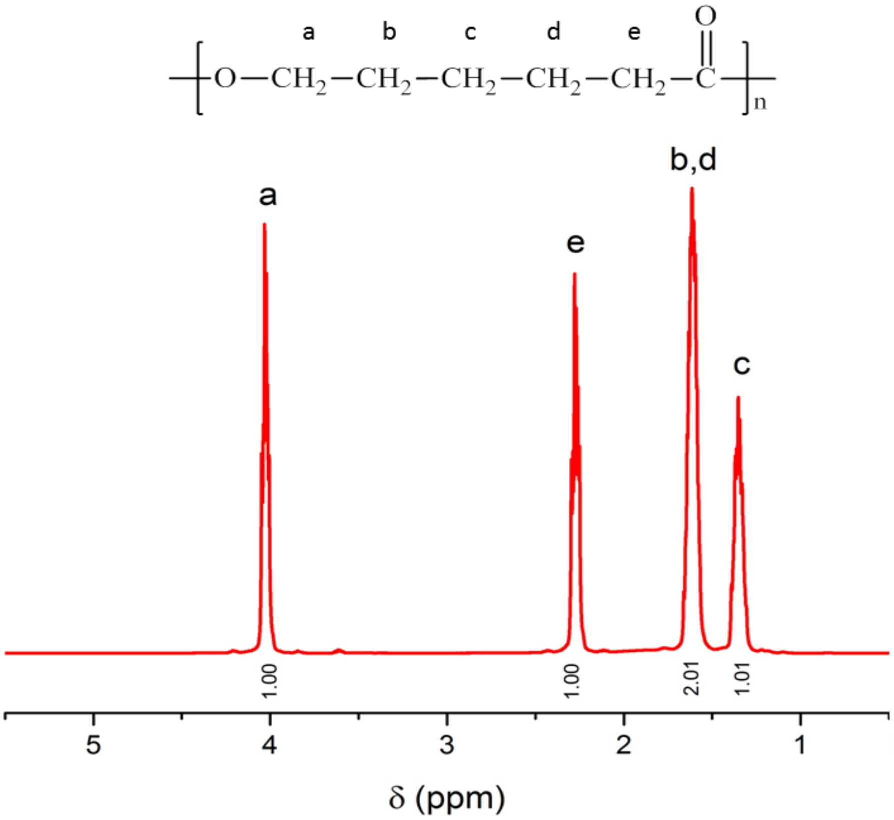


Figure 5.9 ^{1}H-NMR spectrum of the commercial PCL.

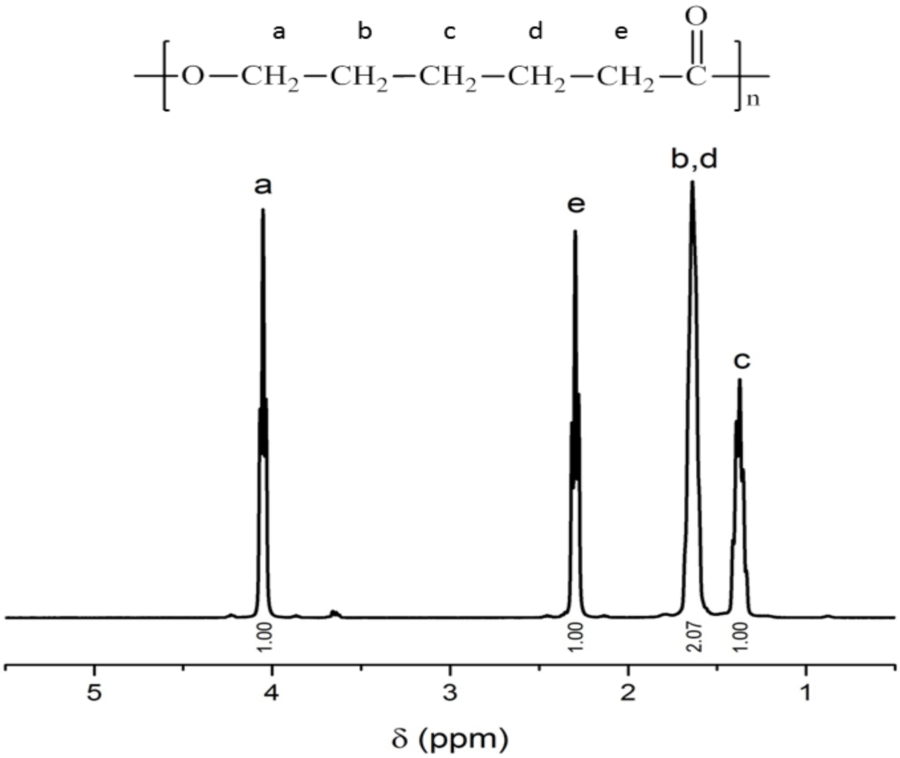


Figure 5.10 ^{1}H-NMR spectrum of PCL synthesised using 0.10 mol % of the solid $Sn(DEG)_2$ initiator.

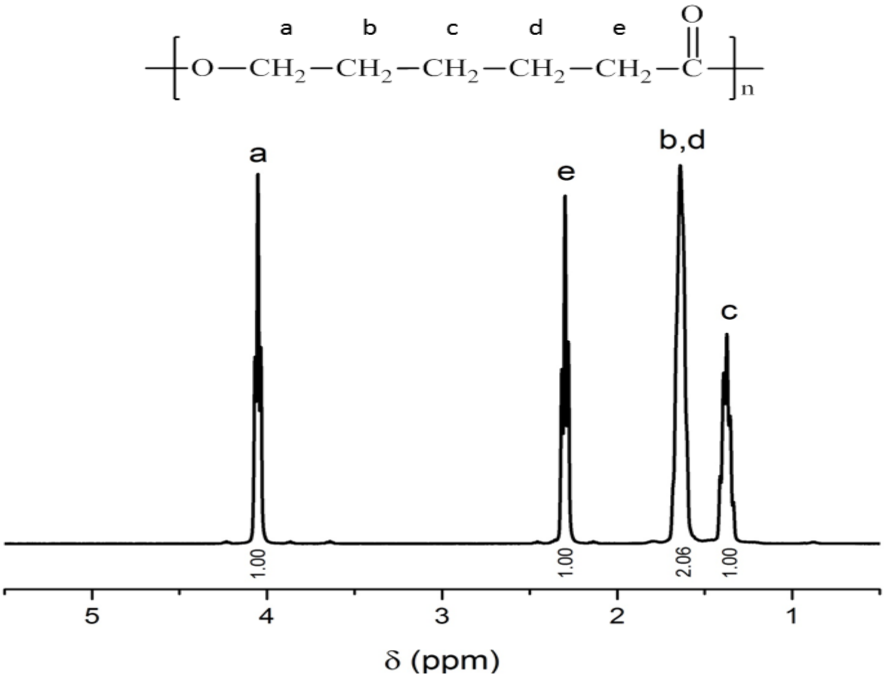
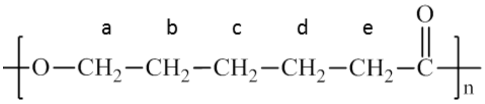


Figure 5.11 ^{1}H-NMR spectrum of PCL synthesised using 0.10 mol % of the liquid $[Sn(Oct)]_2DEG$ initiator.

Table 5.5 Chemical shifts and relative peak intensities of the ^{1}H-NMR spectra of PCL.



$$\left[\mathrm{O} - \overset{a}{\mathrm{CH_2}} - \overset{b}{\mathrm{CH_2}} - \overset{c}{\mathrm{CH_2}} - \overset{d}{\mathrm{CH_2}} - \overset{e}{\mathrm{CH_2}} - \overset{\overset{\displaystyle \mathrm{O}}{\|}}{\mathrm{C}} \right]_n$$

Proton Assignment	Commercial PCL		PCL using 0.10 mol % $Sn(DEG)_2$		PCL using 0.10 mol % $[Sn(Oct)]_2DEG$	
	Chemical Shift, δ (ppm)	Peak Integration	Chemical Shift, δ (ppm)	Peak Integration	Chemical Shift, δ (ppm)	Peak Integration
a	4.133-3.978	1.00	4.104-3.999	1.00	4.106-4.001	1.00
e	2.320-2.217	1.00	2.343-2.254	1.00	2.348-2.238	1.00
b + d	1.678-1.545	2.01	1.709-1.582	2.07	1.708-1.589	2.06
c	1.406-1.267	1.00	1.425-1.324	1.00	1.438-1.319	1.01

Similar to the FT-IR spectra, the ^{1}H-NMR spectra of the PCL products using the different initiators are also seen to be consistent with the commercial PCL.

5.3 Thermal Analysis

5.3.1 Differential Scanning Calorimetry (DSC)

DSC experiments were conducted for the purified PCL products at a heating rate of 10 ^{o}C/min under dry nitrogen atmosphere. PCL sample weights were typically in the range of 3-5 mg. DSC curves reflect changes in the energy of the system under investigation. The DSC thermograms for the PCL products prepared in this work are compared in Figure 5.12. Data analysis results are summarized in Table 5.6. The values of the heat of melting, ΔH_m , were determined from the areas under the melting peak, while the % crystallinities were calculated from the equation:

$$\% \text{ Crystallinity} = \frac{\Delta H_m}{\Delta H_m^*} \times 100 \%$$

where ΔH_m = heat of melting of the sample (from the DSC thermogram)

ΔH_m^* = heat of melting of a 100 % crystalline sample =142 J/g [112] (for PCL)

The melting peak temperatures in Figures 5.12-5.14 and Table 5.6 are consistent with the literature value for PCL. The glass transition temperature ($T_g \approx -60$ ^oC) was not observed here because it is below the temperature limit ($\approx$-25 ^oC) of the DSC instrument used in this study. Therefore, the PCL is in its rubbery state at room temperature (> T_g). A high crystallinity (45-80 %) of PCL was also observed for each initiator used. All of the DSC themograms do not show a crystallisation peak. This is generally found since PCL is a fast-crystallizing polymer when it is left to gradually cool down to room temperature from the melt state.

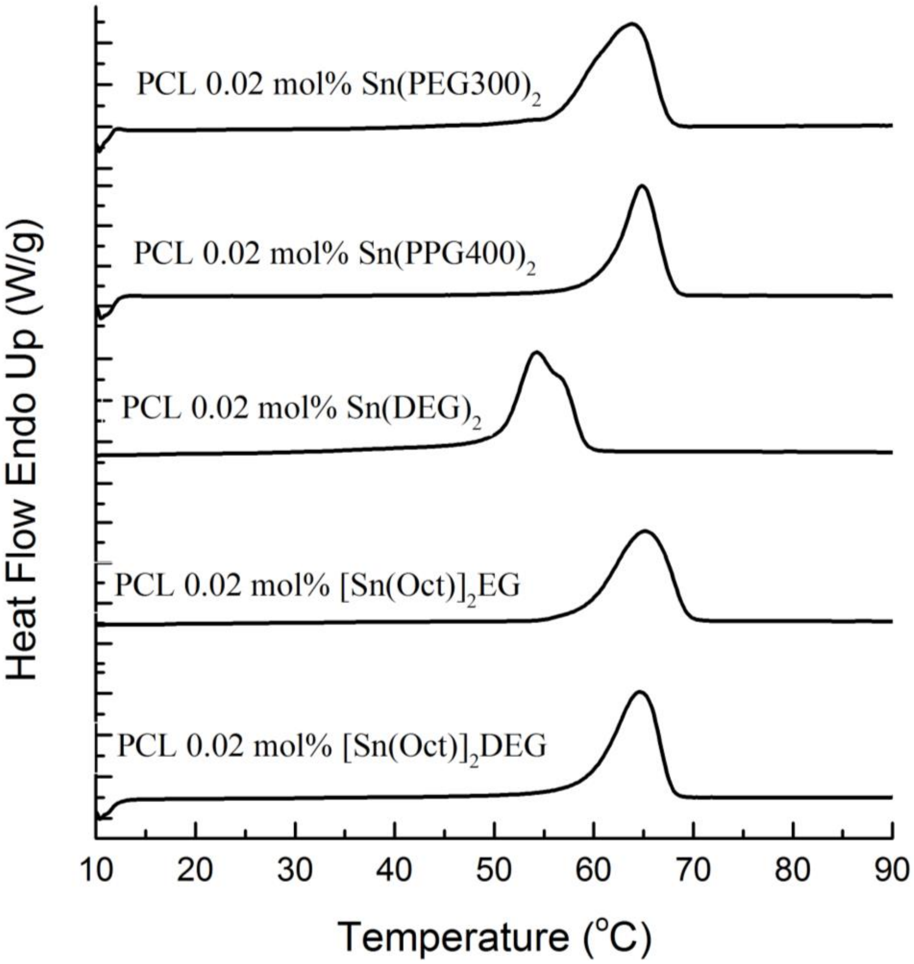


Figure 5.12 DSC (2nd run) thermograms of PCL using 0.02 mol % of the various tin(II) alkoxides.

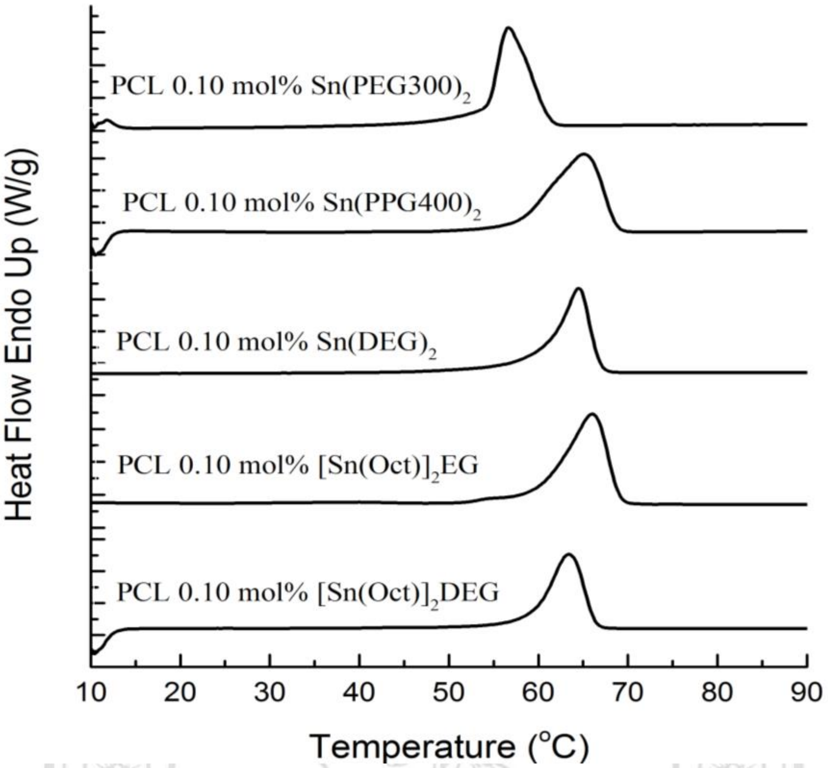


Figure 5.13 DSC (2nd run) thermograms of PCL using 0.10 mol % of the various tin(II) alkoxides.

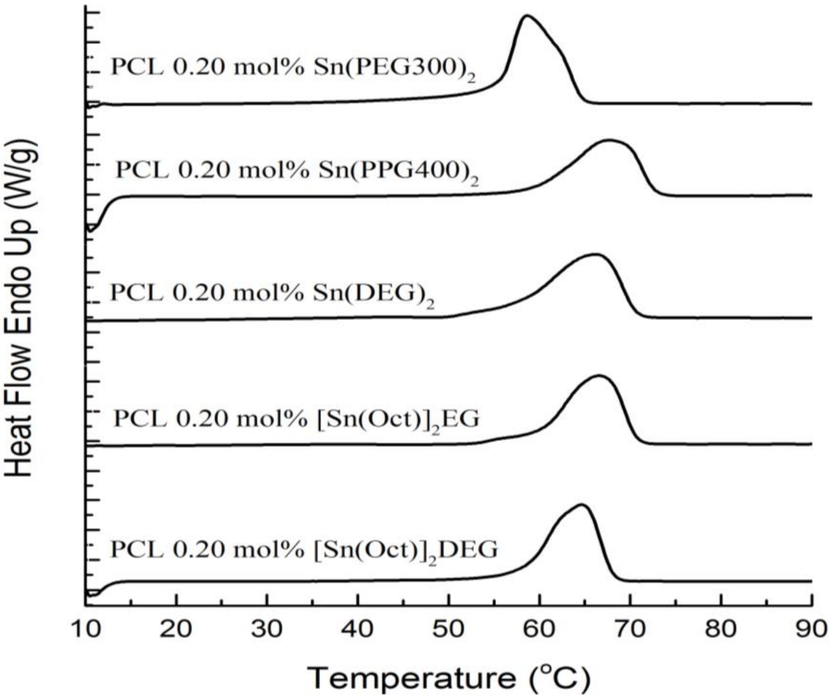


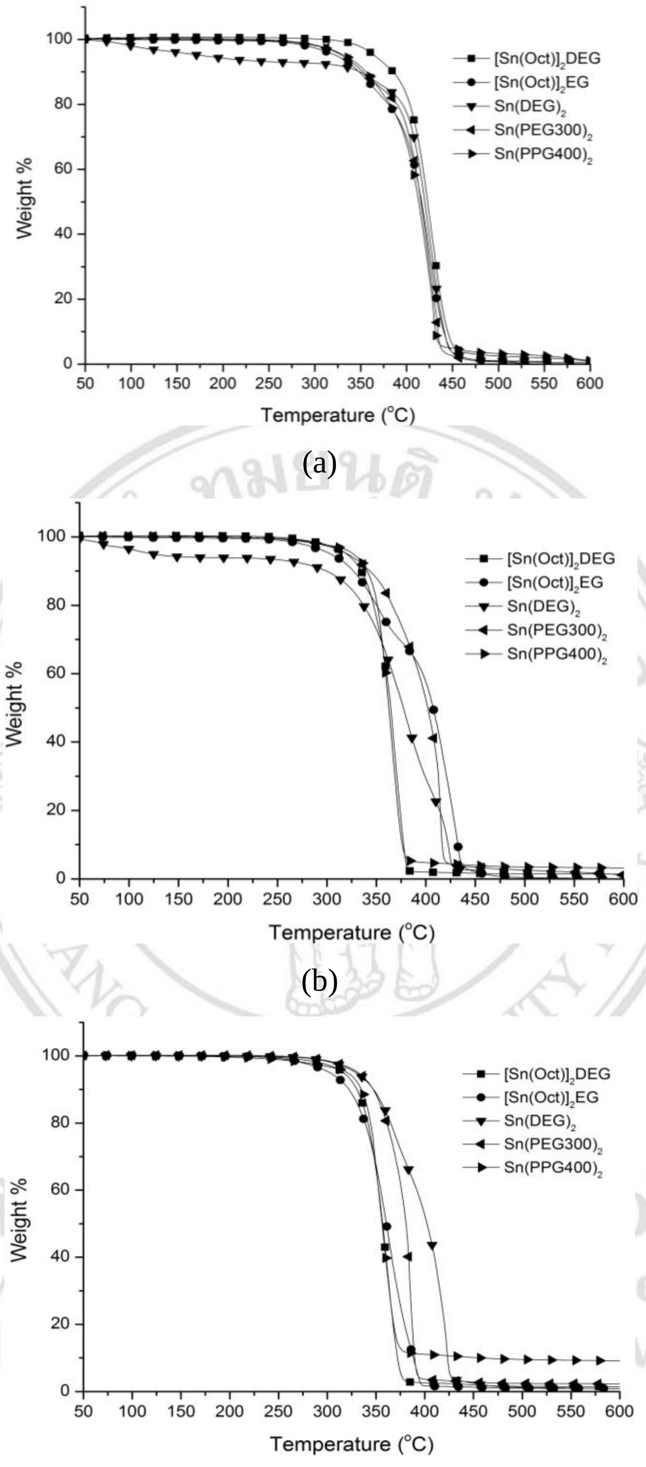
Figure 5.14 DSC (2nd run) thermograms of PCL using 0.20 mol % of the various tin(II) alkoxides.

Table 5.6 DSC (2nd run) data analysis for PCL synthesised using various types and concentrations of the tin(II) alkoxide initiators.

Initiator (I)	**[I] (mol %)**	**DSC data**		
		Peak T_m (°C)	**ΔH_m (J/g)**	**Crystallinity (%)**
$Sn(PEG300)_2$	0.02	63.8	97.2	68.5
	0.10	65.3	94.4	66.5
	0.20	67.5	98.8	69.6
$Sn(PPG400)_2$	0.02	64.8	101.2	71.3
	0.10	65.2	100.1	70.5
	0.20	67.7	95.4	67.2
$Sn(DEG)_2$	0.02	64.2	94.6	66.6
	0.10	64.5	97.0	68.3
	0.20	66.2	97.0	68.3
$[Sn(Oct)]_2DEG$	0.02	64.7	84.0	59.2
	0.10	63.5	81.2	57.2
	0.20	64.7	87.7	61.8
$[Sn(Oct)]_2EG$	0.02	65.2	106.9	75.3
	0.10	66.0	95.2	67.0
	0.20	66.7	98.1	69.1

5.3.2 Thermogravimetric Analysis (TGA)

In order to determine the thermal stability of PCL, non-isothermal TGA was conducted at a heating rate of 20 °C/min under an inert nitrogen atmosphere. The results are shown in Figures 5.15(a)-(c) which compare the thermal degradation profiles of the PCL samples over the temperature range of 50-600 °C. The TGA curves clearly indicate that PCL undergoes mainly a single-step reaction to complete weight loss over a similar range of degradation temperature for each initiator. The initial weight loss temperature of around 250 °C shows that PCL is thermally stable at temperatures well above the temperature (130 °C) at which it was produced. The small weight losses (< 10%) below 250 °C in some of the curves in Figure 5.15 are due to moisture and/or residual volatiles (e.g., solvent / non-solvent) in the sample.



(a)

(b)

(c)

Figure 5.15 TGA thermograms of the purified PCL products synthesised using the various tin(II) alkoxide initiators at different concentrations:

(a) 0.02 mol % (b) 0.10 mol % and (c) 0.20 mol %

(Heating rate = 20 ^{o}C/min, N_2 atmosphere)

5.4 Molecular Weight Determination by Dilute-Solution Viscometry

The viscosity-average molecular weights (M_v) of the purified PCL products were determined from dilute-solution viscometry using chloroform as solvent at 30 °C (± 0.1 °C). The reduced and inherent viscosity-concentration plots and double extrapolations to zero concentration to obtain the intrinsic viscosity [η] values of the polymers are shown in Figures 5.16-5.20. The value of [η] then allows the polymer's viscosity-average molecular weight, $\overline{M}_v$, to be calculated from the Mark-Houwink-Sakurada Equation for poly(ε-caprolactone) in chloroform as solvent at 30 °C [113] as follows:

$$[\eta] = 1.298 \times 10^{-4}\ \overline{M}_v^{\ 0.828}\ \mathrm{dl/g}$$

The calculated $\overline{M}_v$ values are summarized and compared in Table 5.7 below.

Table 5.7 Intrinsic viscosities, [η], and viscosity-average molecular weights, $\overline{M}_v$, of PCL obtained from dilute-solution viscometry in chloroform at 30 °C.

Solid Initiators	**[I] (mol %)**	**[η] (dl/g)**	**$\overline{M}_v$ (x10^{-3})**	**Liquid Initiators**	**[I] (mol %)**	**[η] (dl/g)**	**$\overline{M}_v$ (x10^{-3})**
$Sn(PEG300)_2$	0.02	0.130	4.21	$[Sn(Oct)]_2DEG$	0.02	0.240	8.82
	0.10	0.239	8.78		0.10	0.422	17.44
	0.20	0.541	23.54		0.20	0.379	15.32
$Sn(PPG400)_2$	0.02	0.351	13.96	$[Sn(Oct)]_2EG$	0.02	0.851	40.69
	0.10	0.251	9.31		0.10	0.772	36.17
	0.20	0.579	25.56		0.20	0.847	40.46
$Sn(DEG)_2$	0.02	0.299	11.50				
	0.10	0.461	19.41				
	0.20	0.521	22.50				

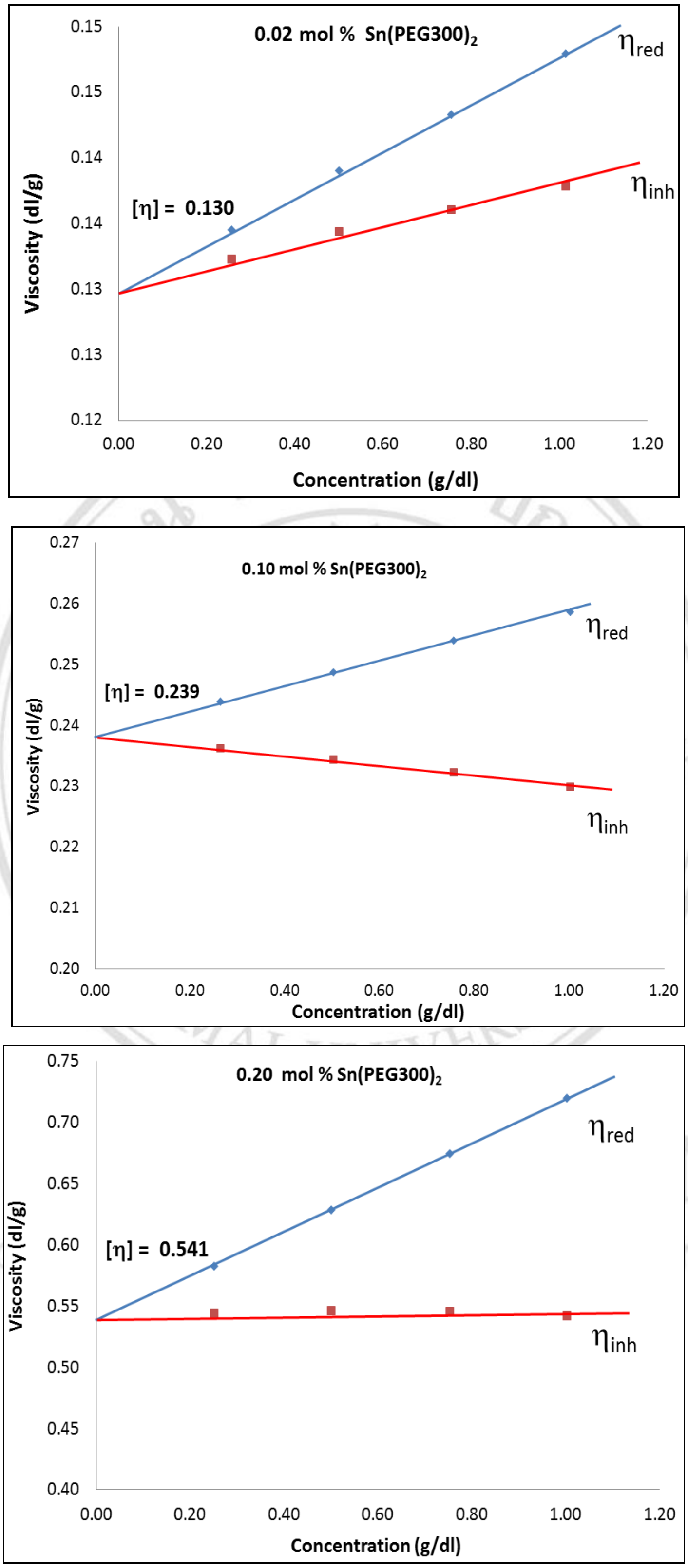


Figure 5.16 Plots of η_{red} and η_{inh} vs concentration of PCL synthesised using the solid initiator, Sn(PEG300)$_2$.

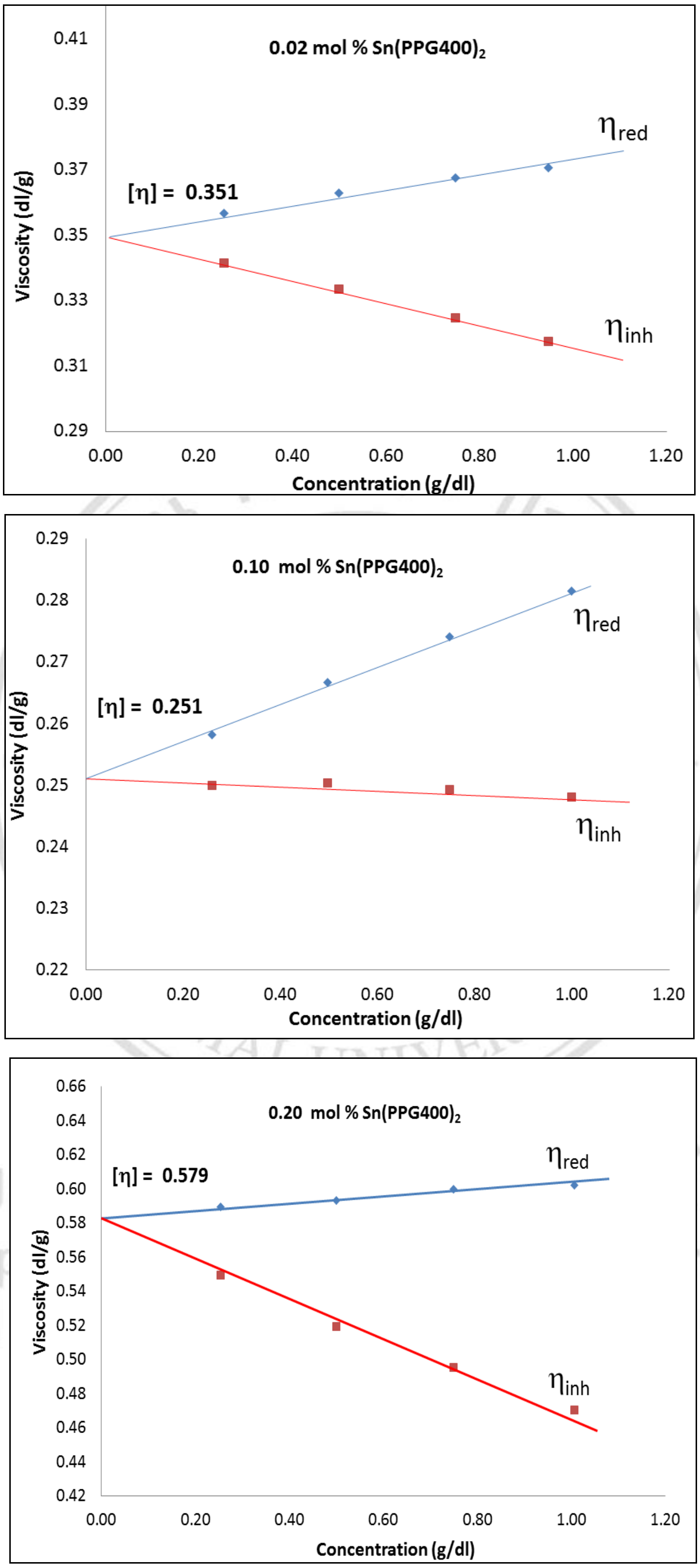


Figure 5.17 Plots of η_{red} and η_{inh} vs concentration of PCL synthesised using the solid initiator, $Sn(PPG400)_2$.

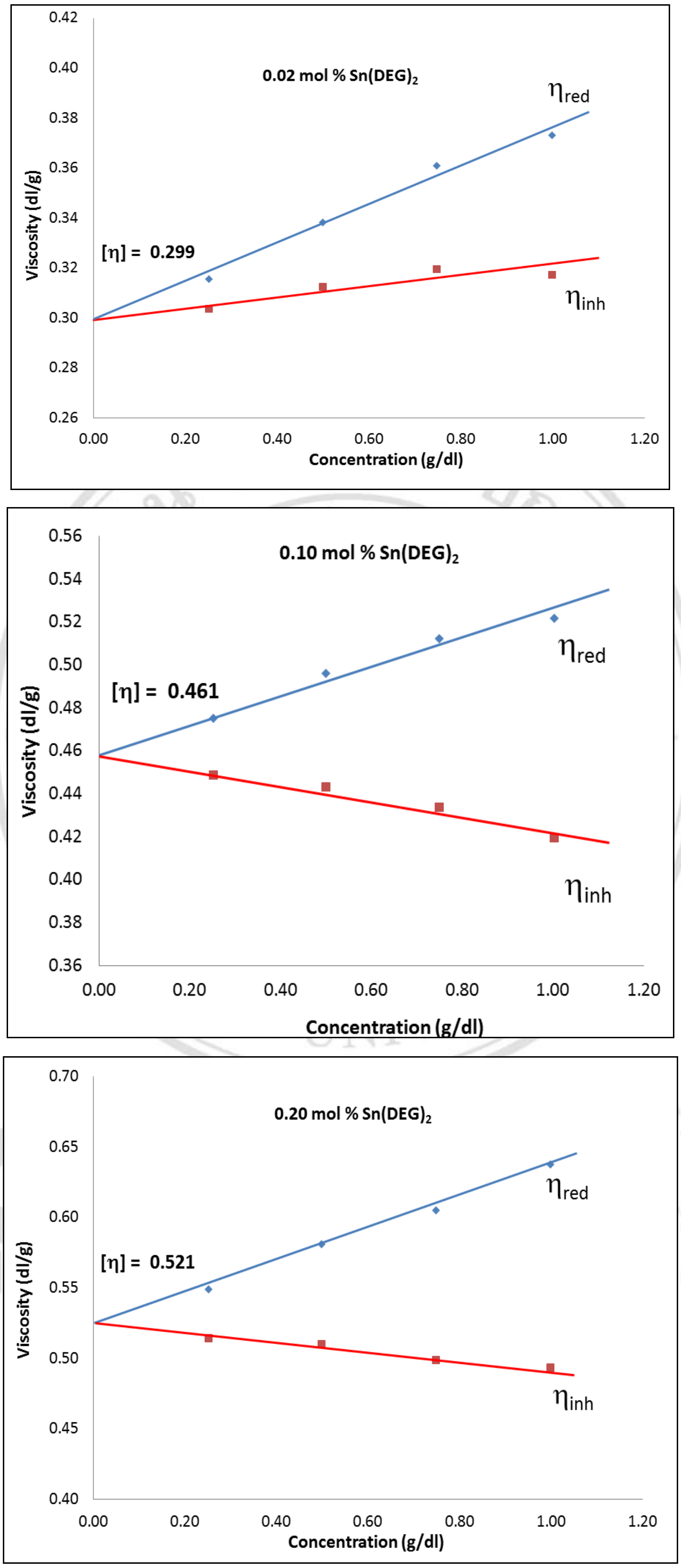


Figure 5.18 Plots of η_{red} and η_{inh} vs concentration of PCL synthesised using the solid initiator, $Sn(DEG)_2$.

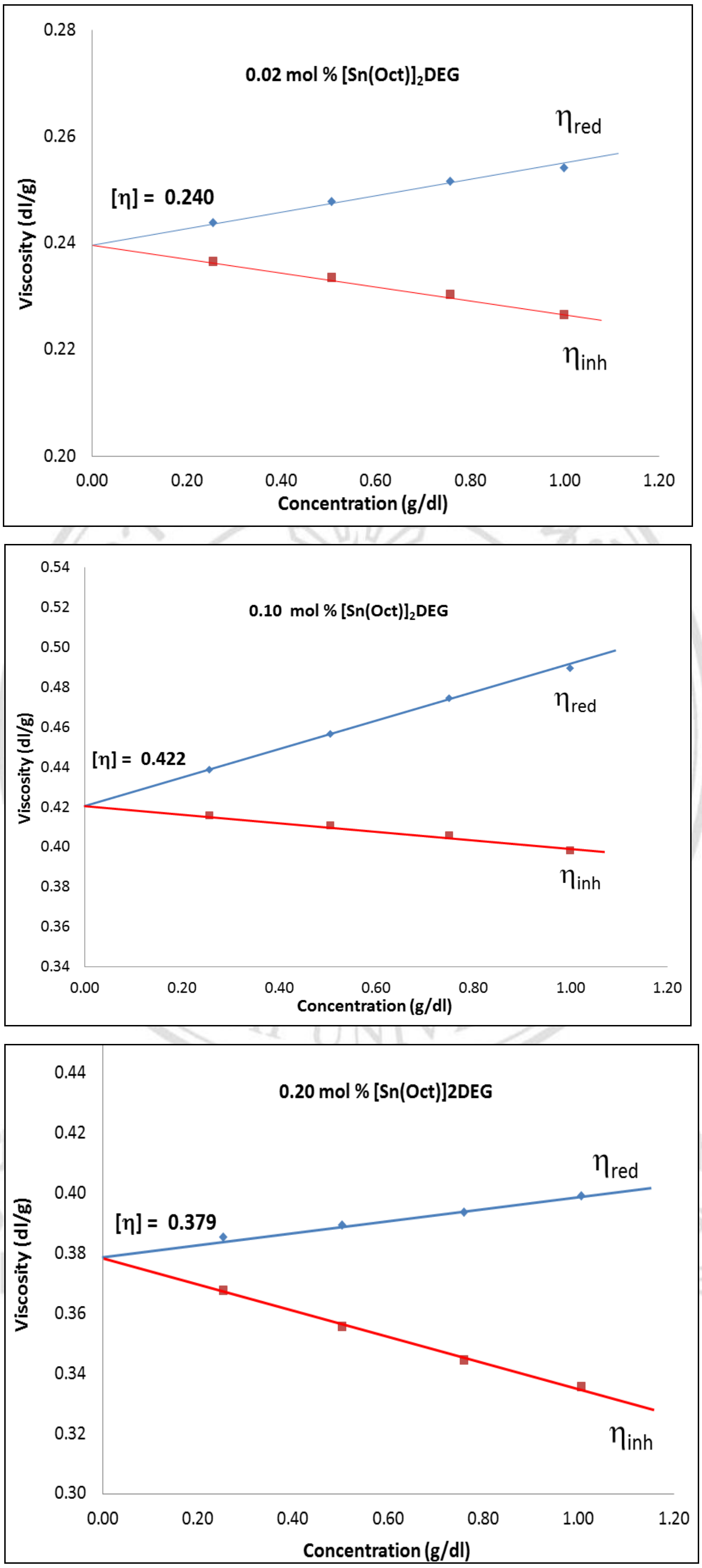


Figure 5.19 Plots of η_{red} and η_{inh} vs concentration of PCL synthesised using the liquid initiators, $[Sn(Oct)]_2DEG$.

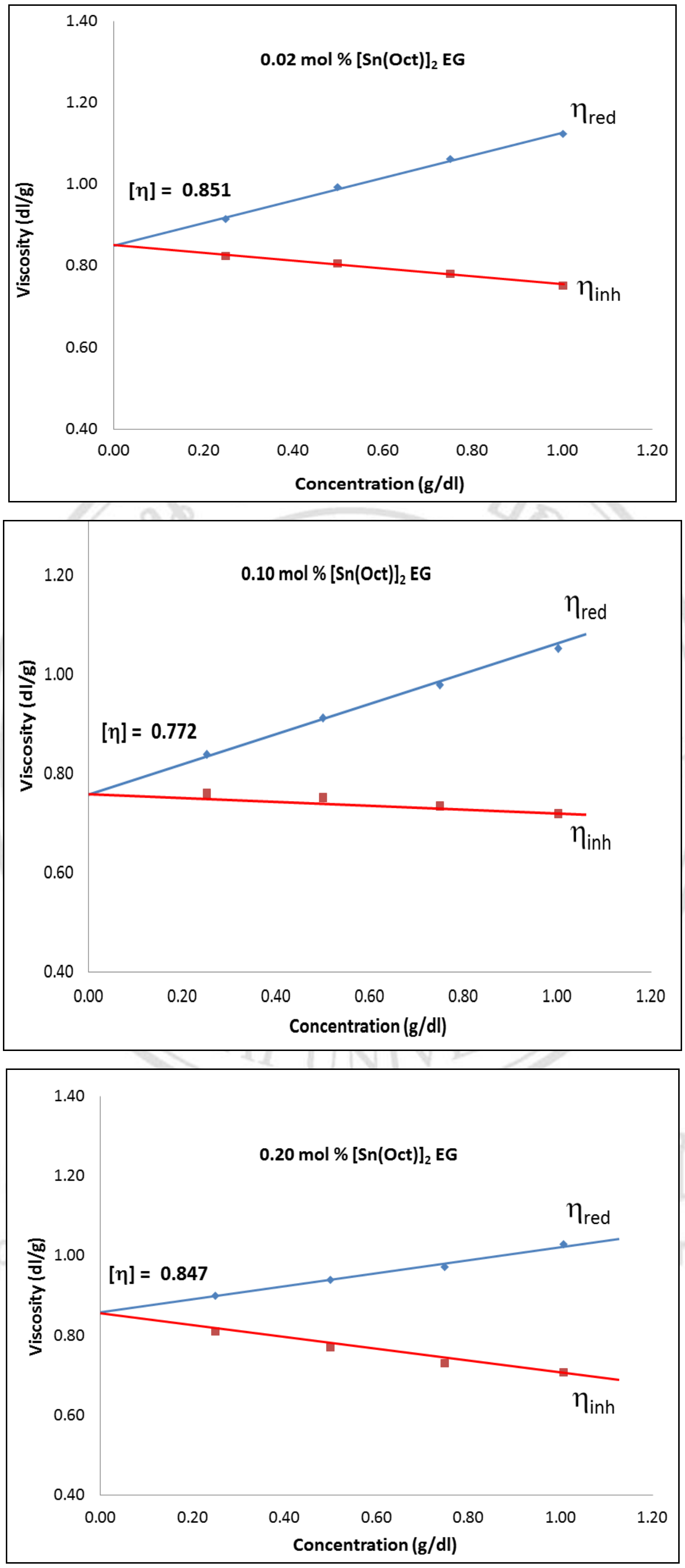


Figure 5.20 Plots of η_{red} and η_{inh} vs concentration of PCL synthesised using the liquid initiators, $[Sn(Oct)]_2EG$.

All of the initiators, both solid and liquid, yielded PCL products in the low-to-medium molecular weight range. As seen in Table 5.7, the highest $\overline{M}_v$ came from the liquid $[Sn(Oct)]_2EG$ initiator. Whereas the two liquid initiators were completely soluble in the CL monomer, the three solid initiators were only partially soluble although solubility did increase with time at the polymerisation temperature of 130 °C. Consequently, whereas initiation by the liquid initiators was completely homogeneous, initiation by the solid initiators was partly homogeneous (soluble fraction) and partly heterogeneous (insoluble fraction), the ratio of which changed with time. Furthermore, the undissolved solid initiator was clearly visible in the solid polymer as an impurity and needed to be removed by careful purification. Therefore, from the point of view of initiator solubility, molecular weight, and polymer purity, the liquid initiators were preferred and tended to give more reproducible results. However, for the copolymer synthesis in the following Chapter 6, both solid and liquid initiators were used for comparison.