

Chapter II

Sunflower oil based terpolymer as sustainable lubricant additive

3.2.1 Introduction

Modern engines must be lubricated to prolong its lifetime. A lubricant performs a number of works in the engine including lubrication, cooling, cleaning and protecting metal surfaces against corrosion. Lubricant comprises base fluid called lubricating oil and a package of additives. The primary function of a lubricating oil is to lubricate and additives carrier.¹

A terpolymer is a copolymer consisting of three different monomers. A terpolymer has a greater interest (in comparison to copolymers having two monomers) due to the presence of different morphology that has been observed so far in the bulk. Moreover, due to the presence of a third block, it may introduce some new set of functions and render some additional parameters to control the copolymer properties.^{2,3}

The commercial synthetic acrylate based additives for lube oil are non-biodegradable and due to the increasing environmental pollution research on environmentally benign polymeric additives in the lubricant chemistry is increasing day by day. There are many works where biodegradable vegetable oils are used for the synthesis of lube oil additives.^{4,5} Due to excellent tribological properties, higher viscosity index, less evaporation, enhanced lubricity which are important properties of lubricant⁶ and mostly polyunsaturated fatty acid composition, sunflower oil was chosen for the present work. Composition of sunflower oil is given in **table 3.2.1**.

Viscosity index (VI) is an arbitrary numbering scale that measures the resistance power of changes of oil viscosity with changes in temperature. A higher viscosity index indicates small changes of viscosity of lube oil with temperature. A low viscosity index indicates higher changes of viscosity with temperature. Therefore, the oil that has high viscosity index can be expected to undergo very small changes in viscosity with rise in temperature. The additive that increases the viscosity index is called viscosity index improver (VII) or viscosity modifier (VM). The viscosity modifier in solution exists as a random coil, which is swollen by lube oil solvent at high temperature and polymer molecules changes from tight coils to an open configuration which has a greater volume. This increase in volume causes increases of viscosity of the oil which offsets the normal reduction in viscosity with increasing temperature.⁷ Antiwear agent is an important additive in lube oil. For the prevention of metal to metal contact in the engine parts, the antiwear additives are to be added with the lubricating oil and acts by forming a layer between the metal surfaces.⁸

Most of the base oil contains some dissolved paraffinic wax. At low temperature, the wax crystallizes to form a rigid structure that trap the oil in small packets in the structure. With sufficient formation of these crystal structures, the oil loses its flow capability. The lowest temperature at which the lube oil just stops its flowing is called pour point .To overcome this problem some high molecular weight polymers are used as pour point depressant (PPD). Pour point depressants, otherwise known as lube oil flow improvers (LOFI), are those additives that improve the low temperature fluidity of the fluid. The pour point depressants act by preventing the formation of a wax crystal structure that would resist the oil flow at low temperatures.⁹

In the present work, the author prepared three terpolymers of octyl acrylate, sunflower oil and styrene at different ratio by weight (1:1:1, 2:1:1 and 3:1:1). The best performance as well as higher molecular weight is observed when the ratio is 2:1:1 (w/w). That is why at this ratio, another two polymers were prepared with different long chain alkyl acrylate (decyl acrylate and dodecyl acrylate). The biodegradable test of the prepared polymers was carried out by disc diffusion method. The author had investigated the efficiency of the prepared polymers as viscosity index improvers, pour point depressant and antiwear additives in two types of base oils. Moreover, powder XRD and photo micrographic image were carried out to study the pour point mechanism of lube oil without and with polymeric additives.

3.2.2 Experimental section

3.2.2.1 Chemicals used

Refined sunflower oil was collected from local market and its fatty acid composition is given **table 3.2.1**. Acrylic acid (99%, Merck Specialities Pvt. Ltd.), styrene (99%, Sigma-Aldrich), 1-octanol (99%, LOBA chemie, India), 1- decanol (99%, Sd. fine chemicals, India) and 1-dodecanol (98%, Sd. fine chemicals, India) were used in esterification without further purification. Toluene (99.5%, Merck Specialities Pvt. Ltd.) and methanol (98%, Thomas Baker Pvt. Ltd.) were used after distillation. Hydroquinone (99%, Merck Specialities Pvt. Ltd.), and azobisisobutyronitrile (AIBN, 98%, Spectrochem Pvt. Ltd.) were purified by recrystallization before use. Conc. H₂SO₄ (98%, Merck Specialities Pvt. Ltd.) was used as received. Base oils were collected from IOCL and BPCL, India. Physical properties of the base oils are given in **table 3.2.2**.

3.2.2.2 Preparation of the esters and their purification

Three esters were prepared by reacting acrylic acid with different alcohols (1-octanol, 1-decanol and 1-dodecanol) in the molar ratio of 1.1:1 in the presence of conc. H₂SO₄ as a

catalyst, 0.25% (w/w) hydroquinone with respect to the total reactants as polymerization inhibitor, and toluene as solvent by using Dean Stark apparatus. The process of esterification and its purification were carried out by the procedure as reported in the chapter II of part I (1.2.2.2 & 1.2.2.3).

3.2.2.3 Preparation of terpolymers

Three terpolymers consisting of octyl acrylate, sunflower oil and styrene were prepared in the ratio of 1:1:1(w/w), 3:1:1(w/w) and 2:1:1(w/w) separately to get three polymers designated by A, B and C respectively. Another two polymers consisting of different alkyl acrylates (decyl acrylate and dodecyl acrylate), sunflower oil and styrene at the ratio of 2:1:1(w/w) were prepared to get the polymers designated by D and E respectively. The polymerization was carried out in three necked round bottom flask fitted with a magnetic stirrer, thermometer, condenser and an inlet for the introduction of nitrogen. The monomers were mixed in toluene solvent and temperature was kept constant at 90° C and then AIBN (1% w/w, with respect to the total monomer) was added and heated for 8 hours. After the reaction is over, the product was poured into methanol with continuous stirring, filtered off and dried.

3.2.3 Measurements

3.2.3.1 Spectroscopic measurements

IR spectra were recorded on a Shimadzu FT-IR 8300 spectrometer using 0.1mm KBr cells at room temperature within the wave number range of 400 to 4000 cm^{-1} . NMR spectra were recorded in Bruker Avance 300 MHz FT-NMR spectrometer using a 5 mm BBO probe. CDCl_3 was used as solvent and tetramethylsilane (TMS) as reference material.

3.2.3.2 Determination of the molecular weight

The number average molecular weight (M_n) and weight average molecular weight (M_w) were measured by GPC method (polystyrene calibration) equipped with a 2414 detector, waters 515 HPLC pump and 717 plus auto sampler. Sample solutions (0.4% w/v in HPLC grade THF) are prepared by dissolving ~4 mg of polymer per ml THF and filtering (0.45- μm Millipore PTFE) to remove suspended particulates. The pump flow rate is 1.0 mL/min with THF as the carrier solvent, and injection volumes are set to 20 μL . The polydispersity index which indicates the nature of the distribution of the molecular weights in the polymers was also calculated.

3.2.3.3 Thermo gravimetric analysis (TGA) data

TGA data was measured on Shimadzu TGA-50 system in air using an alumina crucible at a heating rate of 10° C/ min.

3.2.3.4 Biodegradability test (Disc diffusion method)

The biodegradability test was carried out against *Fussarium equisetae*, *Alternaria alternata* and *Colletrichum gleosporoides* fungals. All the experiments were performed in petridishes and were kept incubator at 37° C for 30 days after addition of approximately 2g of the polymer samples. The fungal growth was confirmed by a change of yellow to blackish colour. Culture media strains were prepared by mixing suitable amount of potato extract, dextrose and agar powder. After 30 days, the polymer samples were recovered from the fungal media by dissolving in chloroform, purified and dried. The dried samples were weighed.¹⁰

3.2.3.5 Performance evaluation as viscosity index improver (VII)

In general the VII property is expressed in terms of an experimental parameter called viscosity index (VI). Greater the values of VI better is the additive performance as VII. Viscosity index was calculated by dissolving prepared polymer in two types of base oils (BO1 and BO2) through the viscosity index test according to ASTM D 2270-10. The kinematic viscosity of the polymer doped base oil was determined at 40° C and 100° C. Different concentrations of additives [ranging from 1% - 5% (w/w)] were used to study the effect of additive concentration on VI.

3.2.3.6 Performance evaluation as pour point depressant (PPD)

Pour point depressants were determined in polymer doped different base oils (BO1 and BO2) through the pour point test according to the ASTM D 97-09 method using the cloud and pour point tester model WIL-471 (India). The effect of additive concentration on pour point was investigated by using different doping concentrations ranging from 1% - 5% (w/w).

3.2.3.7 Evaluation of tribological performance

The antiwear performance in terms of wear scar diameter (WSD) of the lubricant compositions was evaluated by four-ball wear test apparatus (FBWT) following the ASTM D 4172-94 method. In this experiment 392 N (40 Kg) load at 75 ° C for 60 min was applied to measure the wear scar diameter (WSD). The diameter and rotating speed of the ball were 12.7 mm and 1200 rpm respectively.

3.2.3.8 Photographic and powder XRD study

The photomicrograph showing wax behaviour of lube oil (BO2) without and with polymers at 2% (w/w) concentration has been recorded at 0° C temperature. A Banbros polarizing microscope model BPL-400B was used for photographic analysis. The adopted magnification was 200X. For powder XRD (Rigaku, smart lab, 9Kw) analysis, the lube oil without polymer

and with 2% (w/w) polymer were mixed with suitable amount of alumina and PXRD was carried out.

3.2.3.9 Rheological study

Rheological study was carried out with lube oil (BO2) without and with 5% (w/w) copolymer using Brookfield Rheometer (Model DV-III ultra). Dynamic viscosity (cp) and shear rate (sec^{-1}) were measured at two temperatures (40°C and 100°C).

3.2.4 Results and discussion

3.2.4.1 Spectroscopic data analysis

The spectroscopic data of all the prepared five polymers are similar. The IR absorption band at 1744 cm^{-1} was for the ester carbonyl group. The peaks at 2857 cm^{-1} and 2931.5 cm^{-1} were the characteristic of $\text{CH}_3\text{-CH}_2\text{-}$ group. The peaks at 1458.6 cm^{-1} , 1270 cm^{-1} and 1175 cm^{-1} were due to CO stretching vibration and absorption bands at 1051.3 cm^{-1} and 982.5 cm^{-1} were due to bending of C-H bond. Peaks at 810 cm^{-1} , 756 cm^{-1} , 723.6 cm^{-1} and 695 cm^{-1} were attributed to the C-H bending of the phenyl group of styrene. A peak at 3000 cm^{-1} was due to C-H stretching of aromatic ring (**figure 3.2.1**). In the ^1H NMR, the methyl protons appear in the range of 0.87 - 0.89 ppm, the methylene protons appear in the range of 1.28 - 1.62 ppm for all alkyl groups. The peaks in the range of 2.03 - 2.29 ppm appear for the protons of -COCH- group of alkyl acrylate. A peak at 4.08 ppm indicates the protons of $-\text{OCH}_2$ of alkyl acrylate. The peaks in the range of 4.10 - 4.14 ppm indicate the protons of $-\text{COOCH}_2$ group of sunflower oil. A broad peak in the range of 6.80 - 7.64 ppm indicates the protons of aromatic ring (**figure 3.2.2**). In the ^{13}C NMR, the peaks in the range of 14.14 - 41.03 ppm appear due to carbons of all CH_3 and CH_2 groups. The peaks at 58.13 ppm indicate the carbons of $-\text{CH}-$ of $-\text{COCH}-$ group of alkyl acrylate. The peaks in the range of 60 - 62.08 ppm represent the carbons of $-\text{OCH}_2$ groups of alkyl acrylate. The CH_2 carbons of $-\text{OCOCH}_2\text{-}$ group of sunflower oil showed peaks in the range of 64.61– 68.99 ppm. The aromatic carbons appear in the range of 127.93 -130.88 ppm. The peaks in the range of 165.65 -173.00 ppm confirms the carbons of ester groups (**figure 3.2.3**).

3.2.4.2 Molecular weight data analysis

The experimental values of number average molecular weight (M_n), weight average molecular weight (M_w) and polydispersity index (PDI) of polymer A, B, C, D and E are given in **table 3.2.3**. The higher molecular weight is observed when the ratio of acrylate, sunflower oil and styrene is 2:1:1(w/w). Moreover at this ratio, molecular weight increases with increasing the alkyl chain length of alkyl acrylate.

3.2.4.3 TGA data analysis

The TGA values of the five polymers are given in **figure 3.2.5**. From the figure, it is clear that the thermal degradation of polymer E is less than the other polymers which signifies that E is thermally more stable. The polymers A, B, C and D are almost equally stable. In case of polymer E, initial decomposition starts at 250 ° C with a 12% weight loss and another major decomposition is observed at 420° C with a 63% weight loss. For other polymers, initial decomposition is observed approximately at 210° C with a 10% weight loss and another major decomposition is found at 400 ° C with a 60% weight loss.

3.2.4.4 Analysis of biodegradability test results

The biodegradability test were carried out against three different fungals like *Fussarium equisetae*, *Alterneria alternata* and *Colletrichum gleosproides* but it is found that only *Alterneria alternata* is effective against the prepared terpolymers. The loss of mass after biodegradation of the prepared terpolymers is given in **table 3.2.4**; it was further confirmed by the shifting of IR frequency of the ester carbonyl group from 1744 cm⁻¹ to 1730 cm⁻¹ along with other shifted peaks (**figure 3.2.4**). Moreover, molecular weight of the recovered samples after biodegradation was determined by GPC method and the results were compared with the respective samples before biodegradation and given in **table 3.2.5**. Among the five polymers, polymer E is highly biodegradable whereas polymer B is the least.

3.2.4.5 Analysis of viscosity index (VI) data

VI was calculated by dissolving the prepared polymers in two types of base oils (BO1 and BO2) in the concentration range 1% - 5% (w/w). The experimental values of VI are given in **figure 3.2.6 & 3.2.7**. From the experimental data, it is found that VI values increase with increase in concentration of polymer in lube oil. The viscosity of lube oil decreases with the increase in temperature, but simultaneous expansion of polymer chains take place at high temperature leading to an increase in their hydrodynamic volume. This fact is actually responsible for the reduction of the viscosity of the polymer doped lube oil. Therefore, a higher treat level of the polymer may lead to exert higher thickening effect and consequently a much better VI property.¹¹ Among the five polymers, polymer E has highest effect on VI for both the base oils. It may be due to highest molecular weight of polymer E. Among the polymers C, D and E, it is found that there is a gradual increase in the VI property with an increase in their alkyl chain length. Among the copolymers (A, B and C), prepared by using different weight ratios of the respective monomers, copolymer C showed highest VI property.

Further analysis indicates that when the ratio of alkyl acrylate, sunflower and styrene is 2:1:1(w/w), much better VI improver property is predicted.

3.2.4.6 Analysis of pour point data

The polymer doped base oils (BO1 and BO2) at different concentration ranging from 1% - 5% (w/w) were tested for pour point and experimental values are given in **figures 3.2.8** and **3.2.9**. From the values, it is observed that efficiency as pour point depressant decreases with increasing the concentration of polymer in base oil. It may be due to the decrease in solvation power.¹² Consideration of the alkyl chain lengths of the polymer (C, D and E), it is observed that the polymer having shorter alkyl chain length (polymer C) has greater efficiency as pour point depressant. This may be because of the more effective interaction between the short alkyl chain length and paraffinic structure present in the lube oil than the long alkyl, causing the inhibition of wax crystal network formation; similar observation is already reported elsewhere.¹³ Among the three polymers A, B and C, prepared by using different monomer to monomer ratio (w/w), it is found that when the ratio of alkyl acrylate, sunflower and styrene is 2:1:1(w/w), the depression of pour point is maximum.

3.2.4.7 Analysis of tribological properties

The tribological properties of the lubricant compositions were determined by measuring WSD values through FBWT apparatus applying 392 N load and shown in **table 3.2.6**. The anti wear performance of the base oil is significantly improved when the additives are blended with it and is reflected in lower WSD values of the lubricant compositions. The WSD values gradually decreases from A to E. This means that the lube oil blended with the terpolymer E (formed by DDA, SFO and styrene in 2:1:1 ratio) showed lowest value in WSD ($18.33 \pm 1.5\%$, $16.18 \pm 1.5\%$ in BO1 and BO2 oil respectively) followed by D (formed by DA, SFO and styrene in 2:1:1 ratio), $16.9 \pm 1.5\%$ and $14.03 \pm 1.5\%$ in BO1 and BO2 oil respectively. Lubricants form a film on the rubbing zone of engine through chemical and physical bonding by the base oil and functional groups of the additive molecules with the metal atoms on the surface. Stronger the film lower will be the friction. The terpolymers, due to higher number of polar side chains, form stronger films. So, they show excellent antiwear properties. Best antiwear performance (lower WSD) for E and D are due to the longer hydrocarbon chains of DDA and DA counterpart of the respective terpolymer molecules that provide an excellent molecular barrier along with the polar functional groups which coordinate with iron to form stronger protective films on the metal surface.^{14, 15}

3.2.4.8 Powder XRD and photo micrographic images analysis

Powder XRD and photo micrographic analysis were used to study the action mechanism of the pour point depressant (PPD) with the lube oil. The influence of the PPD on the thermodynamics of wax crystallization may be due to the change of wax lattice structure to a different form caused by the long chain polymeric structure of the PPD.¹⁶ It was confirmed by means of X-ray diffraction experiments. The wax present in lube oil is orthorhombic phase.¹⁷ After adding PPD to the lube oil the diffraction line intensities of the orthorhombic phase decrease without any significant variation of Bragg angle values. This may be due to the transformation of wax crystal lattice from orthorhombic (an ordered phase) to hexagonal phase (a disordered phase) in presence of PPD.^{18, 19} It is evident from the **figure 3.2.10** that lube oil without any PPD showed highest intensity. The intensity of lube oil with 2% (w/w) PPD decreases and lowest intensities are found in case of polymer C and D. This is in agreement with the observed pour point values determined by ASTM D 97-09 method.

The photo micro graphs images of lube oil (BO2) without and with different additives are shown in **figure 3.2.11(a-f)**. The figure 3.2.11a, the photograph of the fresh lube oil (pour point = - 6°C) showed large number of cyclic crystalline and some needle shaped wax crystals. When it is treated with the additive (2%, w/w solution), either polymer A (pour point = -10°C) or polymer E (pour point = -12°C), there occurs a small change in the size of wax crystal (figure 3.2.11b and 3.2.11f). But when the same lube oil is treated with (same treatment level) polymer C (pour point = -16°C) or polymer D (pour point= -15°C), a significant reduction of the wax crystal size takes place which appears as a very small dispersed crystals of waxes²⁰ (figure 3.2.11d and 3.2.11e) and is responsible for reducing the pour point to greater extent. Therefore, a correlation between the depression of pour point and degree of wax structure modification has been verified.

3.2.4.9 Analysis of rheological study

Rheological study was carried out at 40° C and 100° C with lube oil (BO2) without and with 5% (w/w) polymer. For fresh lube oil, there is no significant change in viscosity with the increase in shear rate. This indicates that pure lube oil behaves like a Newtonian fluid.²¹ For polymer blended lube oil, it is observed that there is a gradual drop in the viscosity up to a shear rate of 32 S⁻¹, and hence the sample behaves like a non- Newtonian fluid.²² But at high shear rate viscosity of the lubricants approximately remains constant and behaves like Newtonian fluids.²³ At low temperature, viscosity modifiers in lube oil exist as spherical coil form having random orientation and exert high viscosity in absence of shear.²⁴ When shear is applied, the polymeric VM starts rearranging itself in the direction of flow and thereby

decrease the viscosity.²⁵ At high shear rate all the polymers are arranged in the direction of flow and there is a negligible change in viscosity. Viscosity modifiers at high temperature (100° C) exist in the expanded form and hence are easily arranged in the direction of flow under shear and viscosity approximately remains constant under any shear rate for all lubricants. This indicates that the prepared copolymers can compensate the drop of lube oil viscosity. The decrease of viscosity may be due to the applied shear and also due to the rise of temperature from 40° C to 100° C (**figures 3.2.12** and **3.2.13**).

3.2.5 Conclusions

From the above study, it is found that all the prepared terpolymers based on different alkyl acrylates, sunflower oil and styrene are effective as VM, PPD and antiwear additives. The terpolymer prepared by taking monomers in 2:1:1 (w/w) ratio was found to be the most efficient compared to the others. Therefore, it can be said that monomer to monomer ratio by weight has a significant role for the preparation of effective terpolymers. The tribological and VI performance of the prepared terpolymers increases with increasing the alkyl chain length whereas PPD performance decreases. Due to biodegradability the additives are eco-friendly also. Therefore, the above study is definitely a potential approach to formulate multifunctional, better performing and sustainable lubricant composition.

3.2.6 References

References are given in bibliography section of chapter II of Part III (Page No. 197 - 199).

3.2.7 Tables and figures

Table 3.2.1 Composition of sunflower oil

<u>Fatty acid</u>	<u>% Composition</u>
(Carbon atoms: Double bonds)	
C 14:0 (Myristic acid)	0.56
C 16:0 (Palmitic acid)	6.8
C 18:0 (Stearic acid)	4.2
C 20:0 (arachidic acid)	0.41
C 18:1 (Oleic acid)	23.3
C 18:2 (Linoleic acid)	60.8
C 18:3 (Linolenic acid)	2.9

Table 3.2.2 Physical properties of the base oils

Base oil properties	Base oil	
	BO1	BO2
Density (g cm ⁻³) at 40 ° C	0.83	0.84
Viscosity at 40 °C in c St	7.102	23.502
Viscosity at 100 °C in c St	1.850	3.98
Viscosity index	84.56	85.15
Pour point (° C)	-3	-6
Cloud point (° C)	-1	-4

Table 3.2.3 Polymers designation, monomers, monomers ratio, molecular weight values of the polymers A, B, C, D and E

Polymer code no.	Monomers	Monomer ratio(w/w)	Molecular weight		
			M _n	M _w	PDI
A	OA, sunflower oil, styrene	1:1:1	10418	14461	1.39
B	OA, sunflower oil, styrene	3:1:1	12240	15275	1.25
C	OA, sunflower oil, styrene	2:1:1	13611	17003	1.25
D	DA, sunflower oil, styrene	2:1:1	13623	20522	1.51
E	DDA, sunflower oil, styrene	2:1:1	21643	30042	1.39

OA= octyl acrylate; DA= decyl acrylate; DDA= dodecyl acrylate;

M_n = number average molecular weight; M_w = Weight average molecular weight; PDI = polydispersity index

Table 3.2.4 Results of biodegradability test

Fungal pathogens	Polymer samples	Incubation periods(days)	Initial weight (gm)	Final weight (gm)	Weight loss (%)
<i>Alternaria alternata</i>	A	30	2.01	1.48	26.4
	B	30	2.03	1.66	18.2
	C	30	2.05	1.57	23.4
	D	30	2.00	1.52	24
	E	30	2.011	1.41	29.8

Table 3.2.5 Comparative molecular weight (determined by GPC method)

Polymer code	<u>Before biodegradation</u>		<u>After biodegradation</u>	
	M _n	M _w	M _n	M _w
A	10418	14461	9175	12588
B	12240	15725	12082	14880
C	13611	17003	13012	15835
D	13623	20522	12908	18416
E	21643	30042	20073	26872

Table 3.2.6 Antiwear property in terms of wear scar diameter (WSD in mm) values of different lubricant compositions

Polymer code	Base fluids	WSD of lubricant in mm at different additive concentrations (ppm x 10 ⁴)					
		0	1	2	3	4	5
A	BO1	0.982	0.965	0.955	0.93	0.891	0.846
	BO2	1.119	1.079	1.062	1.048	1.016	0.992
B	BO1	0.982	0.964	0.952	0.928	0.89	0.842
	BO2	1.119	1.078	1.061	1.046	1.012	0.984
C	BO1	0.982	0.951	0.944	0.919	0.875	0.833
	BO2	1.119	1.072	1.053	1.038	1.006	0.974
D	BO1	0.982	0.938	0.927	0.906	0.861	0.816
	BO2	1.119	1.061	1.048	1.03	0.991	0.962
E	BO1	0.982	0.919	0.908	0.885	0.844	0.802
	BO2	1.119	1.046	1.031	0.985	0.958	0.938

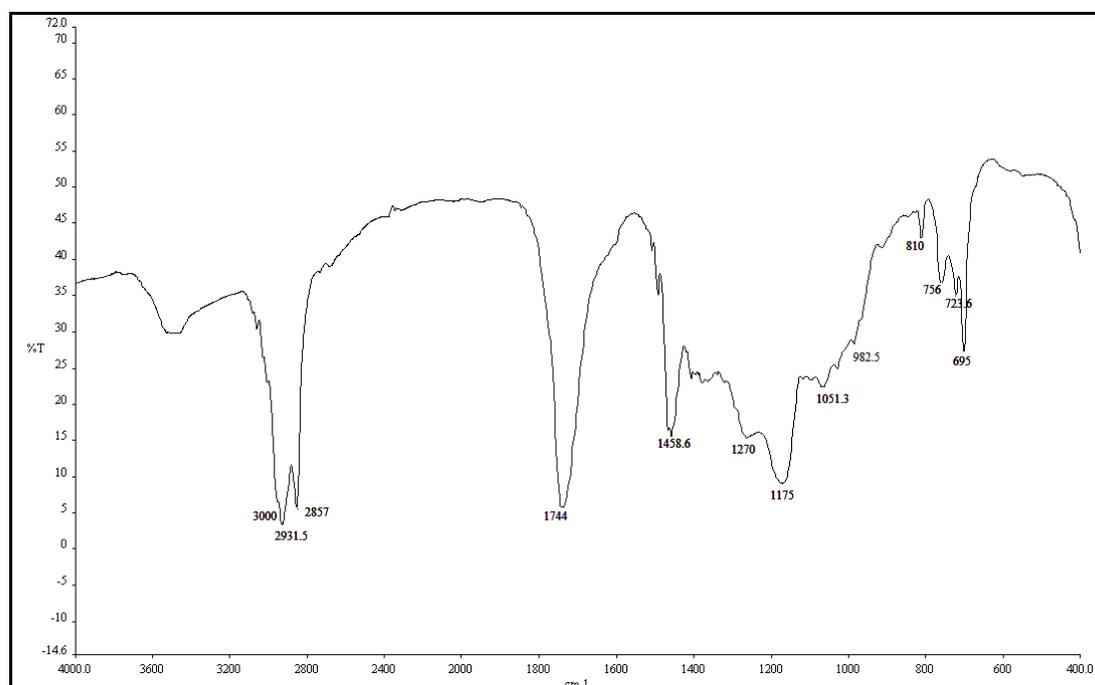


Figure 3.2.1 IR spectra of terpolymer E

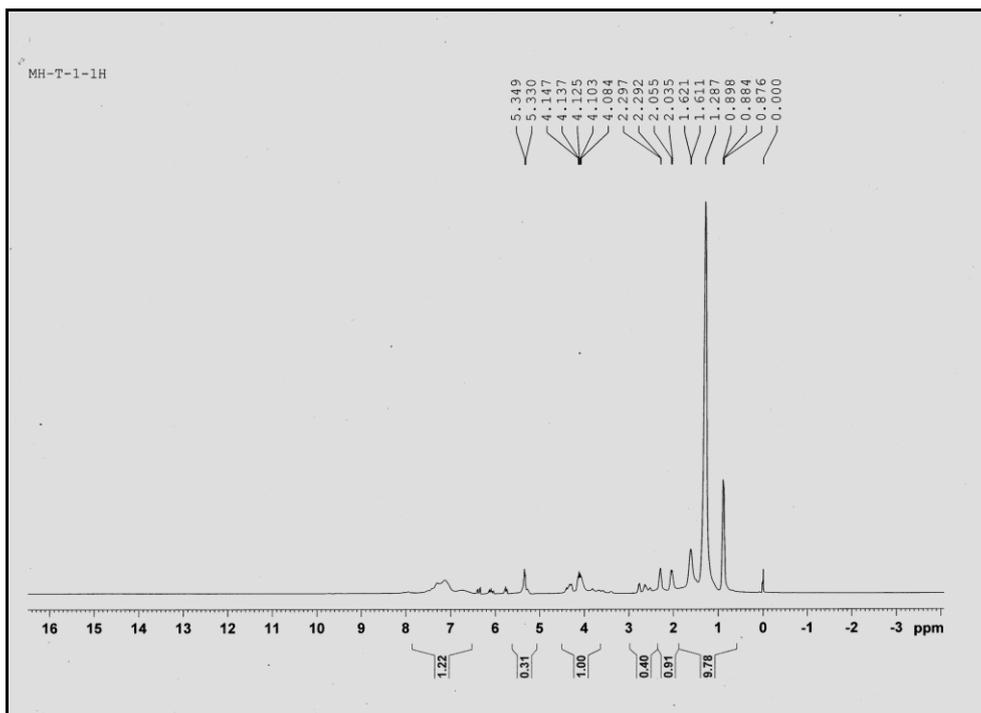


Figure 3.2.2 ^1H NMR spectra of terpolymer E

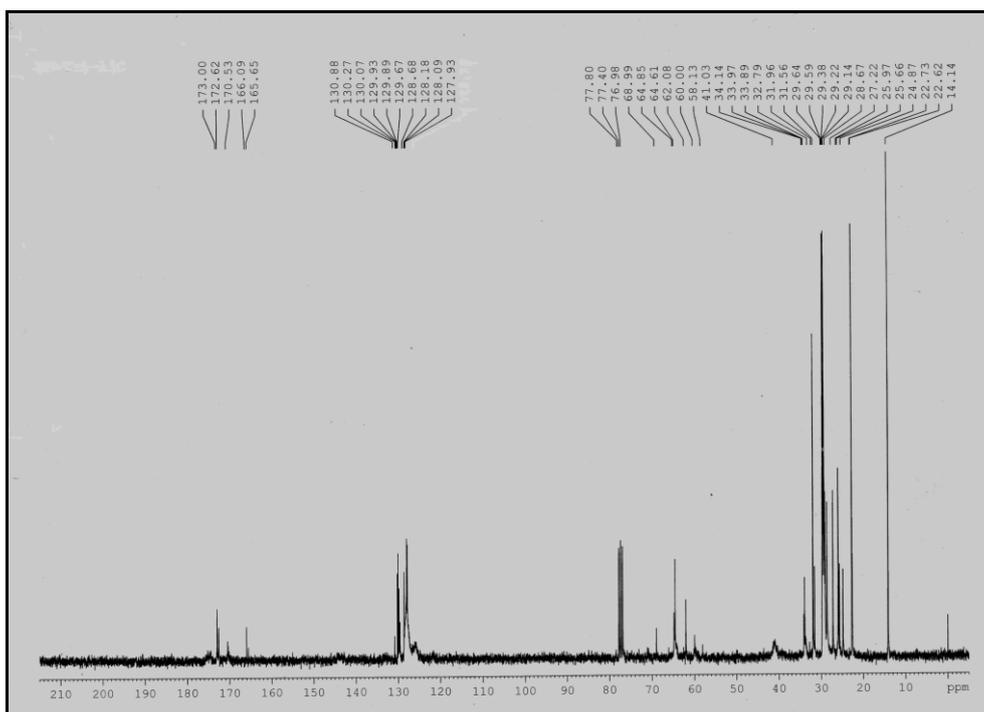


Figure 3.2.3 ^{13}C NMR spectra of terpolymer E

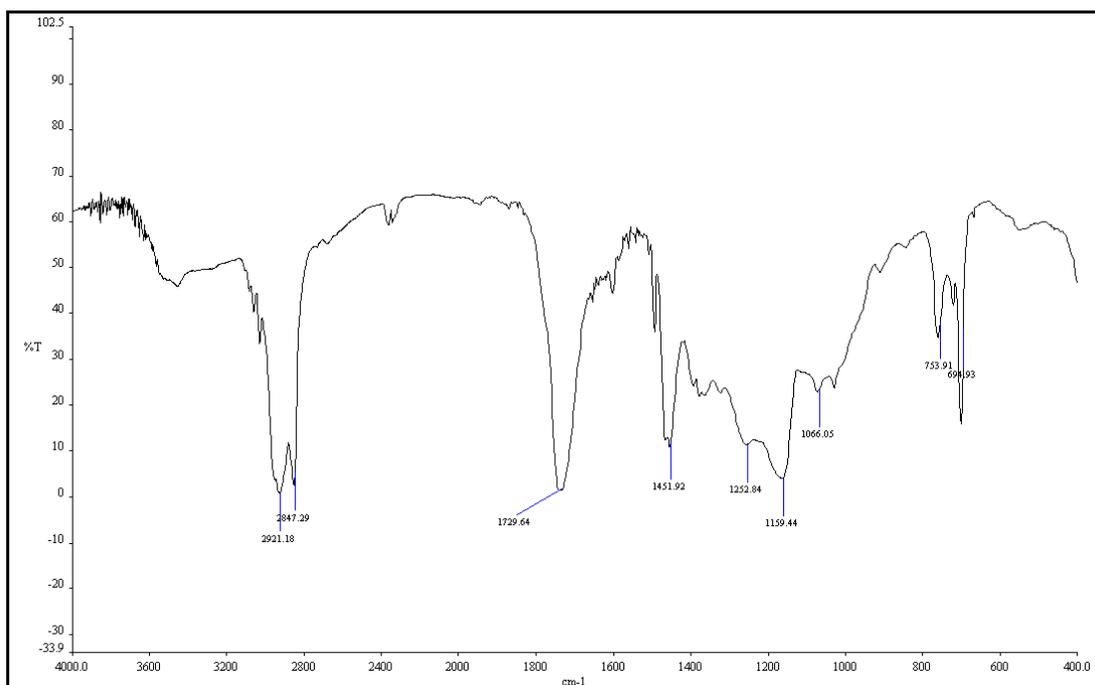


Figure 3.2.4 IR spectra of terpolymer E after biodegradable

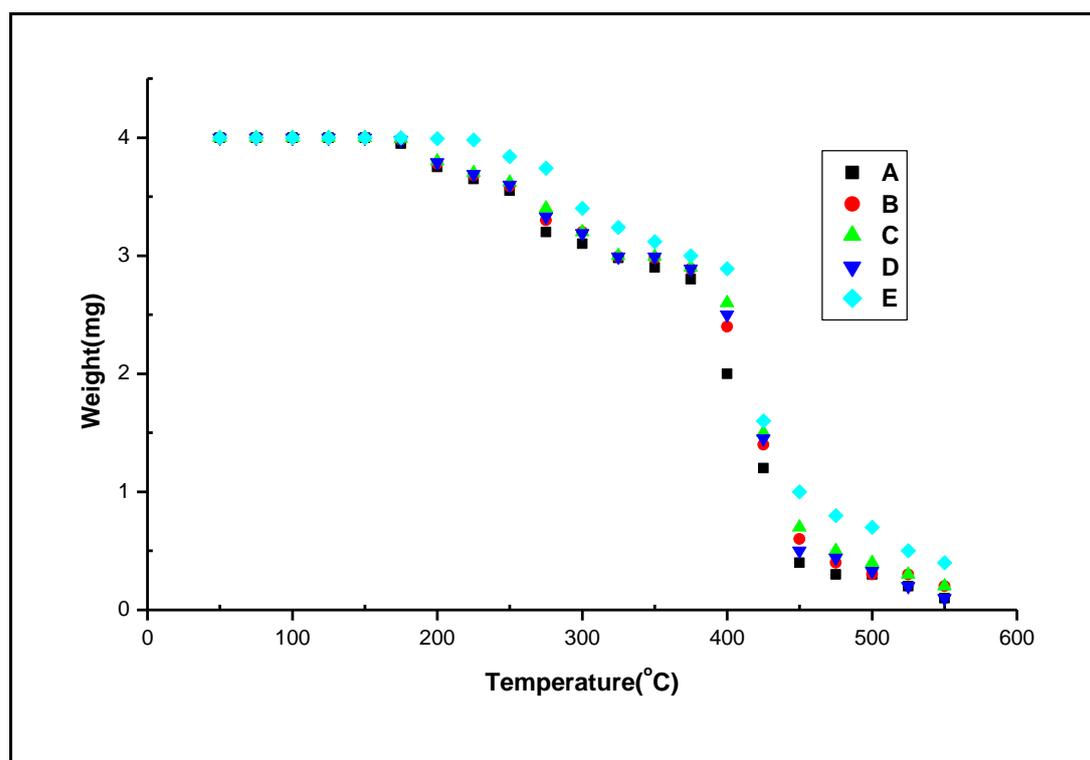


Figure 3.2.5 Thermal degradation of the polymers A, B, C, D and E

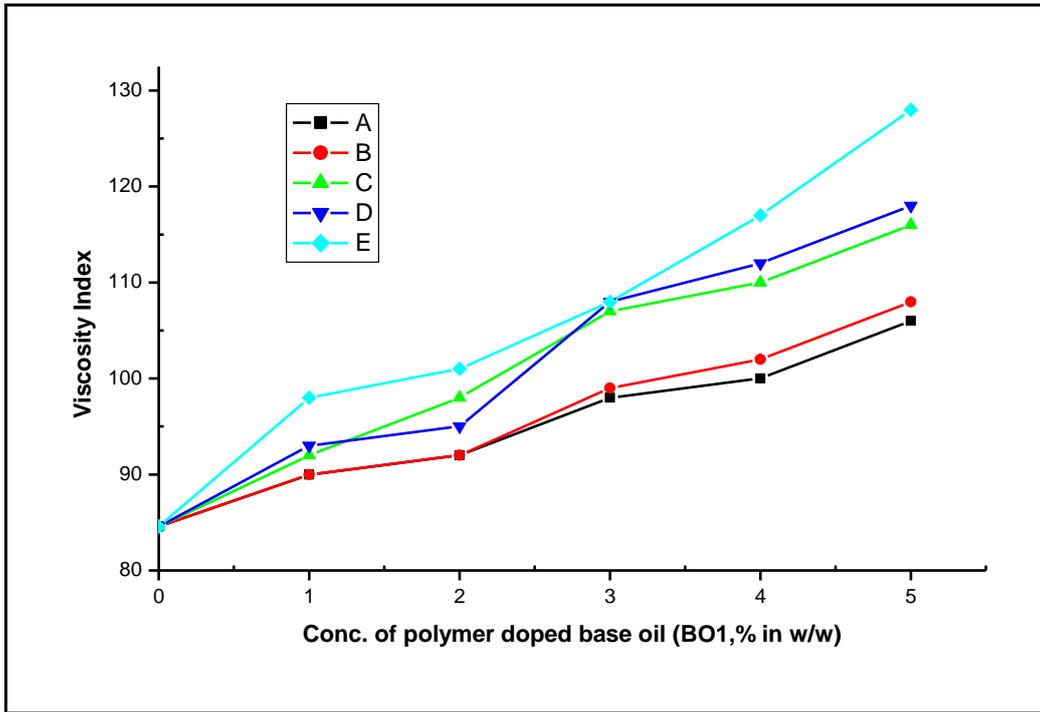


Figure 3.2.6 Variation of viscosity index of polymer doped base oil (BO1) at different concentrations

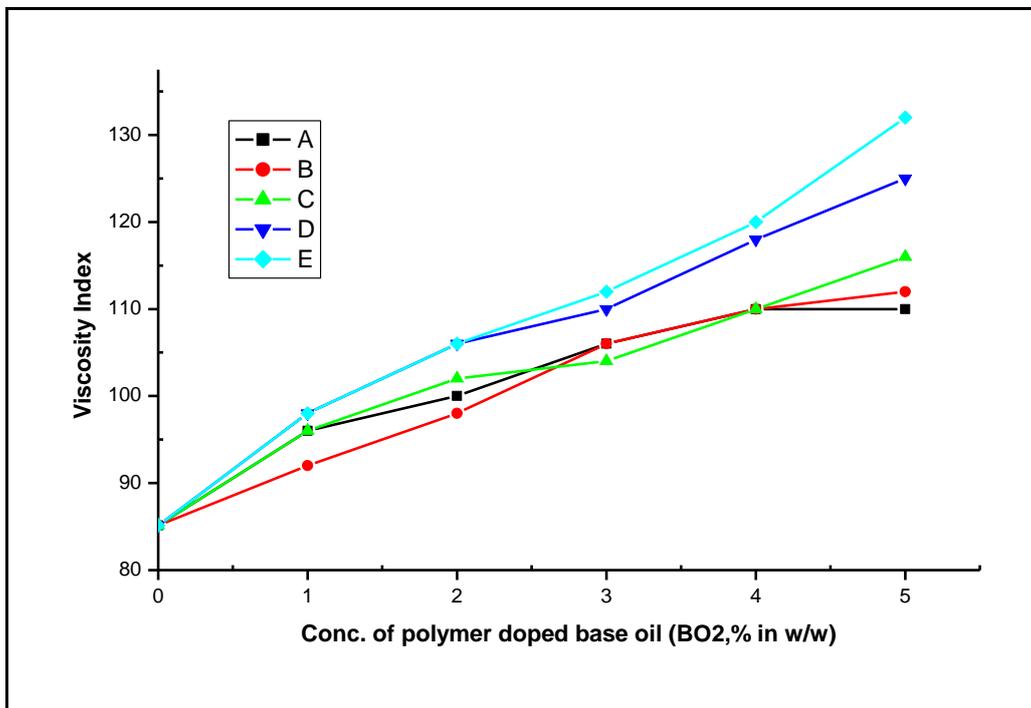


Figure 3.2.7 Variation of viscosity index of polymer doped base oil (BO2) at different concentrations

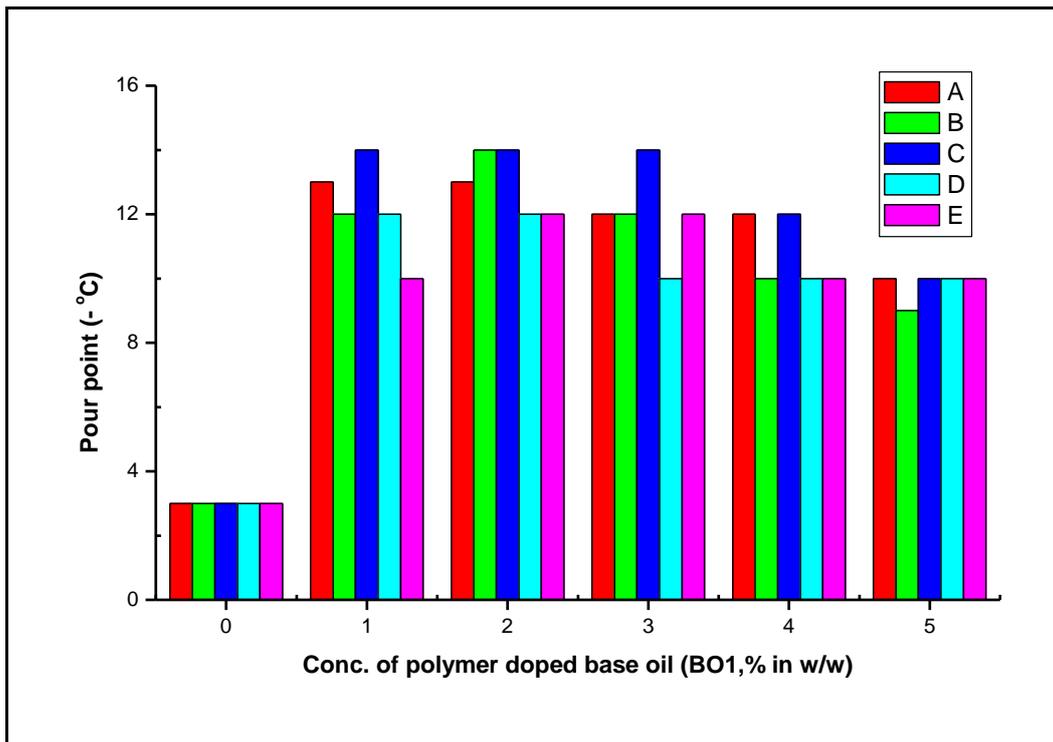


Figure 3.2.8 Variation of pour point of polymer doped base oil (BO1) at different concentrations

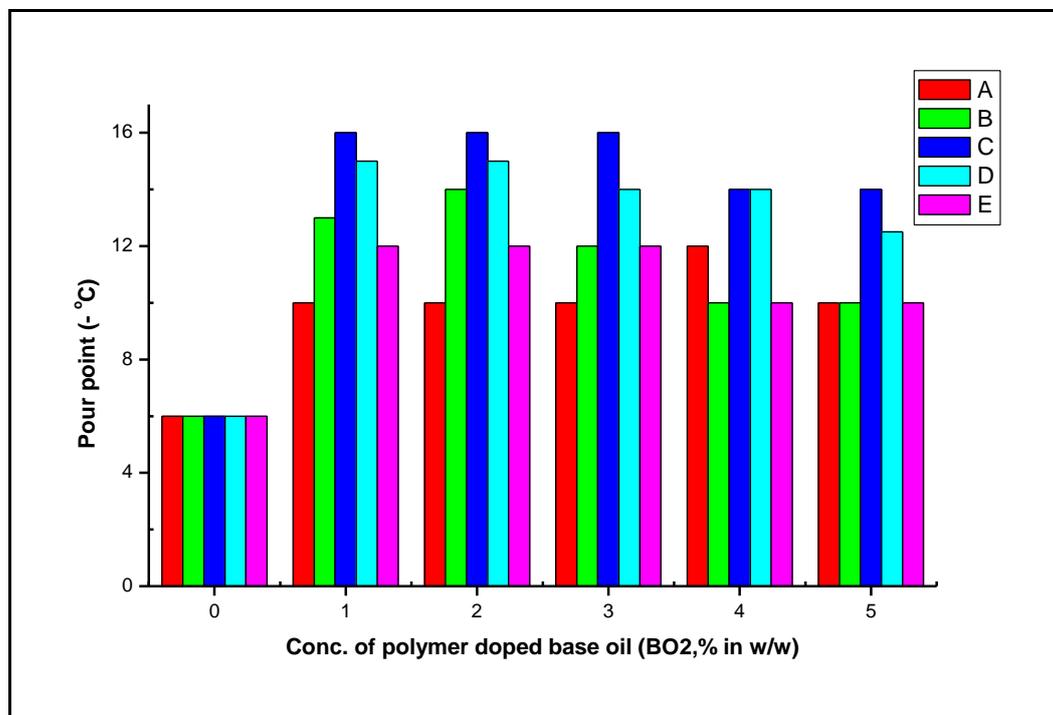


Figure 3.2.9 Variation of pour point of polymer doped base oil (BO2) at different concentrations

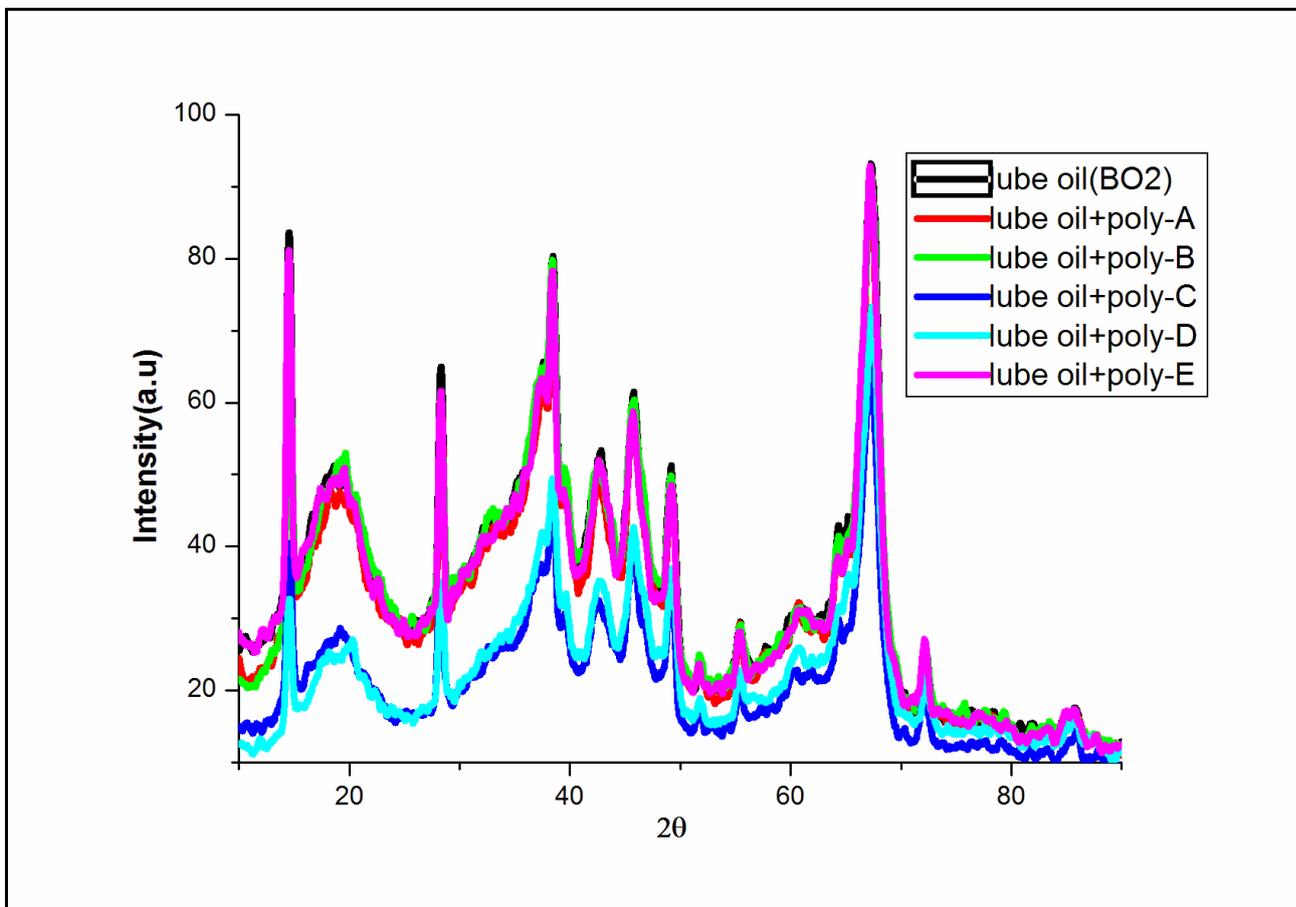
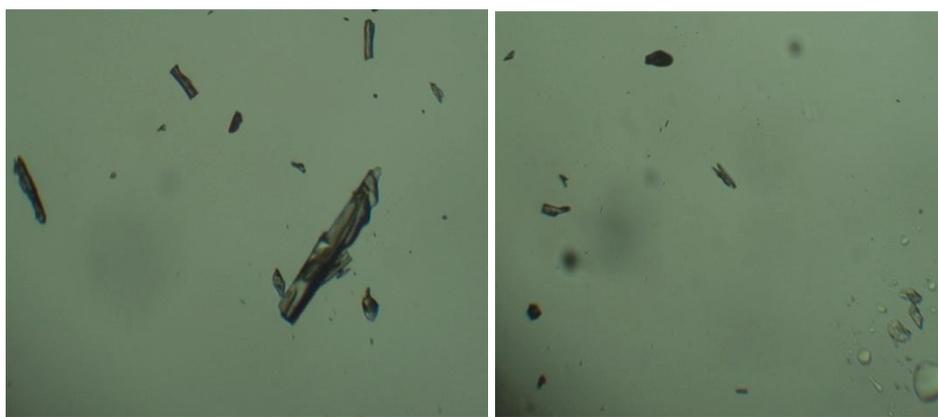
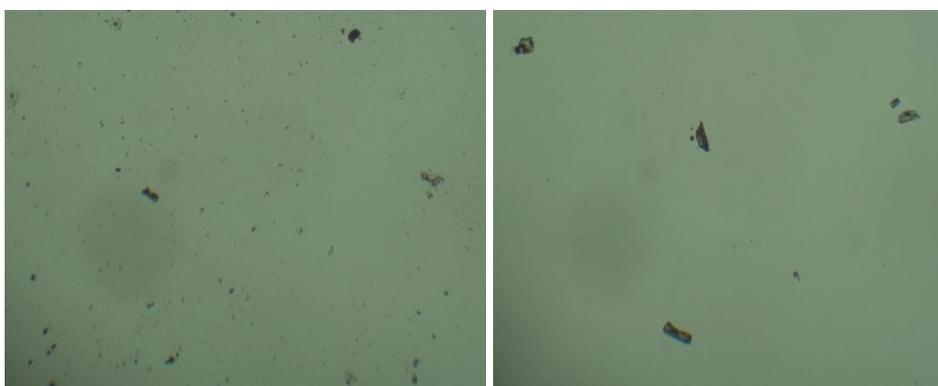


Figure 3.2.10 XRD (powder) patterns of lube oil without and with polymeric additives



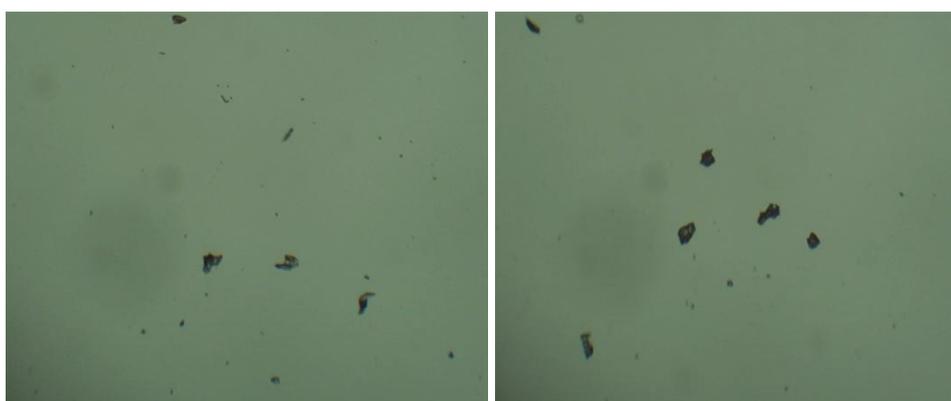
11a (pour point = -6°C)

11b (pour point = -10°C)



11c (pour point = -14°C)

11d (pour point = -16°C)



11e (pour point = -15°C)

11f (pour point = -12°C)

Figure 3.2.11 Photomicrograph of (a) Untreated base oil (BO2); (b) BO2 + polymer A (2%, w/w); (c) BO2+ polymer B (2%, w/w); (d) BO2 + polymer C (2%, w/w); (e) BO2 + polymer D (2%, w/w); (f) BO2 + polymer E (2%, w/w)

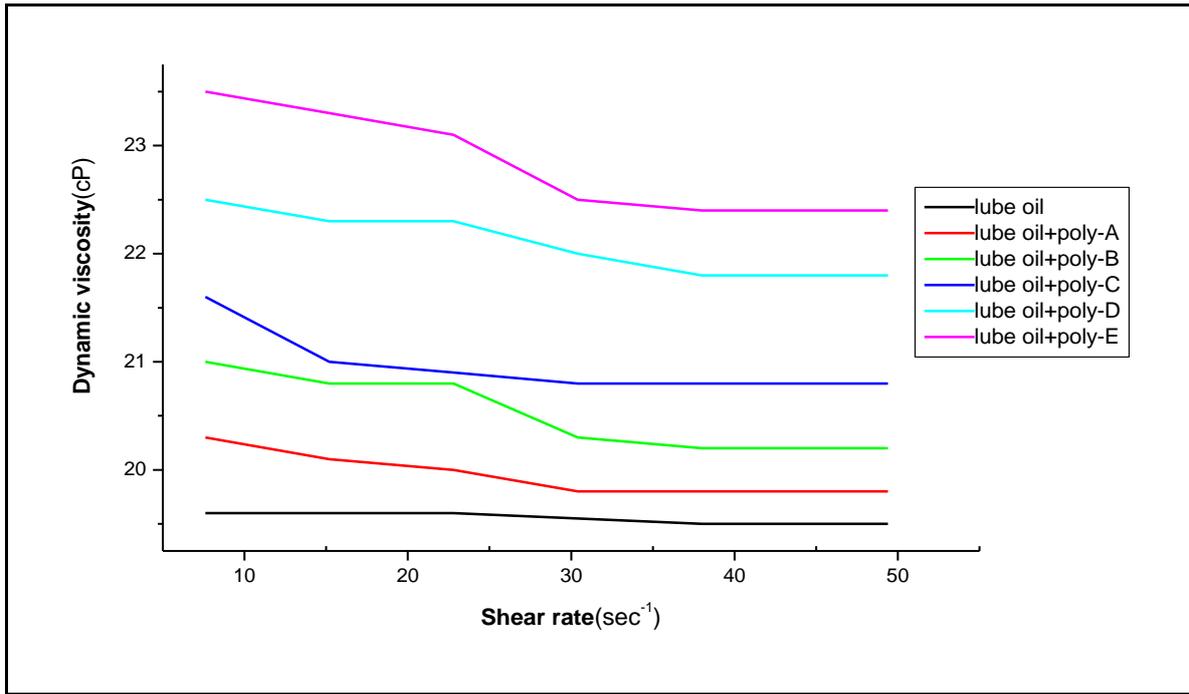


Figure 3.2.12 Variation of dynamic viscosity with shear rate at 40° C

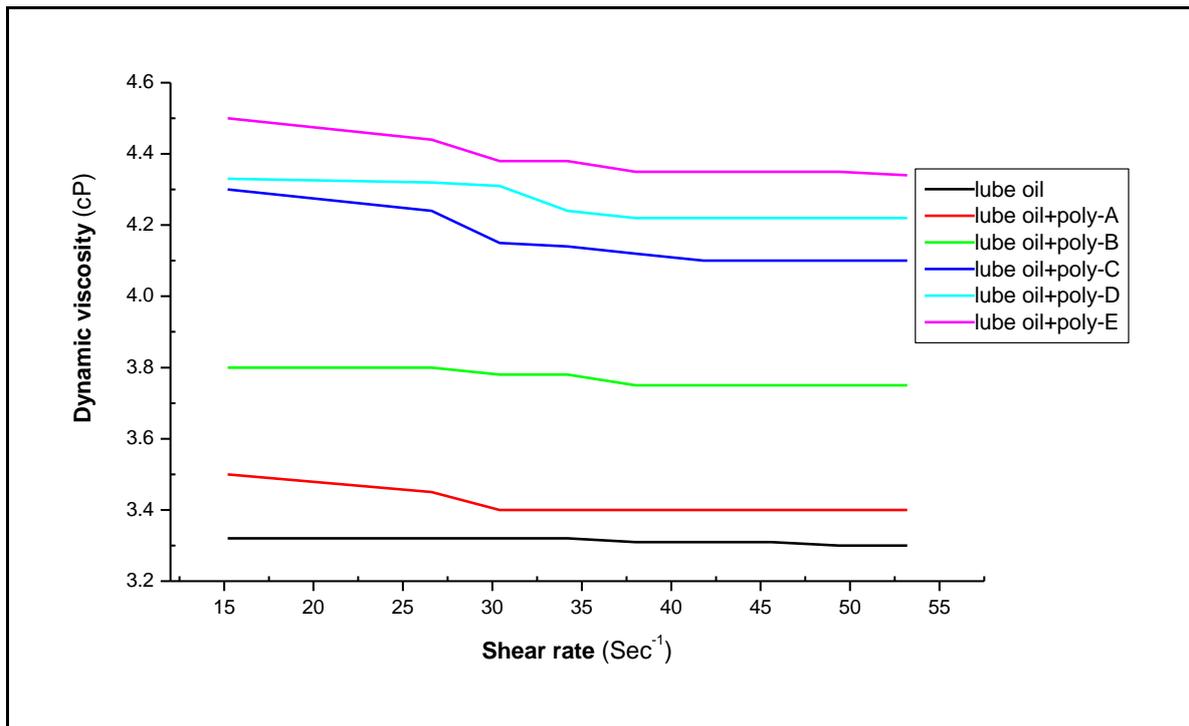


Figure 3.2.13 Variation of dynamic viscosity with shear rate at 100 ° C