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RESEARCH

Vegetable Oil-Based Pentaerythritol Ester for Industrial Air Compressor Applications: A Tribological Investigation

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ABSTRACT

Biolubricants are being developed more frequently as a result of environmental issues, which also improve performance and lessen friction and wear. This study seeks to examine the effects of commercial compressor oil-SAE30, and its blend with pentaerythritol ester (PE) derived from vegetable oil on tribological properties. Two sequential transesterification processes were used to create the pentaerythritol ester made from vegetable oil utilizing the ultrasonic irradiation method. Using an air compressor lubricant, load, and sliding speed for each experimental run, a pin-on-disc tribometer is utilized to examine the friction and wear characteristics of the material. According to the experimental findings, PE 75 (75 vol.% - PE and 25 vol.% - SAE30) performs better than PE and SAE30 in terms of minimum coefficient of friction (COF) and specific wear rate (SWR) under high loads and high sliding speeds. Furthermore, scanning electron microscope (SEM) and Energy Dispersive Analysis of X-Ray (EDAX) analyses were used to examine the morphology behavior of the pin surfaces. Due to the coating that covers the specimen's surface, PE 75 compressor oil displays smoother surfaces than other lubricated surfaces.

1. INTRODUCTION

Compressors can be used for a variety of purposes, including recreation, maintenance, and getting work done safely and efficiently in the workplace or at home. It is only feasible to guarantee that all types of compressors operate effectively and without any power loss due to friction and wear with routine lubricant changes and by choosing an appropriate compressor oil; otherwise, compressors risk being shut down. Still, synthetic-grade oil that was generated from mineral oil is employed as a lubricant in air compressors. Since many years ago, all industrial and other applications have relied on petroleum compounds, or mineral-based lubricants, to reduce wear and friction when moving components come into touch with one another as well as to mine heat. However, there was significant issue with these lubricants, including high toxicity, leakage, and disposal issues after use, which creates environmental concerns and drives up the cost of the product as a result of the decline in supply.

Vegetable oil has the potential to replace petroleum-based lubricants given the issues with mineral oils. Because they are non-toxic, renewable, biodegradable, environmentally benign, and widely accessible, vegetable oils satisfy the requirements of lubricant standards [1,2]. Vegetable oil, on the other hand, has some drawbacks, including poor thermo-oxidative stability and a lower pour point [3]. Vegetable oil qualities are significantly influenced by the fatty acid makeup, including the proportion of saturated and unsaturated fatty acids. Vegetable oil's ability to oxidise more quickly is made possible by the presence of unsaturated fatty acids in it. However, by chemically forming these qualities by epoxidation, transesterification, etc., the researchers have improved them [4]. They demonstrated that modified vegetable oils are a suitable replacement for conventional lubricants. These modified vegetable oils are environmentally friendly and alleviate the difficulties associated with non-biodegradability [5]. In this regard, polyol esters (i.e., bio-based lubricants) such neopentyl glycol [6], trimethylolpropane [7], and pentaerythritol esters (PE), which were created via transesterification process from various vegetable oils [8], are found to have higher thermo-oxidative stabilities. The next step in this project is to create the pentaerythritol ester, which will be used as a biolubricant in air compressor applications. Chemical modification using epoxidation, followed by hydrolysis and esterification, created saturated polyol ester [9]. Continued research by Hashem et al. [10] resulted in the development of pentaerythritol ester from three different vegetable oils and demonstrated good thermal and oxidative stability. Based on the results of this, it was determined that it would take 5 to 9 hours to complete the entire chemical reaction necessary to produce pentaerythritol ester. As a result, there is a potential that more alcohol and power will be consumed, increasing the cost of manufacturing. In response to this worry, pentaerythritol ester was produced from vegetable oil using an ultrasonicator over the course of a 1-hour reaction time, yielding a high percentage with enhanced fluid flow characteristics and higher thermo-oxidative stabilities [11].

Additionally, in order to protect the contact surfaces from friction, wear, corrosion, and heat amputation, researchers have been devoted to testing the tribological characteristics of the material under biolubricant [12]. It is crucial to assess the tribological characteristics under biolubricant in order to broaden the industrial application conditions. The cylinder liner and piston ring components are the main moving parts that are impacted by the contacting surfaces in engines [13]. The identical liner-ring tribo pair material was used for the experimental test in this investigation since reciprocating air compressors have similar configurations. The biolubricant and its effects on the wear and friction of liner-ring tribo pair materials have been the subject of numerous studies using various tribological test methods, including the four-ball tribometer [14], pin-on-disk [15], ball-on-flat [16], and high-frequency reciprocating rig (HFRR) tribometer. According to the findings, vegetable-based lubricants exhibit superior lubricity than mineral-based lubricants because they include unsaturated and polar ester groups, which shield the contacting surfaces of the components from wear and friction while they are in motion [17]. Researchers use several design methodologies, such as response surface methodology (RSM) [18], Taguchi, D-optimal [19], etc., to select various process parameters to determine the tribological qualities. The process parameters that were chosen include things like sliding distance, load, biolubricant, materials, and sliding speed. In order to examine the tribological features of surfaces using different tribometers, all these process parameters are crucial [20,21]. Using a four-ball and high-frequency reciprocating test rig (HFRR) test rig, we recently investigated and reported the impact of the ultrasonicated transesterification process on yield % and its tribological properties. The outcomes showed that PE and its blends performed better in terms of low wear and friction. The blend PE75 exhibits a greater impact on tribological behavior than base oil and other lubricants based on PE among all lubricants [11,22].

Many industries, including the automotive industry, rely heavily on-air compressors. When there is no friction, which is only possible with proper lubrication, a healthy air compressor performs more efficiently. The available mineral-based lubricants are insufficient to solve the environmental issue and achieve cost savings. In light of this, it is crucial to research the lubricant's tribological characteristics and state over the course of around an hour before using it in air compressors right away. Therefore, the goal of this study is to determine how pentaerythritol ester (PE) and its mixture perform in terms of tribological qualities. With a pin-on-disc tribometer under wet conditions (PE, PE75, and SAE30 air compressor oils), the coefficient of friction and specific wear rate are evaluated over the course of an hour at five different sliding speeds (1, 2, 3, 4, and 5 ms^{-1}) and two different loads (50N and 100N).

2. EXPERIMENTAL PROCEDURE

2.1 Preparation of pentaerythritol ester-based compressor oil

Two sequential transesterification procedures are employed to transform the vegetable oil into a polyolester-based pentaerythritol ester using an ultrasonic irradiation approach. In order to create pentaerythritol ester using ultrasound and N_2 atmosphere, vegetable oil was first converted into methyl ester in a four-necked round-bottomed flask (the center neck was used to insert the ultrasonic probe, one neck to supply N_2 gas, another neck to insert a thermometer to measure the temperature, and the last neck to supply chemicals into the flask). In addition, the blended PE 75 air compressor oil, which was chosen from our earlier work based on the tribological performance of various lubricants using HFRR and a four-ball tribometer [11], was prepared on a volume basis. It contains 75 vol.% of PE and 25 vol.% of SAE30 synthetic air compressor oil. Fig. 1 depicts the synthesis and its process. PE (100% PE) and PE75 (75% PE and 25% base oil by volume) are the prepared oil samples. The physical-chemical, thermal, and tribological characteristics of the oil samples were assessed in accordance with American Society for Testing and Materials (ASTM) standards, and the results are shown in Table 1. These characteristics include wear scar diameter and COF, as well as viscosity, viscosity index, flash point, pour point, and total acid number.

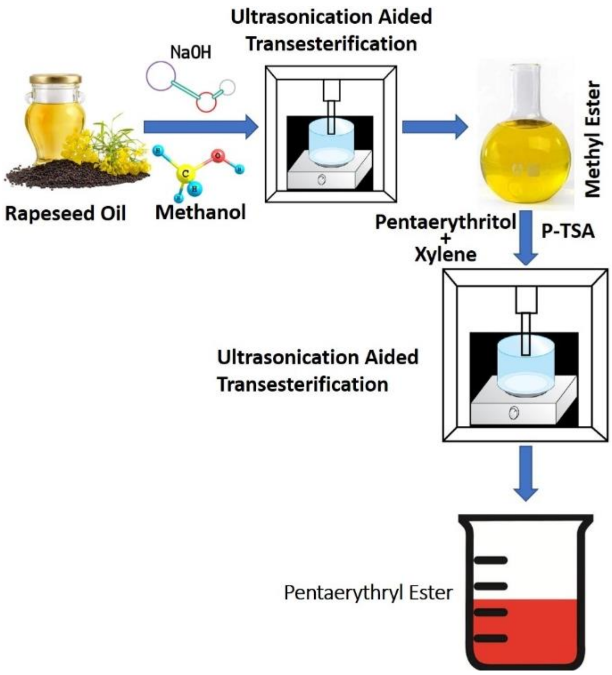

Fig. 1. Ultrasonication aided the transesterification process.

Table 1. Properties of compressor oil samples.

Properties	Standard	Compressor Oil		
		SAE30	PE	PE75
Kinematic viscosity @100˚C, cSt	ASTM D445	9.19	9.09	8.76
Viscosity Index	ASTM D2270	98	128	107
Flash Point, ˚C	ASTM D92	218	210	242
Pour point, ˚C	ASTM D97	<-10	<-10	<-10
Total Acid Number (TAN)	ASTM D664	0.95	1.77	1.09
4-Ball Wear [11] Characteristics	ASTM 4172			
i) Wear Scar Diameter		0.9663	0.428	0.451
ii) COF		0.1009	0.0813	0.0538
Oxidation Stability [11]	ASTM E2009			
i) T_{onset} (˚C)		240	263	-
ii) T_{endset} (˚C)		236	253	-

2.2 Tribological tests

According to ASTM G99 standards, the tribological properties of the bio-based lubricant tests were carried out using a pin-on-disc tribometer (as shown in Fig. 2. a & b) under atmospheric circumstances for one hour and a sliding distance of 1000m. The TR-20LE, pin-on-disc tribometer from M/s DUCOM Instruments Pvt. Ltd. in Bangalore. The test pins, which have ϕ8 x 30 mm, were made of ENJL 1020 grey cast iron, a hardness of 58 HRC, and a disc, which has dimensions of 165 x ϕ8 mm and a hardness of 65 HRC, was made of EN31 steel. Each time an experiment is done, the sump's oil pump constantly pumps test compressor oils between the pin and disc. Figure 1 depicts the pin-on-disc tribometer's schematic and photographic view (a & b). The expression shown below was used to determine the specific wear rate during the testing as the load cell continuously records the frictional force.

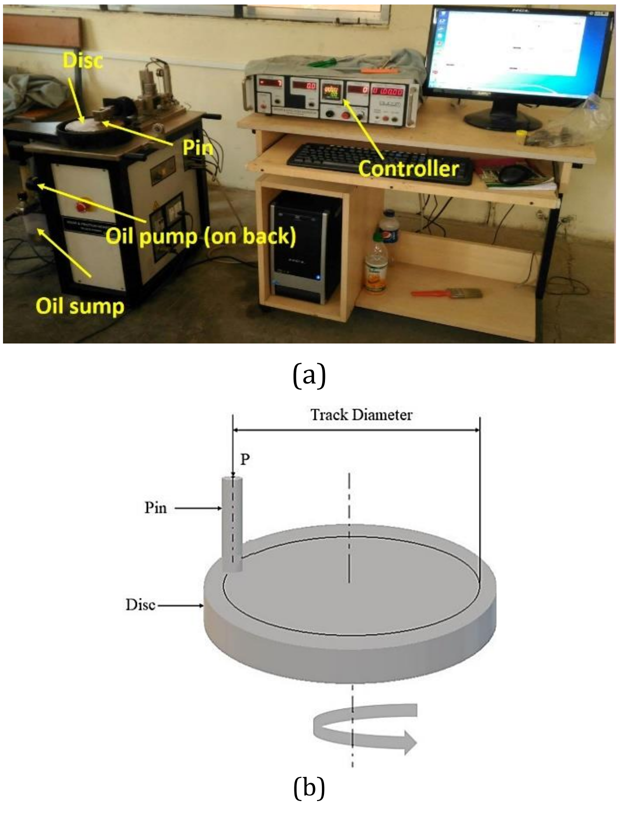

Fig. 2. Pin-on-disc tribometer (a) Photographic view (b) Schematic view of pin-on-disc tribo pair.

$$SWR = \frac{V}{W \times D} \frac{mm^3}{N-m} \quad (1)$$

Where V is the volumetric weight loss in mm³, W is the applied load in N and D is the sliding distance in m.

$$V = \frac{\text{weight of the pin before the test} - \text{weight of the pin after the test}}{\text{Density of the pin material}} \times 1000 \quad (2)$$

Before and after each experimental test, the pin weight was measured using an electronic weighing device. Table 2 displays the pin-on-disc tribometer test conditions.

Table 2. Test conditions.

Parameters	Values
Sliding Speed, m/s	1, 2, 3, 4 & 5
Sliding Distance, m	1000
Track Diameter, mm	50
Load, N	50, 100
Temperature °C	Ambient Temperature
Time in sec	3600
Lubricants	SAE30, PE & PE75

3. RESULTS AND DISCUSSIONS

3.1. TGA/DTG Analysis

Figure 3 compares the TGA and Derivative Thermogravimetry (DTG) curves of samples of blended compressor oil, such as PE/PE75, and synthetic grade/biodegradable compressor oil. The decomposition mechanisms are described using the TGA curve, which shows the percentage weight loss of the compressor oil sample as a function of temperature, and the DTG curve, which shows the rate of change of weight loss of the compressor oil as a function of temperature. From Fig. 3, it can be shown that synthetic compressor oil and biodegradable compressor oil underwent single-stage decomposition and two-stage decomposition, respectively. For synthetic compressor oil and biodegradable compressor oil, respectively, no major breakdown occurred up to 300 °C and 386 °C. The oxidation of saturated fatty acids in the PE ester caused the first transition to be noticed at 340 °C, and the oxidation of unsaturated fatty acids in the PE ester caused the second transition to be noticed at 414 °C. However, with synthetic compressor oil, a single breakdown peak was seen at 386 °C. In contrast to SAE30, Fig. 3 demonstrated that biodegradable compressor oil had better heat stability. As can be observed from Fig. 3, there were multiple stages of disintegration in each of the two compressor oil samples, PE/PE75. For PE and PE75 type mixed compressor oils, the beginning breakdown was measured at 340 °C and 304 °C, respectively. Even yet, for PE and PE75, the final disintegration was measured at 414 °C and 400 °C, respectively. When PE75 was compared to SAE30 and other blended compressor oil samples, it was discovered that PE75 had significantly improved thermal stability.

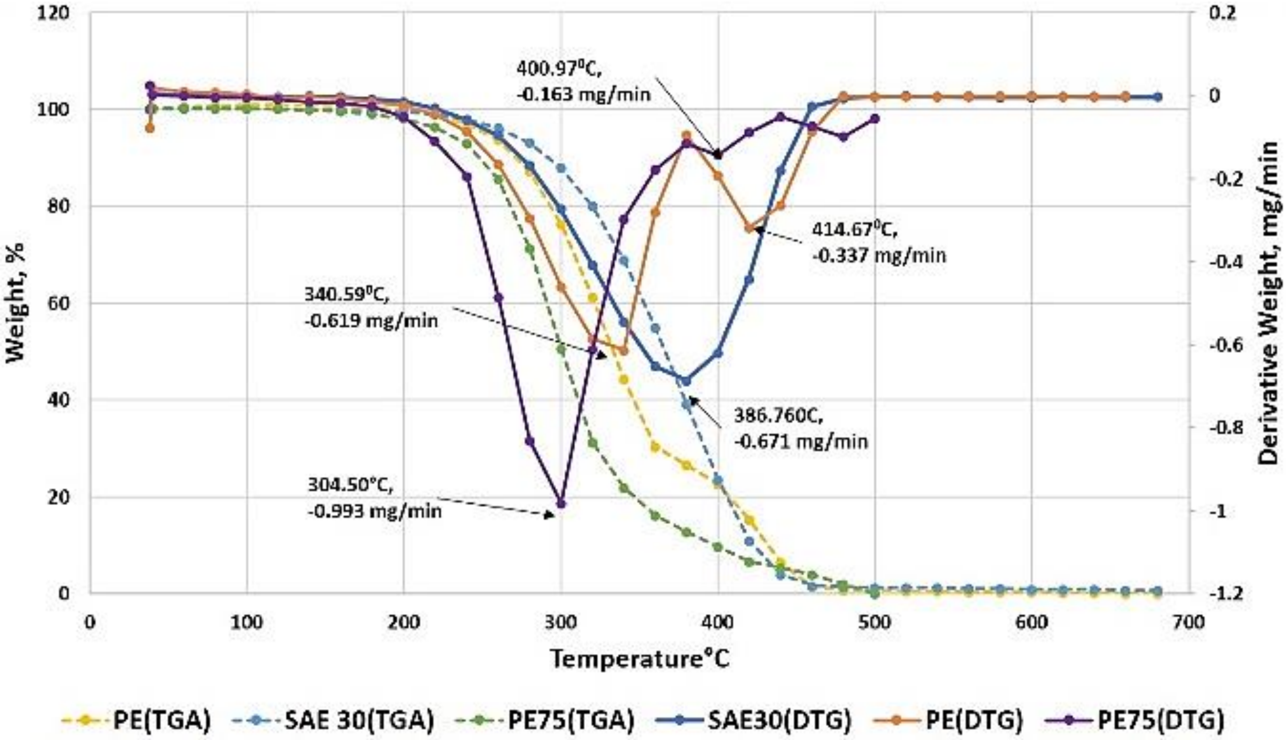

Fig.3. TGA/DTG Curve of Pentaerythritol ester and SAE30 compressor oil

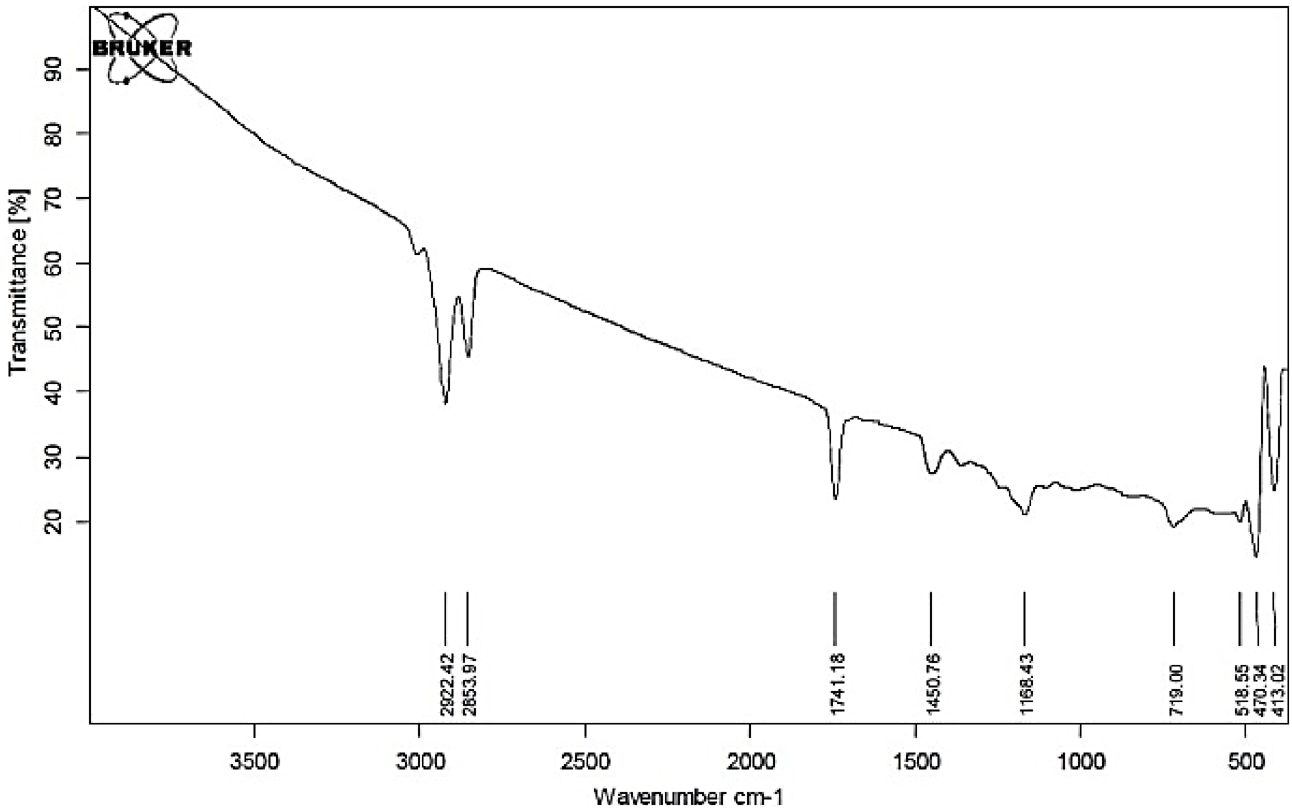

Fig. 4. FTIR spectrum of pentaerythritol ester.

Table 3. Pin-on-disc tribometer experimental results.

S. No.	Sliding Speed, m/s	Speed, rpm	Oil	COF		SWR, X 10^{-3} mm^3/Nm	
				Load, N		Load, N	
				50	100	50	100
1	1	381	SAE30	0.085	0.091	1.5641	1.8211
2	2	636	SAE30	0.081	0.086	0.7971	1.3315
3	3	818	SAE30	0.078	0.088	0.7064	0.9524
4	4	954	SAE30	0.084	0.093	0.5927	0.8045
5	5	1061	SAE30	0.087	0.096	0.5787	0.7324
6	1	381	PE	0.081	0.085	1.4903	1.5211
7	2	636	PE	0.075	0.079	0.8845	1.1015
8	3	818	PE	0.072	0.076	0.6076	0.8824
9	4	954	PE	0.075	0.081	0.4706	0.7145
10	5	1061	PE	0.077	0.092	0.4194	0.6324
11	1	381	PE75	0.075	0.079	1.3007	1.2891
12	2	636	PE75	0.067	0.071	0.5534	0.7124
13	3	818	PE75	0.061	0.066	0.4381	0.6104
14	4	954	PE75	0.057	0.059	0.2883	0.5214
15	5	1061	PE75	0.059	0.065	0.2231	0.3382

3.2 FTIR analysis

The FTIR spectrum of synthesised pentaerythritol ester is shown in Figure 4. The prominent peaks in the pentaerythritol ester's FTIR spectrum can be seen at 1785 cm^{-1} (the ester carbonyl group, or C=O), 1213 cm^{-1}, and 1126 cm^{-1} (the ester C-O), which are slightly offset from their corresponding frequencies in the precursor methyl oleate, where the corresponding peaks can be seen at 1748 cm^{-1} and 1124 cm^{-1}, respectively. The presence of the pentaerythrityl group is indicated by the extra PE ester peaks at 1005 cm^{-1} and 649 cm^{-1}. The production of a pentaerythritol ester of rapeseed oil is aided by these frequency shifts and extra peaks.

3.3 Tribological analysis

The tribological behaviour of the material is examined in the current work using a pin-on-disc tribometer under varied lubrication and load circumstances. On a pin-on-disc tribometer, triplicate experimental run were carried out using different loads, sliding velocities, speeds, and compressor oils under the conditions listed in Table 3. The findings of the SWR and COF are displayed in Table 3. In comparison to SAE 30 synthetic grade compressor oil and pure pentaerythritol ester, PE 75 compressor oil plays a significant role among all lubricants in terms of lowering the coefficient of friction and specific wear rate at high loads and high speeds (PE).

3.4 Influence of compressor oil on coefficient of friction

Various compressor oils (SAE 30, PE, and PE 75) and loads are depicted on a graph between the coefficient of friction and sliding velocity in Figure 5 (a&b) (50 and 100N). In contrast to other lubricants, PE 75 lubricant at 50N was found to produce the pin's low coefficient of friction. Even with a high load and high sliding velocity, such as 100 N and 5 m/s, a pin lubricated with PE 75 results in a reduced coefficient of friction. When subjected to loads of 50 N and 100 N, a PE-lubricated pin exhibits a low coefficient of friction with a low sliding velocity i.e., 1 m/s, but as the sliding velocity is increased to 5 m/s, the coefficient of friction likewise rises the PE-lubricated pin. Even at a high sliding velocity, PE75 exhibits a lower coefficient of friction than other lubricants with varying loads, whereas other lubricants exhibit a higher coefficient of friction at the beginning of the test.

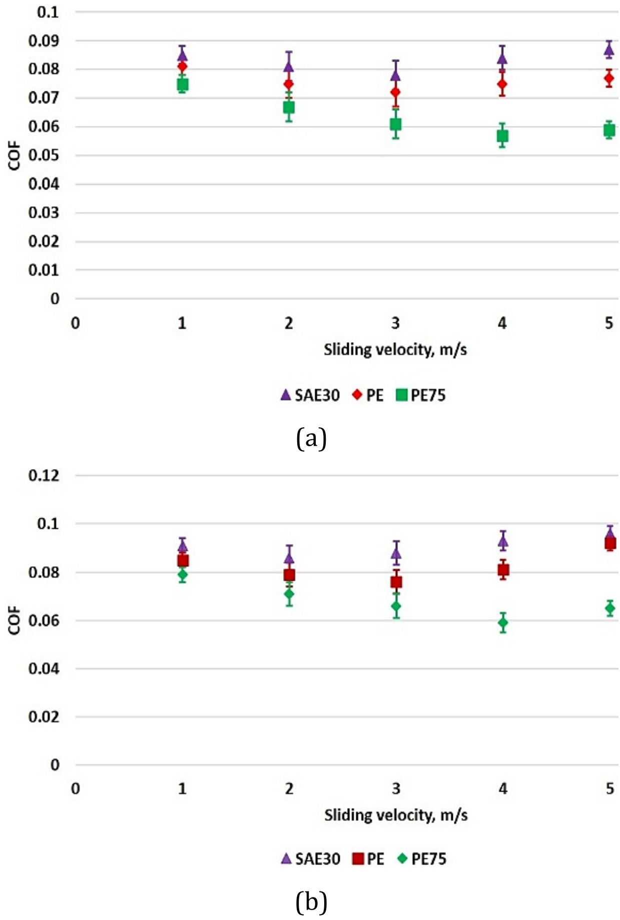

Fig. 5. Coefficient of friction for various compressor oils (a) 50 N and (b) 100 N.

The experimental graph showing successful outcomes with a pin greased with PE75 was impressive. According to the findings, PE75 has a lower coefficient of friction than those other lubricants. This is because between the moving pieces, such as the pin and disc, which have differing loads and sliding velocities, tribo-film forms [23]. The ester groups found in pentaerythritol ester and the additives in synthetic compressor oil cause stable film layers to form between the pin and disc. The lowering of the friction coefficient is significantly impacted by these film layers [24,25].

3.5 Influence of compressor oil on specific wear rate

Figures 6 (a&b) depict the variance in the tested pin's particular wear rate under various testing circumstances (lubricants, load, and sliding velocity). According to Fig. 6 a, all of the tested pins' specific wear rates are similar at 50 N of load. However, there is a slight difference between SAE 30 lubricated pins and PE and PE75 lubricated pins. The PE75 lubricated tested pins have a lower specific wear rate than the other lubricated pins out of all the lubricated tested pins. As demonstrated in Fig. 6 b, the pins lubricated with PE and PE75 exhibit the least amount of SWR under high load, or 100N, as compared to SAE30 grade compressor oil. The fluid layer that exists between the pin and the rotating disc is to blame for this. A robust film with a high viscosity is formed in part by the free fatty acids (from the vegetable oils) [26]. Even at high loads and high sliding velocity, this film separates and avoids the metal-to-metal contacting surfaces between the pin and disc [27,28].

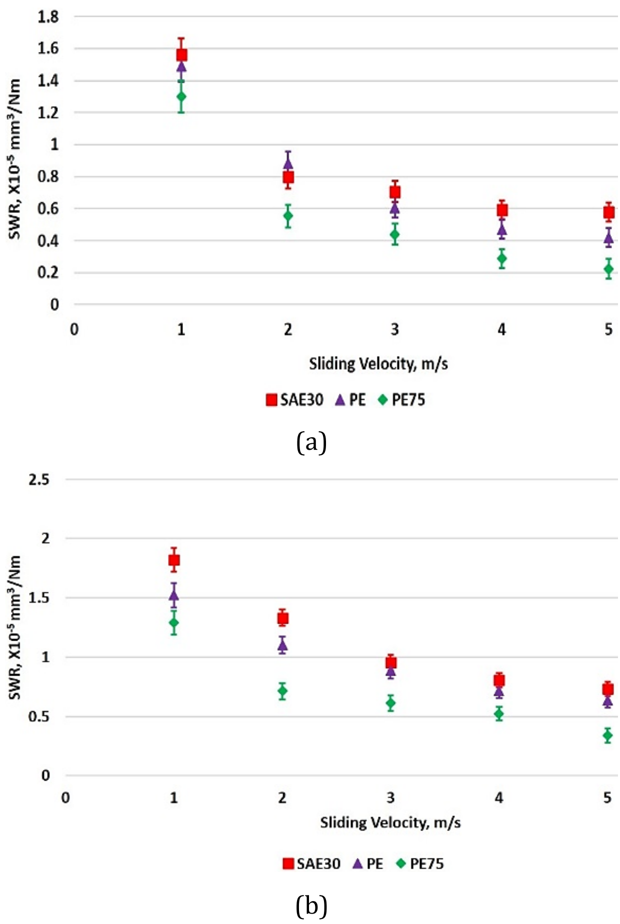

Fig. 6. Specific wear rate for various compressor oils (a) 50 N and (b) 100 N.

3.6 Wear morphology analysis

Fig. 7 displays the morphological images of the worn surfaces of the pin tested under 50N load. Images of SAE 30 lubricated testing pins with grooves and pore-filled surfaces can be seen; this is a result of metal-to-metal contact caused by the absence of a lubrication film between the surfaces.

While the vegetable oil-based biolubricant, i.e., PE and PE 75 lubricated tested pin, had no such type of grooves and pores appeared on the surfaces, the base oil SAE30 is not managed to develop a sufficient oil film at the juncture of the pin, and disc tribo-pair causing the material loss of the specimen. This is primarily because there was sufficient tribo film between the contact areas, which separates and provides smooth rotational movement between the pin and disc surface. After passing tribological tests at 100 N load with various lubricants, the worn surfaces of the pin are depicted in Fig. 7(b, d, & f) in terms of their shape. According to Figure 7(f), the pin lubricated with PE 75 outperformed the others in terms of surface smoothness. This may be due to the creation of a robust tribo layer between the pin and disc that shields the surface even at high sliding speeds. The pin lubricated with PE at 100 N load displays more wear scars, specifically grooves. This is because the lubricant film between the pin and disc has completely broken, indicating that PE was unable to sustain the continuous formation of film between the surface at high loads and during operation [29,30].

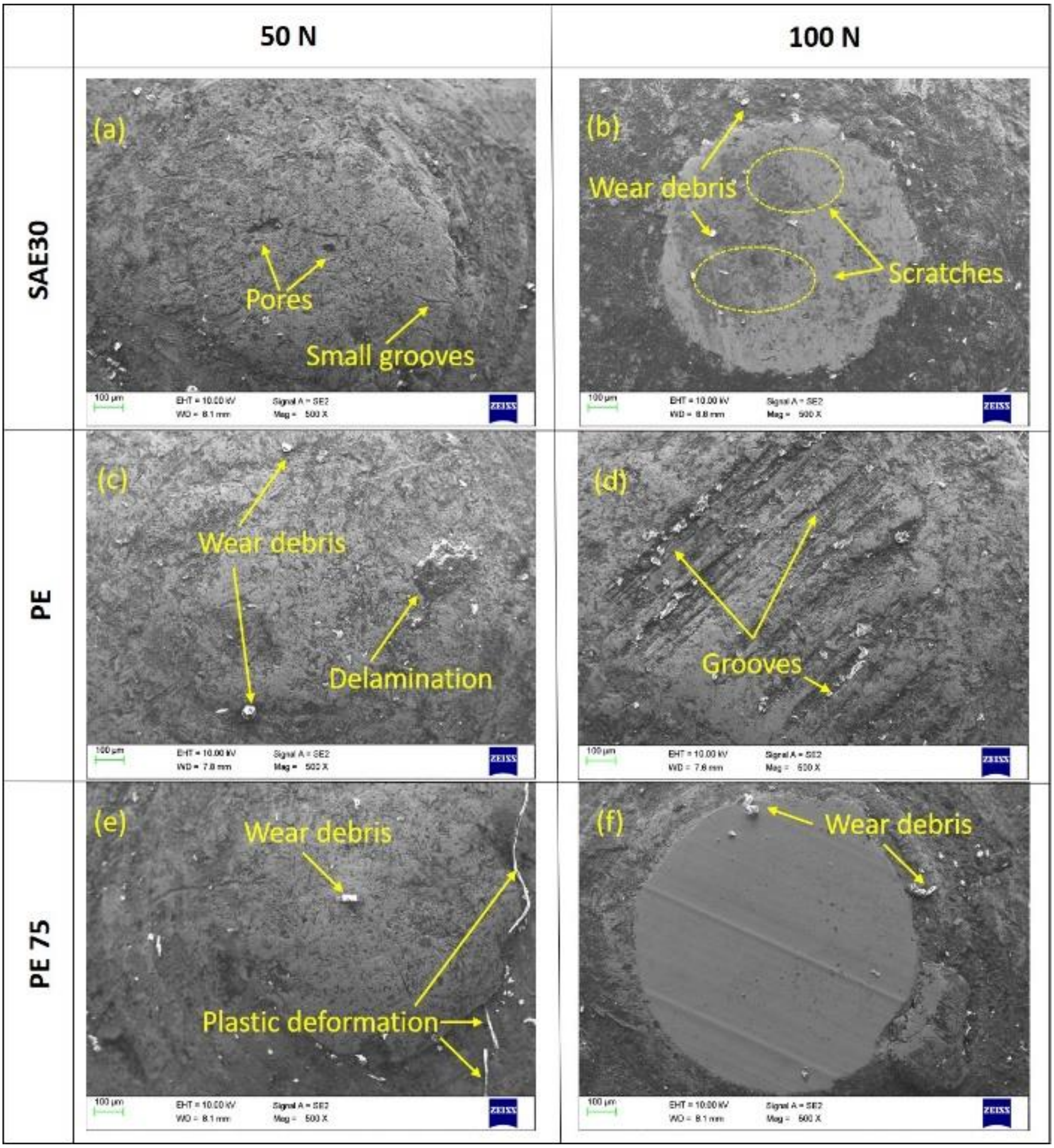

Fig 7. Morphology images of lubricated pins under 50 N and 100 N load for the sliding velocity of 5 m/s.

3.7 Energy dispersive X-ray analysis of pins

The energy-dispersive spectra of the worn surfaces (pins) lubricated with SAE 30, PE, and PE 75 are shown in Fig. 8. Carbon (C), oxygen (O_2), potassium (Na), magnesium (Mg), aluminum (Al), silicon (Si), calcium (Ca), and iron (Fe) may all be seen on the worn surfaces of the examined material in the EDS spectra, as shown in Fig. 8. From all EDS spectra, the presence of iron (Fe) on the surface reveals that the alloying of liner surfaces represents the base metal substance and other existing elements. A higher amount of carbon (C) content on the surface, which is observed with PE 75 lubricated test specimen for both 50 N and 100 N load conditions as compared to other lubricated test specimens, namely SAE 30 and PE, plays a significant role among all the factors, as shown in Fig. 8. Furthermore, due to vegetable oil's enhanced polarity, which aids in the surface bonding of tetra carboxylate ester molecules, carbon is probably derived from the structure of vegetable oil [31,32].

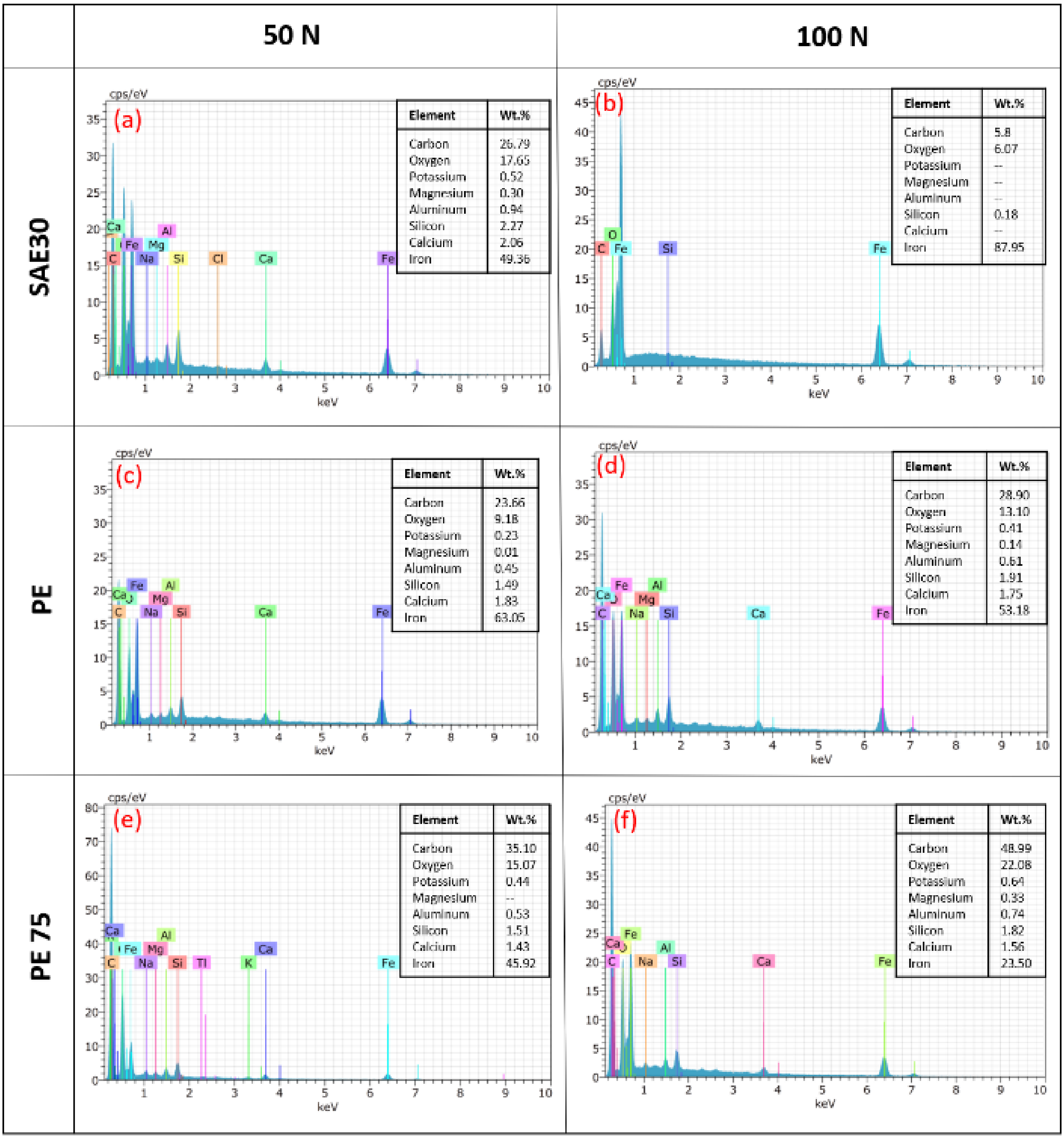

Fig. 8. EDS Spectra of worn pin specimens.

4. CONCLUSION

- PE based polyol ester met the requirements for SAE grade compressor oil in terms of viscosity, viscosity index, and flash point.
- The higher thermal and oxidative stability of blended compressor oil samples was identified by thermo-gravimetric analysis.
- The results of a pin-on-disc test revealed that biodegradable pentaerythryl compressor oil had significantly improved tribological characteristics; in particular, PE75 had a significant improvement in its ability to reduce friction and prevent wear.
- A SEM micrograph of the tested cylinder liner surfaces further demonstrated PE75's superior wear reduction ability by revealing much smoother, thinner scars and narrow grooves.
- Of all the lubricants, PE 75 (75% pentaerythritol ester and 25% SAE30) showed better tribological properties in terms of reduction in specific wear rate.
- It can be inferred from the tribological research that adding pentaerythrityl ester of rapeseed oil to synthetic grade compressor oil has significant potential as a renewable lubricant for reciprocating air compressor lubrication use in the future.

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