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Characterization Degradation of Some Commonly Used Lubricants in Machine Tools Applications

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Abstract: Machine tools play very significant roles in many industries, workshops and factories. Their proper functionality and durability depend so much on lubricants. Four samples each of fresh and used mineral-based oil were selected, and 12 parametric analyses were conducted. The fresh oil analysis provided initial baseline physicochemical conditions of the samples. The used oils were obtained from centre lathe after every 250 hours for a total of 4000 hours operating time. Sampling was carried out immediately after machine shutdown then, stored in clean and airtight containers. Physical inspections were equally employed, and laboratory analysis done following standard procedures. Comparative analysis was carried out and graphs plotted to establish degradation trends. Additionally, statistical analysis and weighting techniques were used. The results recorded deviations in parametric characterization; for ISO VG 10, kinetic viscosity: 2.0cSt., TAN: 0.52mg KOH/g, oxidation: 0.29A/cm, water: 260ppm, particle content: 860 particle/mL, flash point: 15℃, friction coefficient: 0.019, density: 16kg/m^3, and colour change to black/dark opaque brown. For ISO VG 32; kinetic viscosity: 5.0cSt., TAN: 0.97mg KOH/g, oxidation: 0.40A/cm, water: 410ppm, particle content: 1700 particle/mL, flash point: 16℃, friction coefficient: 0.031, density: 28kg/m^3, and colour change to dark, degraded/sludge tendency status. For ISO VG 46; kinetic viscosity: 8.8cSt., TAN: 1.22mg KOH/g, oxidation: 0.67A/cm, water: 3700ppm, particle content: 2060 particle/mL, flash point: 19℃, friction coefficient: 0.020, density: 16kg/m^3, and new appearance of black/dark opaque brown. For ISO VG 68; kinetic viscosity: 7.1cSt., TAN: 1.97mg KOH/g, oxidation: 0.44A/cm, water: 420ppm, particle content: 1500 particle/mL, flash point: 17℃, friction coefficient: 0.019, density: 16kg/m^3, and current status of black/dark opaque brown. ISO VG 46 recorded 24 weighting points, ISO VG 32 and ISO VG 68 had 20 each, and ISO VG 10 had 10 points. Therefore, ISO VG 10 is recommended particularly when prolonged usage is paramount.

Keywords: *Machine Tools, Functionality, Lubricants, Baseline Conditions, Prolonged Usage.*

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I. INTRODUCTION

Lubricants in machine tool applications, such as cutting fluids, gear oils, hydraulic oils, and greases, are critical for reducing friction, dissipating heat, preventing wear, and ensuring reliable operations of machinery [1],[2]. During service, however, lubricants undergo degradation due to mechanical, thermal and chemical stresses, which leads to loss of performance and possible equipment failure if not properly monitored and managed [1],[3],[4].

Tribological contacts are very crucial in machine tools especially in gear transmission system, where these contacts are usually subjected to energy losses due to friction, which impact significantly on the overall energy efficiency of mechanical systems [5],[6]. Because lubricants play an important role in machine tools, their selection requires a thorough design technique to ensure optimal outputs [7]. However, exposure of the lubricating oils to high temperature and solar radiation can prompt oxidative degradation of the lubricants, possibly causing the mechanical systems more harm than good [8],[9].[10],[11].

Following the crucialness of lubricants in machine tools applications especially in terms of enhanced functionality, reliability, dimensional accuracy, surface finish quality, devastating effects of high frictional and tool wear rates, unplanned downtime, and reduced machine efficiency [7],[12],[13],[14],[15], as well as accumulated economic wastes on bearing failures, spindle damages, and premature

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components replacement [16],[17],[18], it is therefore necessary to expand research frontiers to tackle the standardization and real-time in situ monitoring technologies of lubricant characterization degradation. Additionally, there is a need to examine the setbacks of time-based lubricant replacement, and then propose a condition-based monitoring system for an optimised machine tool performance, machining efficiency and reduced maintenance costs [19],[20],[21],[22].

Identifying factors promoting the propagation of characterization degradation of lubricants and their measure effects on machine tools efficiency, as well as standardizing the models for predicting of the remaining useful life (RUL) of used lubricant oils also form part of the concern of this study.

There are three (3) basic types of lubricant degradation namely; chemical degradation, mechanical and shear degradation, and contamination and wear particle interaction degradation, with each having its subdivisions [2],[3][11]. Chemical degradation primarily involves oxidation, additive depletion, and formation of acidic and polymeric product in the lubricants [15],[23]. Oxidation and thermo-oxidation, subdivisions of chemical degradation are caused by exposure to oxygen and elevated temperatures promoting the oxidation of hydrocarbon chains and additive breakdown [23],[24],[25]. Oxidation products such as carboxylic acids, ketones, and oligomers are formed, leading to changes in viscosity and the formation of sludge and varnish deposits [26]. These high molecular weight oxidation products often increase viscosity before eventual breakdown reduces film-forming capability [8],[9]. Additive depletion is also another type of chemical degradation, a condition where anti-wear and antioxidant additive such as zinc dialkyldithiophosphate (ZDDP) are consumed during operation, diminishing protective film formation and increasing wear [27].

Mechanical and shear degradation constitutes the second category of lubricant degradation. In machine tool environments, sliding contacts and high loads cause mechanical shearing of the lubricant film, which breaks down long molecular chains and alters the rheological properties. Greases experience thickener breakdown and loss of consistency under repeated shear [10],[28]. The next classification of lubricant degradation is contamination and wear particle interaction. Here contaminants such as metal wear debris, dust, water, and coolant residues accelerate lubricants degradation by catalytic oxidation and abrasive interactions. The presence of wear particles increases mechanical degradation and contributes to tribofilm breakdown. Wear debris concentration itself is often used as a degradation indicator [20],[29],[30].

There are unique indicators and consequences of lubricant degradation comprising physical property changes and measurement, tribological performance metrics, characteristic techniques, and tribological testing [1],[4],[11]. Physical property changes include colour, presence of debris, and viscosity, being one of the primary indicators of lubricant health. Oxidation and additive depletion often first lead to increased viscosity due to polymer formation, followed by viscosity loss due to molecules fracture. Acidity/total acid number (TAN) increases with oxidation and contaminant entry, reflecting the formation of acidic degradation products. Having declining pH shifts indicates increasing acidic degradation products, another main indicator of degradation [31].

For tribological performance metrics, wear scar diameter is very useful particularly in lubricant performance tests, for example in four-ball wear tests, where degraded lubricants typically show larger wear scars and reduced load-carrying capacity. Friction coefficient variations equally serve as a sensitive indication. Altered lubricant chemistry and shear degradation usually change friction behaviour at interfaces, thereby increasing wear under boundary lubrication conditions [32]. Considering characterization techniques, various analytical methods have been employed to characterize lubricant degradation quantitatively and qualitatively [5],[6],[33]. These procedures include spectroscopic and chemical analyses using Fourier Transform Infrared Spectroscopy (FTIR) to identify functional groups formed during oxidation and additive breakdown, for example, peaks at 1720 cm^{-1} indicating carboxylic acids, together with pH and TAN measurements for simple chemical indicators of acidic degradation [34].

Furthermore, physical property measurement uses viscosity tests linking kinematic and dynamic viscosity measurements to track changes in base oil molecular integrity. Wear debris analysis handles online and offline particle counting and sizing widely via centrifugation and Scanning Electron Microscopy (SEM) to identify contamination and correlate with wear progression. Permittivity and dielectric tests are also employed in online monitoring to infer oxidation levels [35],[36]. Additionally, tribological testing also evaluates load-carrying and anti-wear performance. Comparing fresh versus used lubricants, mini traction machine and high-frequency reciprocating rig tests assess friction and wear under controlled contact conditions [37].

Typically, monitoring of lubricant degradation in machine tool shops is done via two (2) techniques [17], that is; online monitoring approaches for real-time inspections using sensors for viscosity, permittivity, and wear particles which provides dynamic insights into lubricants health, enabling predictive maintenance before catastrophic failure. Secondly, lifecycle and performance trends presenting that lubricants degrade rapidly during initial use and may reach a quasi-steady state after prolonged operation; signifying the importance of condition-based testing rather than relying solely on fresh lubricant benchmarks [38]. Lubricant degradation directly affects tool life, component wear, surface finish, and overall operational efficiency [2],[10],[11]. As lubrication quality declines, friction increases, wear accelerates, and maintenance costs rise. Thus, accurate characterization and monitoring are essential to ensure reliability and optimized maintenance scheduling [18],[20],[30],[39],[40].

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II. MATERIALS AND METHODS

The materials used in this research were centre lathe, test samples (fresh and used lubricants), viscometer (Redwood), flash and fire point apparatus (Cleveland open cup), pH meter and TAN (total acid number) test kit for comparison, density bottle, hydrometer, thermometer, magnetic particle separator, filter paper, glass beaker, test tubes, sampling bottles, weighing balance and oven. Other materials were reagents and chemicals, basically solvents (kerosene and hexane) for cleaning, distilled water and standard reagents for TAN test.

The methods adopted in the study followed established standard procedures, and are categorized as presented [1],[2],[3],[9],[27],[41];

- *Machinery Selection*

The study was carried out on centre lathe, one of the frequently used machine tools in production factories and mechanical engineering workshop. This selection was due to its continuous usage and its high dependence on lubricants for smooth operations, good surface finish and wear reduction. Other close substitute could be milling, drilling, shaping, and surface/angle grinding machines.

- *Lubricant Selection*

The following mineral-based lubricating oils; ISO VG 10, ISO VG 32, ISO VG 46 and ISO VG 68 were selected as per machine specification for the analysis. For each lubricant, fresh (unused) and degraded (used) oil were employed, with the unused being reference sample as control experiments.

- *Lubricant Sampling Procedures*

Lubricants samples were collected separately from the test machine tool at different operating time intervals: after 0, 250, 500, 750, 1000, 1500, 1750, 2000, 2500, 3000, 3500, and 4000 hours of operation. Sampling was carried out after machine shutdown while the oil was still warm to ensure uniformity, then the samples were stored in clean, labelled, and airtight containers to avoid additional contamination.

- *Visual Inspection*

Each lubricant sample was visually inspected for the following; colour change, presence of suspended particles and cloudiness or sludge formation. Colour darkening and sediment formation were considered as preliminary indicators of lubricant degradation.

- *Kinematic Viscosity Test*

Kinematic viscosity was measured at a standard temperature of 40℃ using viscometer. Oil samples were heated to test temperature and the flow time recorded. Then viscosity was calculated using viscometer constant. A decrease or excessive increase in viscosity indicated breakdown or contamination of the lubricants.

- *Flash and Fire Point Test*

Flash and fire points were determined to assess volatility and safety degradation. Test samples were heated gradually, during which flash points were noted when ignition occurred momentarily. The fire points were also recorded when sustained combustion occurred. Reduction in flash and fire points are indications of contamination or oxidation.

- *Density Measurement*

Density was measured using hydrometer and density bottle separately at room temperature to make provision for dataset comparison. Changes in density are usually associated with oxidation, contamination, and/or metal particle presence.

- *Acidity (TAN/pH) Test*

Total acid number (TAN) or pH was determined to evaluate oxidation and acid formation. Oil samples were tested using pH meter and TAN kit. Increase in acidity indicates lubricant oxidation and degradation.

- *Wear Particle Analysis (Qualitative)*

Lubricant samples were passed through filter paper, and magnetic particles separated using a magnet. The presence of metallic debris normally confirms the existence of machine wear and lubricant degradation.

- *Contamination Test (Crackle Test)*

A small drop of oil was placed on a hot plate at approximately 120℃ for crackle test. Crackling sound indicates water ingress or contamination.

- *Degradation Data Analysis*

The results were compared with the properties of fresh oil. Degradation trends were plotted against operating hours and acceptable limits compared with manufacturer standards. Lubricants replacement intervals were recommended based on results. The general assessment of lubricant degradation was fashioned using standard procedures [28],[34],[35],[36],[40], and was based on the following; percentage change in viscosity, reduction in flash and fire points, increase in acidity, presence of wear particles, increase in density, decline in friction coefficient and visual contamination indicators.

III. RESULTS AND DISCUSSIONS

Table 1 illustrates the characterization of four (4) different fresh (unused) mineral oil lubricants commonly applicable in machine tools as shown;

Table 1 Characterization of Selected Fresh (Unused) Mineral Oil Lubricants at 40℃

Parameters	**ISO VG 10**	**ISO VG 32**	**ISO VG 46**	**ISO VG 68**
Viscosity (cSt)	10.01	31.99	46.18	68.47
TAN (kg KOH/g)	0.22	0.32	0.35	0.37

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TBN (kg KOH/g)	0.89	0.99	0.97	0.93
Water (ppm)	80	99	118	149
Density (kg/m^3)	840	841	849	874
Particle count	117	149	179	188
Oxidation - FTIR (A/cm)	0.009	0.018	0.019	0.017
Flash point	179	215	227	239
Fe (ppm)	0.90	1.46	1.98	2.47
Cu (ppm)	0.28	0.38	0.49	0.68
Pb (ppm)	0.98	0.95	0.99	0.97
Al (ppm)	0.19	0.20	0.29	0.40
Si (ppm)	2.0	2.4	2.9	3.48
Na (ppm)	3.78	3.83	3.94	3.79
Appearance	Clear, very pale yellow	Clear/bright	Very clear, pale yellow	Clear/pale yellow

The characterization of the unused lubricants was necessary to establish the initial physicochemical conditions of the test samples prior to their exposure to machine tool operating conditions [25]. The unused samples comprised ISO VG 10, ISO VG 32, ISO VG 46 and ISO VG 68 lubricants. These samples served as reference materials against which changes occurring during service, including oxidation, thermal degradation, contamination and viscosity alteration, could subsequently be evaluated. Establishing the properties of the fresh lubricants was particularly important because degradation can only be reliably quantified when the initial conditions of each lubricant are known [14].

The most distinguishing characteristic among the four lubricants is their viscosity grade [10], [12],[15]. The ISO VG classification is primarily based on the nominal kinematic viscosity of an industrial lubricant at 40 °C. Consequently, ISO VG 10 represents the lowest viscosity oil investigated, whereas ISO VG 68 represents the highest viscosity oil among the selected ones. The expected increase in viscosity of each oil reflects an increasing resistance to flow, and very significant because viscosity influences the formation and maintenance of lubricating films, frictional losses, heat generation, leakages and lubricant functionality with closely fitted or high-speed components [28].

As the experimentally determined values were close to their respective ISO VG nominal ranges, it confirmed that the samples were appropriately classified and suitable for use as baseline materials having aligned with manufacturers' dataset. However, any substantial deviations could designate differences in formulation, storage, sampling or presence of contaminants [6].

The viscosity behaviour at 100°C provided additional information on temperature dependence of the lubricants. Generally, the viscosity of petroleum-based lubricants decreases as temperature increases because the increase in molecular mobility reduces resistance to flow. The extent of this reduction is usually related to the viscosity index (VI) of the lubricant. A relatively high viscosity index specifies that the lubricant undergoes a smaller change in viscosity over a given temperature range, which is advantageous for machine tool components subjected to variations in operating temperature [38].

Density is also an important reference property of the unused oils. Although density is not the primary parameter used to assign an ISO VG classification, density results should be interpreted alongside viscosity and other physicochemical properties, and any changes in density after service can potentially provide evidence of contamination, oxidation products or changes in lubricant composition. The total acid number (TAN) of the unused lubricants is normally relatively low because fresh oils have not undergone significant oxidation. TAN represents the quantity of acidic constituents present in the lubricant and is commonly used as an indicator of lubricant oxidation and degradation. The measured TAN values of the unused samples therefore constitute critical reference values for subsequent used oil analysis. An increase in TAN after operation would generally indicate the formation and accumulation of acidic oxidation products, particularly when accompanied by changes in viscosity, colour or infrared spectra [23],[31].

The FTIR spectra of the unused lubricants likewise provide an important chemical fingerprint for comparison with the corresponding used samples. Characteristic hydrocarbon-related absorption bands associated with the base oil are expected to dominate the spectra of fresh lubricants, while pronounced oxidation-related absorption, particularly in the carbonyl region, would generally be limited in properly stored unused oil. Comparison of the fresh and used-oil spectra can consequently be used to identify the development of oxidation products during machine tool operation. The baseline spectra are especially valuable because they distinguish degradation products formed during service from functional groups already present in the original lubricant formulation [12],[17],[40].

➢ *Parametric Analysis of Degraded Lubricants*

After 4000 hours of machine operating time at every 250 hours' time interval, the parametric characterization of the selected degraded lubricants was analysed and respectively presented in Table 2, Table 3, Table 4 and Table 5. Each table has the following parametric headings; OT = operating time (h), KV = kinetic viscosity (cSt), TAN = total acid number (mg KOH/g), $OX = \text{oxidation value (A/cm)}$ $H_2O = \text{water (ppm)}$, $Fe = \text{iron (ppm)}$, $Cu = \text{copper (ppm)}$, $Al = \text{aluminium (ppm)}$, $Si = \text{silicon (ppm)}$, PC = particle content (particle/mL), FP = flash point (℃), FC = friction coefficient, $\rho = \text{density}$ (kg/m^3), and appearance (colour).

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Table 2 Lubricant Degradation of ISO VG 10 Mineral Oil after 4000 Operating Hours

OT	KV	TAN	OX	H_2O	Fe	Cu	Al	Si	PC	FP	FC	ρ	Appearance
0	10.2	0.24	0.01	80	1.0	0.2	0.2	2.0	120	179	0.065	841	Clear, very pale yellow
250	10.3	0.26	0.02	88	1.4	0.3	0.2	2.1	140	178	0.066	842	Pale yellow
500	10.4	0.28	0.03	98	1.8	0.4	0.3	2.3	160	177	0.067	843	Light yellow
750	10.5	0.30	0.04	109	2.4	0.5	0.4	2.4	185	176	0.068	844	Yellow
1000	10.5	0.32	0.05	121	2.8	0.6	0.4	2.6	220	175	0.069	845	Yellow/amber
1250	10.6	0.34	0.06	134	3.3.	0.7	0.5	3.5	253	174	0.070	846	Light amber
1500	10.7	0.37	0.08	149	4.0	0.8	0.5	2.9	290	174	0.071	847	Amber
1750	10.8	0.40	0.09	164	4.7	0.9	0.6	3.0	334	173	0.072	848	Amber/brown
2000	10.9	0.43	0.11	181	5.5	1.0	0.7	3.2	380	172	0.073	849	Brownish amber
2250	11.0	0.46	0.13	198	6.4	1.1	0.8	3.4	432	171	0.074	850	Brown
2500	11.1	0.50	0.15	216	7.5	1.3	0.9	3.5	490	170	0.075	851	Dark brown
2750	11.2	0.54	0.17	233	8.7	1.5	1.0	3.6	556	169	0.076	852	Dark brown/opaque
3000	11.4	0.58	0.19	251	10.0	1.7	1.1	3.8	630	168	0.078	853	Very dark brown
3250	11.6	0.62	0.21	272	11.4	1.9	1.2	4.0	707	167	0.080	854	Dark brown/black
3500	11.7	0.67	0.24	295	13.0	2.1	1.4	4.1	790	166	0.081	855	Very dark brown
3750	11.9	0.71	0.27	317	14.5	2.3	1.6	4.2	881	165	0.082	856	Near-black brown
4000	12.2	0.76	0.30	340	16.5	2.6	1.7	4.4	980	164	0.084	857	Black/dark opaque brown

Table 3 Lubricant Degradation of ISO VG 32 Mineral Oil after 4000 Operating Hours

OT	KV	TAN	OX	H_2O	Fe	Cu	Al	Si	PC	FP	FC	ρ	Appearance
0	32.1	0.32	0.02	100	1.5	0.4	0.2	2.5	150	214	0.078	842	Clear/bright
250	32.2	0.35	0.04	115	2.3	0.6	0.3	2.7	195	213	0.079	845	Clear
500	32.4	0.38	0.06	130	3.2	0.7	0.4	2.9	230	212	0.081	846	Clear/slightly darker
750	32.6	0.42	0.08	147	4.3	1.0	0.5	3.1	286	211	0.082	847	Bright amber
1000	32.8	0.46	0.11	165	5.5	1.1	0.6	3.3	350	210	0.084	848	Clear
1250	33.0	0.50	0.13	182	6.9	1.3	0.7	3.5	420	209	0.085	849	Slight darkening
1500	33.3	0.56	0.17	205	8.5	1.6	0.9	3.7	500	208	0.087	850	Clear/slight haze
1750	33.5	0.61	0.20	225	10.3	1.8	1.0	3.9	590	207	0.089	851	Noticeable darker
2000	33.9	0.68	0.24	250	12.5	2.2	1.2	4.1	700	206	0.091	853	Slight haze
2250	34.2	0.74	0.27	270	14.7	2.5	1.4	4.3	805	205	0.093	855	Darkening evident
2500	34.6	0.81	0.32	300	17.5	2.9	1.6	4.6	920	204	0.095	857	Slight haze
2750	34.9	0.88	0.36	327	20.1	3.3	1.8	4.8	1030	203	0.097	859	Hazy
3000	35.4	0.96	0.41	360	23.0	3.7	2.0	5.1	1180	202	0.099	861	Hazy, possible fine deposits
3250	35.8	1.03	0.46	393	25.9	4.1	2.2	5.3	1330	201	0.101	863	Dark/hazy
3500	36.3	1.12	0.51	430	29.5	4.6	2.5	5.6	1490	200	0.104	865	Dark brown
3750	36.7	1.15	0.55	465	32.3	5.0	2.7	5.8	1661	199	0.106	867	Dark brown
4000	37.2	1.29	0.62	510	36.5	5.6	3.0	6.1	1850	198	0.109	870	Dark, degraded/sludge tendency

Table 4 Lubricant Degradation of ISO VG 46 Mineral Oil after 4000 Operating Hours

OT	KV	TAN	OX	H_2O	Fe	Cu	Al	Si	PC	FP	FC	ρ	Appearance
0	46.2	0.35	0.02	120	2.0	0.5	0.3	3.0	180	226	0.082	850	Very clear, pale yellow
250	46.3	0.37	0.03	132	2.7	0.6	0.4	3.1	212	225	0.083	851	Pale yellow
500	46.5	0.40	0.04	150	3.6	0.8	0.5	3.3	250	224	0.084	852	Light yellow
750	46.7	0.43	0.06	162	4.8	1.0	0.6	3.5	302	223	0.085	853	Yellow
1000	47.0	0.47	0.08	179	6.2	1.2	0.8	3.7	360	222	0.087	854	Yellow/amber
1250	47.4	0.52	0.10	198	8.0	1.5	0.9	3.9	426	221	0.088	855	Light amber
1500	47.8	0.58	0.13	220	10.0	1.8	1.1	4.2	512	220	0.089	856	Amber
1750	48.3	0.65	0.17	243	13.2	2.3	1.3	4.5	609	219	0.090	857	Amber/brown
2000	48.8	0.72	0.20	266	16.8	2.7	1.6	4.7	720	217	0.092	858	Brownish amber
2250	49.4	0.80	0.24	293	19.3	3.2	1.9	4.9	848	216	0.093	859	Brown
2500	50.0	0.89	0.29	315	24.0	3.7	2.1	5.2	990	215	0.094	860	Dark brown

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2750	50.7	0.98	0.34	339	26.8	4.3	2.4	5.4	1191	213	0.095	861	Dark brown
3000	51.5	1.09	0.40	366	31.5	4.9	2.8	5.7	1320	212	0.097	862	Very dark brown
3250	52.3	1.19	0.46	390	34.9	5.6	3.2	5.9	1524	211	0.098	863	Dark brown/black
3500	53.2	1.32	0.54	420	40.0	6.5	3.7	6.2	1740	210	0.099	864	Very dark brown
3750	54.0	1.43	0.60	452	43.9	7.1	4.1	6.4	1980	208	0.101	865	Near-black brown
4000	55.0	1.57	0.69	490	49.0	8.0	4.7	6.7	2240	207	0.102	866	Black/dark, opaque brown

Table 5 Lubricant Degradation of ISO VG 68 Mineral Oil after 4000 Operating Hours

OT	**KV**	**TAN**	**OX**	**H_2O**	**Fe**	**Cu**	**Al**	**Si**	**PC**	**FP**	**FC**	**ρ**	**Appearance**
0	68.5	0.38	0.02	150	2.5	0.7	0.3	3.5	190	238	0.075	875	Clear/pale yellow
250	68.7	0.41	0.03	164	3.2	0.8	0.4	3.6	222	237	0.076	876	Pale yellow
500	68.9	0.43	0.04	180	4.0	0.9	0.5	3.8	260	237	0.077	877	Light yellow
750	69.2	0.46	0.06	197	4.9	1.1	0.6	4.0	307	236	0.078	878	Yellow
1000	69.5	0.50	0.07	220	6.0	1.2	0.7	4.2	360	235	0.079	879	Yellow amber
1250	69.8	0.53	0.09	237	7.2	1.4	0.8	4.4	423	234	0.080	880	Light amber
1500	70.2	0.58	0.11	260	8.5	1.6	0.9	4.6	490	233	0.081	881	Amber
1750	70.6	0.63	0.13	283	9.8	1.8	1.1	4.8	567	232	0.082	882	Amber/brown
2000	71.0	0.68	0.16	310	11.5	2.1	1.2	5.0	650	231	0.083	883	Brownish amber
2250	71.4	0.73	0.19	333	13.1	2.3	1.4	5.2	746	230	0.084	884	Brown
2500	72.0	0.79	0.22	360	15.0	2.6	1.5	5.4	850	229	0.085	885	Dark brown
2750	72.5	0.84	0.25	387	16.8	2.9	1.7	5.6	963	228	0.086	886	Dark brown
3000	73.1	0.91	0.29	420	19.0	3.2	1.9	5.8	1080	227	0.088	887	Very dark brown
3250	73.6	0.96	0.32	451	21.1	3.5	2.1	6.0	1212	225	0.089	888	Dark brown/black
3500	74.3	1.04	0.37	490	23.5	3.9	2.3	6.2	1360	224	0.091	889	Very dark brown
3750	74.8	1.10	0.40	528	25.6	4.2	2.5	6.4	1422	223	0.092	890	Near-black brown
4000	75.6	1.19	0.46	570	28.5	4.7	2.8	6.7	1690	221	0.094	891	Black/dark opaque brown

From Tables 2 – 5, it can be seen that the degradation was a combined chemical, mechanical, shear, contamination, and wear particle interactive type generally, for ISO VG 10, ISO VG 32, ISO VG 46, and ISO VG 68 mineral oil, where all the rates of degradation were directly proportional to operating time. In Table 2 (ISO VG 10), the following highest deviations were recorded; kinetic viscosity: 2.0 cSt., TAN: 0.52 mg KOH/g, oxidation: 0.29 A/cm, water: 260 ppm, particle content: 860 particle/mL, flash point: 15℃, friction coefficient: 0.019, density: 16 kg/m^3, and from clear, very pale yellow to black/dark opaque brown.

For Table 3 (ISO VG 32), the deviations stood at; kinetic viscosity: 5.0 cSt., TAN: 0.97 mg KOH/g, oxidation: 0.40 A/cm, water: 410 ppm, particle content: 1700 particle/mL, flash point: 16℃, friction coefficient: 0.031, density: 28 kg/m^3, and from clear/bright to dark, degraded/sludge tendency status. Table 4 (ISO VG 46), deviations were; kinetic viscosity: 8.8 cSt., TAN: 1.22 mg KOH/g, oxidation: 0.67 A/cm, water: 3700 ppm, particle content: 2060 particle/mL, flash point: 19℃, friction coefficient: 0.020, density: 16 kg/m^3, and from very clear pale yellow to black/dark opaque brown. For Table 5 (ISO VG 68), the following deviations were recorded; kinetic viscosity: 7.1 cSt., TAN: 1.97 mg KOH/g, oxidation: 0.44 A/cm, water: 420 ppm, particle content: 1500 particle/mL, flash point: 17℃, friction coefficient: 0.019, density: 16 kg/m^3, and from clear, pale yellow to black/dark opaque brown.

➢ *Comparative Degradative Analysis of Selected Lubricants*

Comparative plots for kinetic viscosity, total acid number (TAN), oxidation values, water content, particle content, flash point, friction coefficient, and density each against operating time for the four selected lubricants are respectively presented in Figure 1, Figure 2, Figure 3, Figure 4, Figure 5, Figure 6, Figure 7 and Figure 8 thus;

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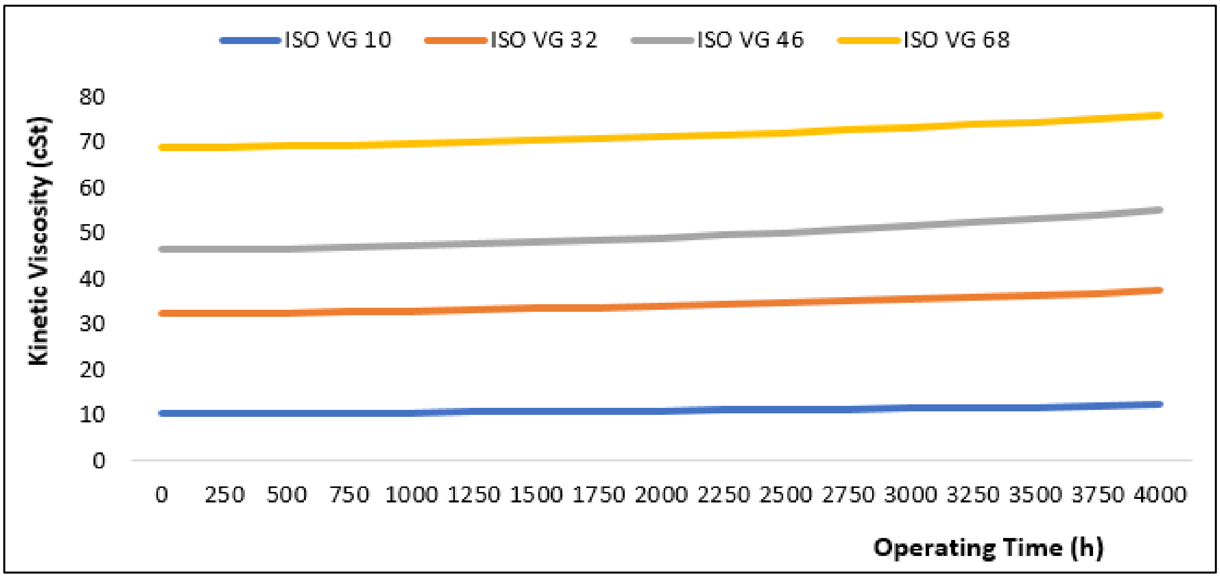

Fig 1 Kinetic Viscosity Against Operating Time for Degraded Lubricants

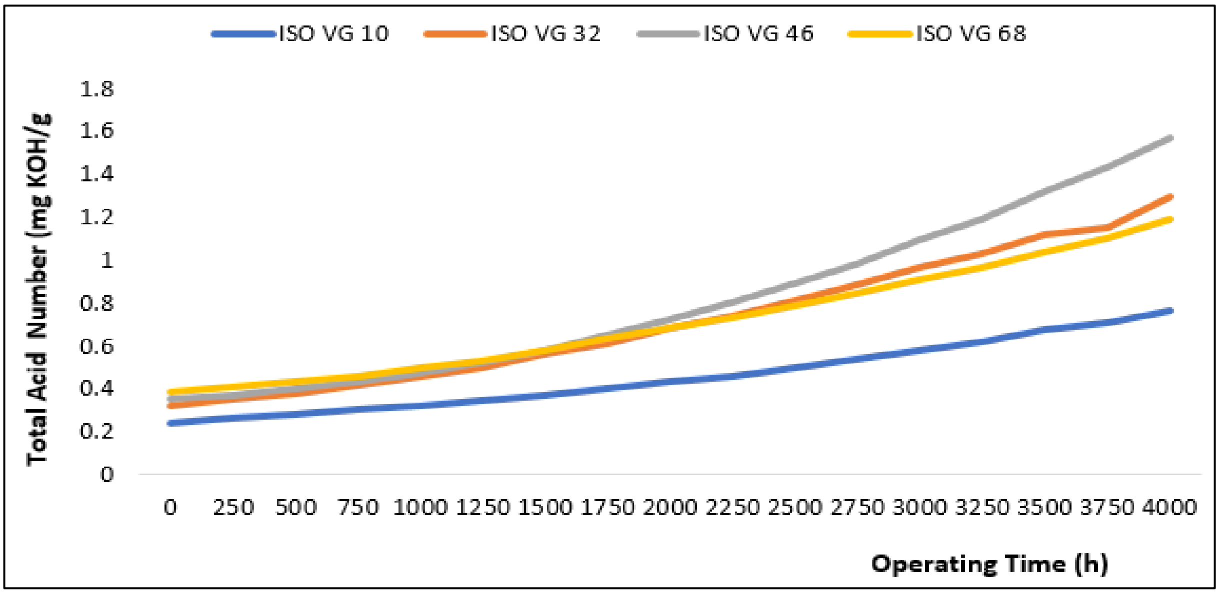

Fig 2 TAN Against Operating Time for Degraded for Lubricants

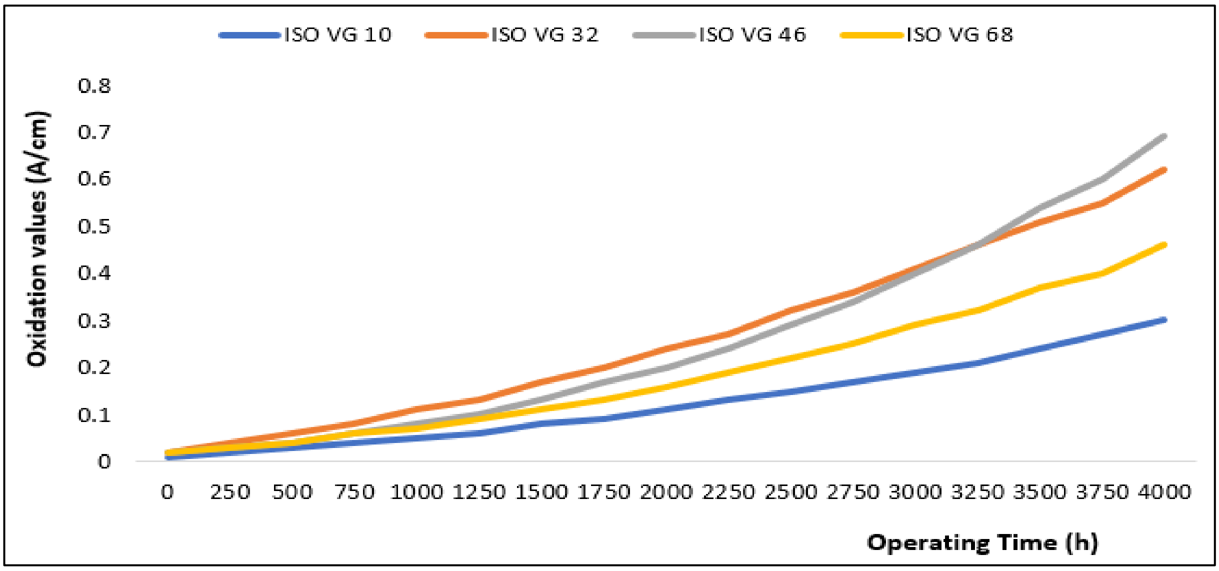

Fig 3 Oxidation Values Versus Operating Time for Degraded Lubricants

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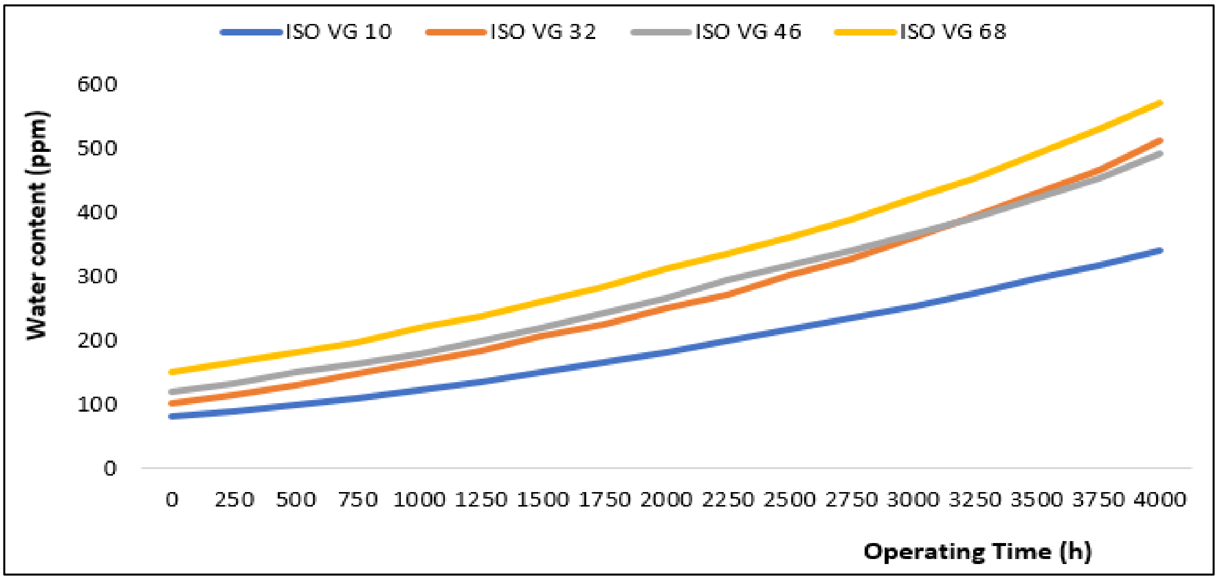

Fig 4 Water Content Versus Operating Time for Degraded Lubricants

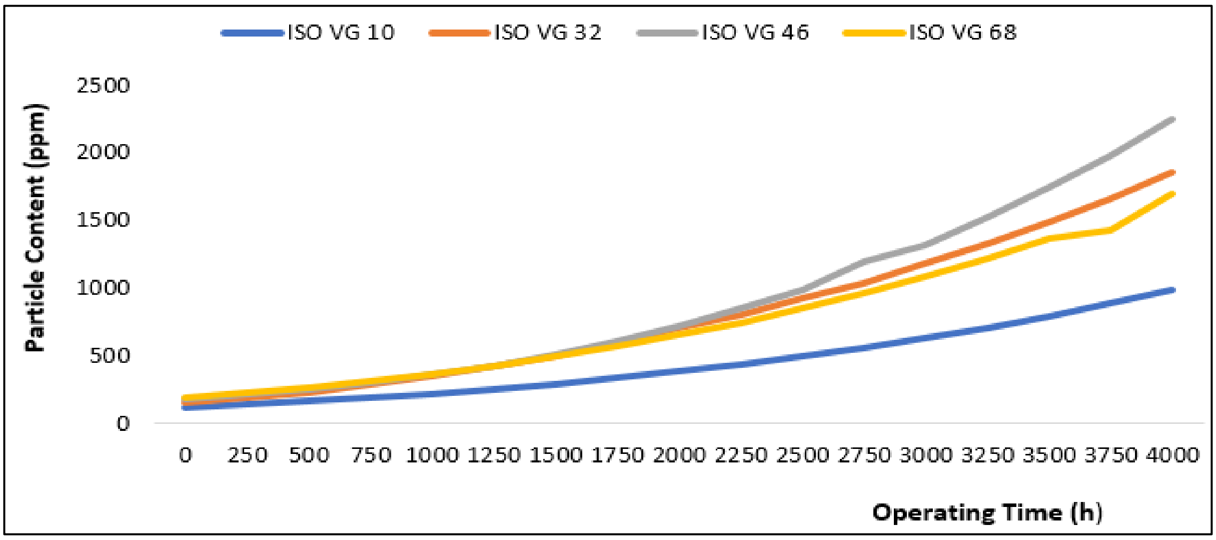

Fig 5 Particle Content Against Operating Time for Degraded Lubricants

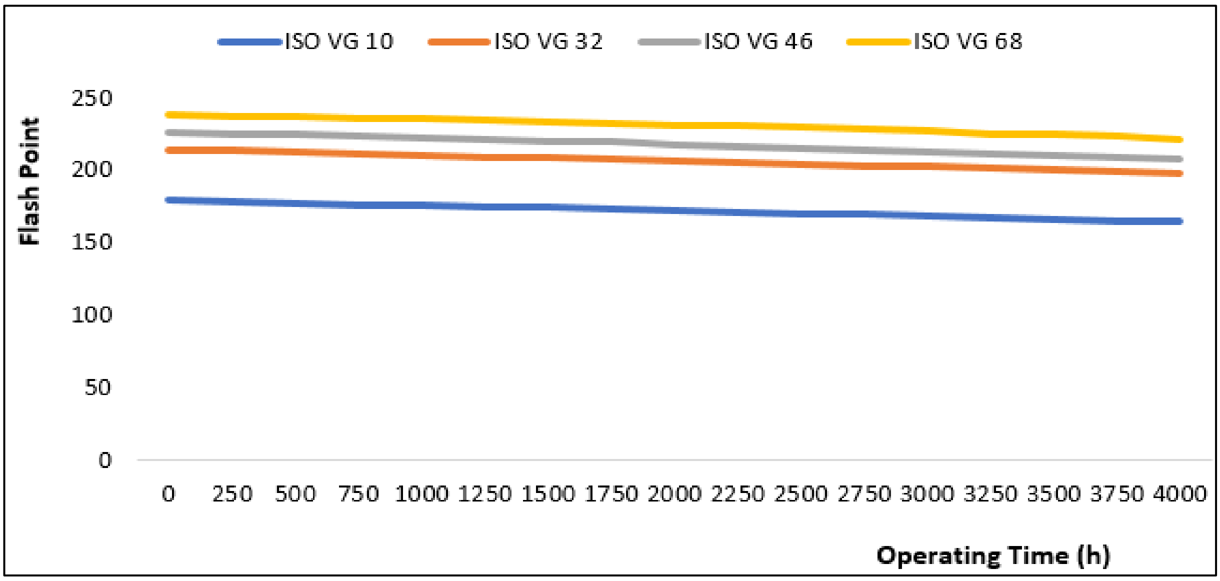

Fig 6 Flash Point Versus Operating Time for Degraded Lubricants

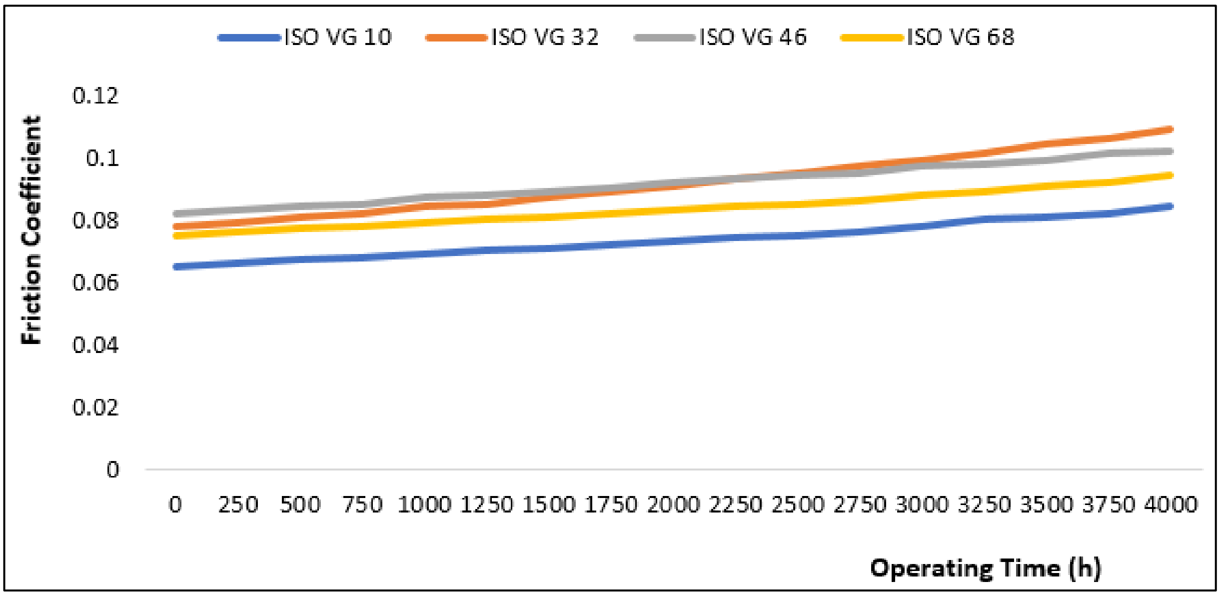

Fig 7 Friction Coefficient Versus Operating Time for Degraded Lubricants

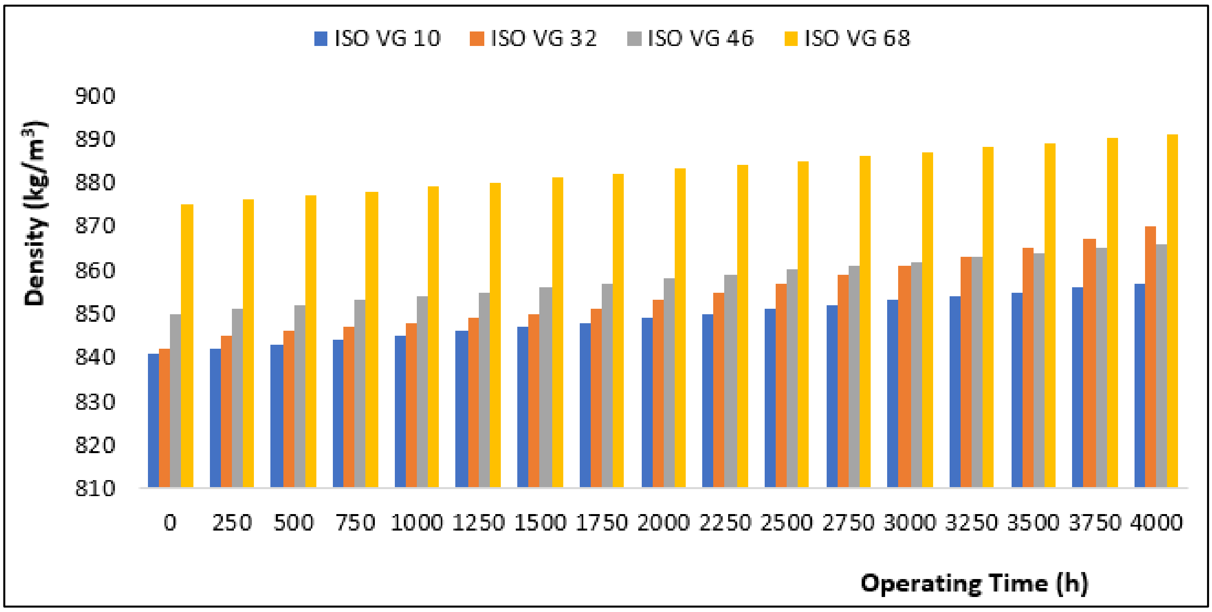

Fig 8 Density Deviation Versus Operating Time for Degraded Lubricants

From Figures 1 – 8, it is clear that the combined degradation followed a unique trend as seen in the curve paths and bars shapes of each plotted degraded lubricant dataset. All had significant deviations from the baseline parameters of unused fresh oils, having increase parametric deviation with prolonged operating time. ISO VG 46 recorded the highest deviation in kinetic viscosity (8.8 cSt) followed by ISO VG 68 (7.1 cSt), then ISO VG 32 (5.0 cSt) and ISO VG 10 with the least (2.0 cSt). ISO VG 68 had TAN of 1.97 mg KOH/g (highest), then ISO VG 46 (1.22 mg KOH/g), ISO VG 32 (0.97 mg KOH/g), and ISO VG 10 (0.52 mg KOH/g) the least. Other parameters followed this order; oxidation, ISO VG 46, ISO VG 68, ISO VG 32 and ISO VG 10 with 0.67, 0.44, 0.40 and 0.29 A/cm respectively; water: ISO VG 68 (420 ppm), ISO VG 32 (410 ppm), ISO VG 46 (370 ppm) and ISO VG 10 (260 ppm). Particle content: ISO VG 46 (2060 particle/mL), ISO VG 32 (1700 particle/mL), ISO VG 68 (1500 particle/mL) and ISO VG 10 (860 particle/mL). Flash point: ISO VG 46 (19°C), ISO VG 68 (17°C), ISO VG 32 (16°C) and ISO VG 10 (15°C). Friction coefficient documented ISO VG 32 (0.031), ISO VG 46 (0.020), ISO VG 68 (0.019) and ISO VG 10 (0.019). Finally, for density: ISO VG 32 had 28 kg/m^3, ISO VG 10, ISO VG 46 and ISO VG 68 had 16 kg/m^3 each.

➢ *Degradation Trends and Implications on Machine Tools*

Viscosity had a gradual increase, accelerating after approximately 2000 – 3000 hours due to oxidation and polymerization. TAN progressively increased as acidic oxidation products were formed. Water content gradually intensified due to environmental ingress/condensation. Increase in iron (Fe) was occasioned by continuous wear of steel components. Copper (Cu) increased more slowly, potentially indicating bearing, brass, or/and copper-alloy wear. Aluminium (Al) was generally low but increased with component wear, whereas particle count increased with wear

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debris and oxidation products. Oxidation also had progressive increase, particularly at higher operating hours. All these increases in degradation and contamination impact negatively on the machine tool and the workpiece specifically in terms of loss of performance, poor functionality, tools wear and possible equipment failure, energy losses due to friction, poor surface finishing, dimensional inaccuracy, lack of reliability and absence of quality assurance.

IV. CONCLUSIONS

From the study, having applied different statistical analysis and weighting techniques of 1 – 4 scaling, with 1 representing least deviation and 4 highest deviation, ISO VG 46 recorded the highest negative impacts on the machine tool with 24 weighting points, whereas ISO VG 32 and ISO VG 68 had the same influence of 20 weighting points each, and ISO VG 10 showcased the least negative effect on the system with 10 weighting points. Therefore, ISO VG 10 is recommended particularly when prolonged usage is paramount. Regular parametric characterization and proper storage are also recommended for optimal machine tool applications.

Generally, understanding and monitoring lubricant characterization degradation is critical to improving machine tool reliability and operational efficiency. Implementing structured lubricant analysis programs, improving contamination control practices, and selecting lubricants optimized for specific machining conditions can significantly mitigate degradation effects and deliver measurable performance and cost benefits across machine tool operations.

➢ *Authors' Contributions*

- Conceptualization, Methodology, Field Sampling, Laboratory Analysis, Writing – Original Draft: Enefiok O. Usungurua
- Data Curation, Formal Analysis, Visualization: Enefiok O. Usungurua, Whyte A. Akpan, Uchechi E. Iroekwe, William A. Onuh
- Resources, Investigations, and Funding: Enefiok O. Usungurua, Whyte A. Akpan
- Validation, Writing – Review and Editing: Enefiok O. Usungurua, Uchechi E. Iroekwe
- Supervision, Project Administration: Enefiok O. Usungurua, William A. Onuh

➢ *Competing Interests*

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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➢ *Ethical Approval*

The authors declare that this research do not require any ethical committee approval or legal authorization. All authors have read and agreed to the publication of this research work, as well as the published version of the manuscript.

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