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Investigation of Hydraulic Oil Quality and Its Influence on Fuel Consumption and Environmental Performance of Motor Graders Operating under Hot and Dusty Climatic Conditions

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Abstract

This study investigates the performance characteristics of UNO HV (HVLP)-46 hydraulic oil used in GR-165 series D motor graders operating under hot and dusty climatic conditions. Physicochemical and spectral analyses were conducted to evaluate viscosity stability, contamination level, wear metal concentration, and additive behavior during service. The results indicate that the used oil contains wear metals such as aluminum (Al), iron (Fe), chromium (Cr), and copper (Cu), as well as atmospheric dust contamination represented by silicon (Si). Degradation products of additives, including sulfur (S), phosphorus (P), and chlorine (Cl), were also detected. The findings demonstrate that maintaining viscosity stability reduces internal leakage within the hydraulic pump, improves volumetric and mechanical efficiency (ηv, ηm), decreases engine load, and consequently lowers fuel consumption and exhaust emissions under severe operating conditions.

Keywords: Hydraulic oils, viscosity stability, wear metals, contamination, fuel consumption, CO_2 emissions, durability.

Introduction

Hydraulic systems transmit mechanical energy through an incompressible working fluid[1]. Hydraulic fluid serves not only as an energy transmission medium but also as an essential structural and functional element of the entire system[2]. Elevated temperatures, frictional heating, high operating pressures, and throttling through narrow clearances significantly influence the physicochemical stability of hydraulic oils[3].

During operation, hydraulic oil is exposed to thermal, mechanical, and oxidative stresses that accelerate degradation processes and shorten service life[4]. In hot climatic regions, operating conditions are further aggravated by high atmospheric dust concentrations, which may reach 5–10 g/m³, thereby substantially increasing the wear rate of hydraulic components[5].

Statistical data indicate that approximately 70% of hydraulic system failures are related to oil condition[6]. Among these failures, nearly 40% are directly associated with oil degradation, while about 60% result from contamination and insufficient oil cleanliness[7]. These findings emphasize the critical importance of maintaining hydraulic oil quality to ensure reliability and durability under severe environmental conditions.

Methodology

Experimental studies were carried out on GR-165 and GR-180 series D motor graders operating under hot and dusty environmental conditions. Oil samples were collected at predetermined operating intervals (moto-hours) and analyzed using standardized physicochemical and spectrometric analysis methods[8].

The following parameters were evaluated: kinematic viscosity, base number (alkaline number), moisture content, concentration of mechanical impurities, and wear metal content[9].

The contamination analysis revealed intensive accumulation of mechanical impurities and moisture under high dust conditions[10]. Operational data indicate that downtime of GR-165 motor graders due to hydraulic system failures accounts for approximately 49% of the total downtime[11].

Operation at elevated ambient temperatures (+40°C to +50°C) leads to deterioration of physicochemical properties, including viscosity reduction and accelerated oxidation[12]. The observed viscosity variations are primarily attributed to oxidative degradation and the accumulation of contaminants during service life[13].

Results and Discussion

Oil samples were collected under summer operating conditions at the Bukhara road-construction complex. The baseline physicochemical properties of the hydraulic oil were determined prior to service to establish reference values for subsequent comparative analysis.

Table-1: Viscosity variation of different hydraulic oils (HYDRO ISO-46, Fastroil Hydraulic Oil 46, and Chilon UNO HVLP-46) over operational time at different moto·hours.

Moto·soat	HYDRO ISO-46			Fastroil Hydraulic Oil 46			Chilon UNO HVLP-46			Me'yor
	1	2	3	1	2	3	1	2	3	
0	46.0	46.0	46	46.0	46.0	45.5	46.0	46.0	45.7	>40
300	45.0	44.8	44.2	45.2	45.0	44.5	45.5	45.3	44.8	>40
600	43.5	43.3	42.7	44.0	43.8	43.1	44.7	44.5	44.0	>40
900	41.8	41.6	40.9	42.5	42.3	41.5	43.6	43.4	42.8	>40
1200	39.5	39.3	38.5	40.3	40.1	39.2	42.4	42.2	41.6	>40
1500	36.4	36.1	35.0	37.5	37.2	36.2	41.0	40.8	40.3	>40

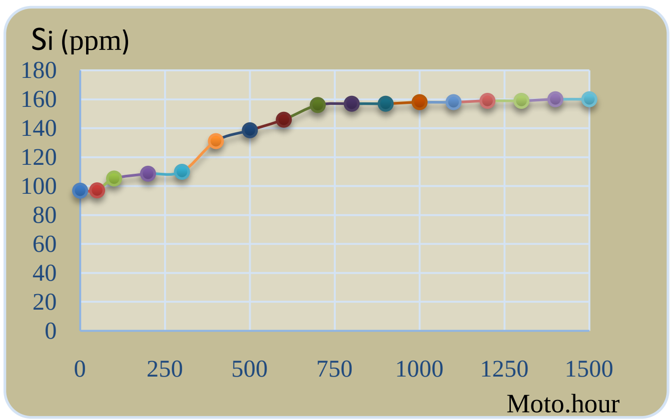

Figure-1: Dependence of silicon (Si) concentration on operating time.

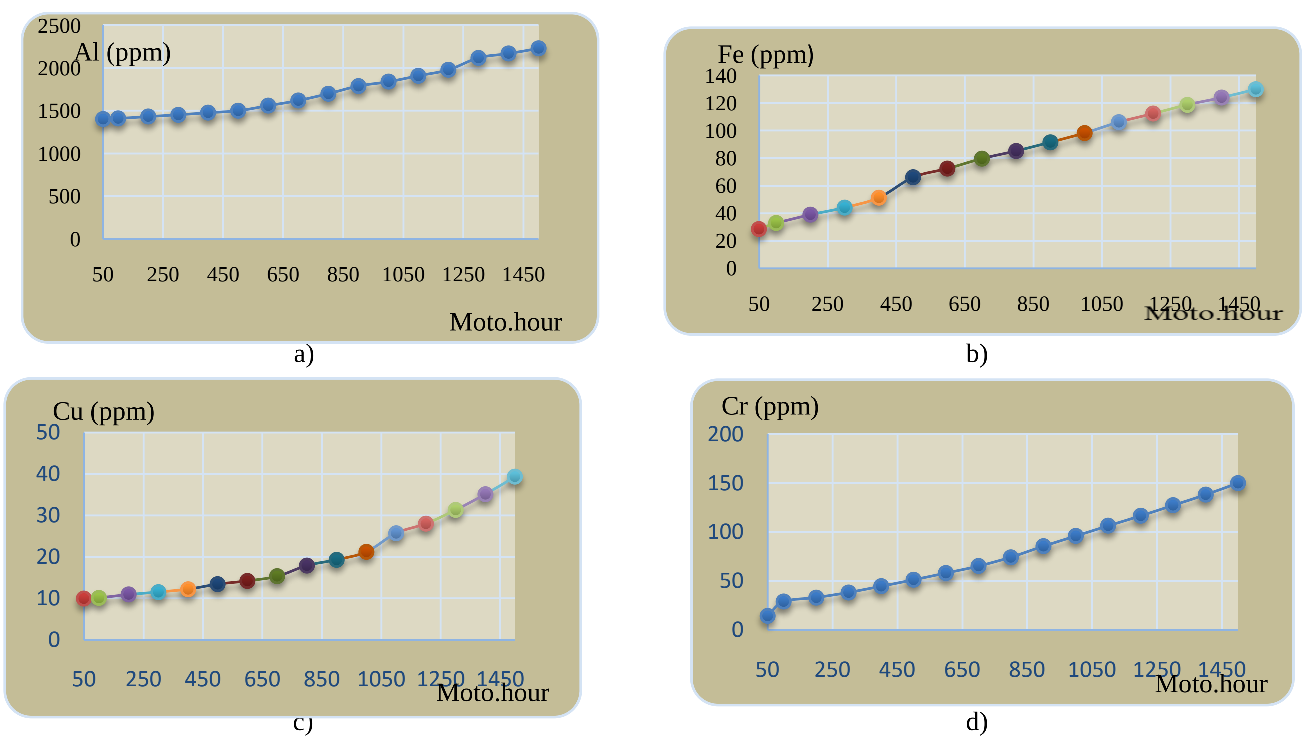

Figure-2: (a–d).Variation of aluminum (Al), iron (Fe), chromium (Cr), and copper (Cu) concentrations with operating time.

Mechanical impurity concentration increased progressively with operating time[14]. Spectral analysis confirmed increasing wear metal concentrations (Al, Fe, Cr, Cu)[15].

Viscosity stability directly influences pump volumetric and mechanical efficiency (ηv, ηm), thereby reducing fuel consumption[16]. For diesel fuel, the CO_2 emission factor is approximately 2.64 kg of CO_2 per liter of fuel consumed[17].

The formation of NOx emissions increases exponentially with rising combustion temperature and engine load. Contamination of working fluids significantly reduces system reliability and component durability. Modern hydraulic systems incorporate precision assemblies with extremely small diametrical clearances, which increases their sensitivity to the presence of solid particles in the fluid. Insufficient lubricating properties accelerate wear processes and degrade system performance.

During prolonged operation, the accumulation of mechanical impurities in the oil initially increases and subsequently stabilizes due to retention by filtration and cleaning units, establishing a dynamic equilibrium state.

An analysis of changes in individual physicochemical parameters of the operating oil shows that each parameter responds distinctly to external disturbances affecting hydraulic system components.

The results of the spectral analysis of wear products in UNO HV (HVLP)-46 hydraulic oil—aluminum (Al), iron (Fe), chromium (Cr), and copper (Cu)—as a function of operating time in GR-165 series D motor graders are presented in Figure-2 (a–d).

The wear of hydraulic system components can be monitored by measuring the concentration of metallic wear particles in the oil. A significant increase in the concentration of a specific element indicates intensified wear of the corresponding component materials. For example, the concentration of iron (Fe) serves as a direct indicator of wear intensity and reflects changes in the anti-wear performance of the oil.

The analysis shows that used oil predominantly contains wear products in the form of aluminum (Al), iron (Fe), chromium (Cr), and copper (Cu). As illustrated in Figure-2 (a–d), deviations in aluminum (Al) and iron (Fe) concentrations become pronounced after approximately 1000 moto-hours of operation. Elevated concentrations of aluminum (Al), iron (Fe), and chromium (Cr) indicate intensified wear processes. Increasing levels of these metals alter the frictional, anti-wear, antioxidant, and detergent properties of the oil. This phenomenon is associated with disruption of the lubrication regime in rubbing pairs, which consequently leads to increased load and temperature at contact interfaces.

According to the results of the spectral analysis, UNO HV (HVLP)-46 oil contains phosphorus-based additives. During operation, organic phosphates were found to contribute to an increase in viscosity, acid number, and foam formation. In addition, progressive darkening of the oil was observed, accompanied by the formation of brittle carbonaceous deposits on metal surfaces.

Organic esters of phosphoric acid are generally chemically inert toward metals under normal conditions. However, under thermal decomposition or hydrolytic conditions, they can form substituted phosphoric acids that promote corrosion, particularly of copper-containing components. The relatively low lubricity and high cost of such fluids limit their widespread industrial application.

Table-2: Spectral analysis of the response of the additive in UNO HV (HVLP)-46 hydraulic oil during operation in GR-165 series D motor graders.

Element	Ishlashdavri, (moto·soat)						
	0	300	600	900	1200	1500	Meyyor
Si	–	5	8	13	19	25	<30
Al	0.6	3	4	6	8	11	<15
Fe	–	7	10	14	18	23	<30
Cr	–	3	6	9	14	18	<20
Cu	0.2	8	15	20	24	28	<30
Cl	–	9	14	19	24	30	<50
Ca	300	230	190	150	120	110	>100
Mg	100	95	92	90	87	85	>80
Zn	350	330	315	290	265	230	>200
P	450	420	390	355	320	290	>200
S	420	370	330	290	250	230	>200

Based on the comprehensive experimental data obtained from the analysis of oil quality parameters, the introduction of performance-enhancing additives is recommended. The most effective antioxidant behavior was observed in additives containing metal, sulfur, and phosphorus within the same molecular structure. The results indicate that zinc, in combination with sulfur and phosphorus, provides enhanced anti-wear and antioxidant performance.

The principal advantage of the proposed PSZn-11 additive lies in its synergistic composition, combining zinc with sulfur and phosphorus, thereby improving thermal stability, oxidation resistance, and overall operational performance of the hydraulic oil.

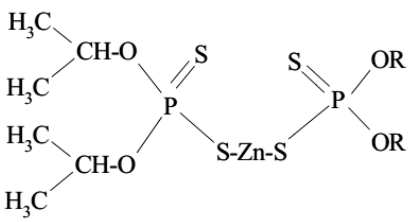

Figure-3: Chemical structure of PSZn-11 additive[18].

The PSZn-11 additive is completely soluble in hydraulic oil and insoluble in water, ensuring stable dispersion within the working fluid without moisture interaction. Compared to conventional antioxidant and anti-wear additives, PSZn-11 demonstrates superior thermal stability and performance under elevated temperature conditions. Its effectiveness is particularly pronounced under moderate to high contact stresses, where enhanced anti-wear and load-bearing properties are required.

During the experimental investigation, UNO HV (HVLP)-46 hydraulic oil containing PSZn-11 was subjected to physicochemical analysis to evaluate compliance with standard quality requirements. After confirming full dissolution and compatibility of the additive with the base oil, the alkaline (base) number was determined for different additive concentrations ranging from 1% to 5%.

The analysis revealed that the base number increased proportionally with additive concentration; however, excessive concentrations did not provide proportional performance improvement. Based on the optimal alkaline number and stability characteristics (Figure-3), the 2.5% concentration of PSZn-11 was identified as the most effective formulation for ensuring enhanced oxidative stability and operational reliability under hot and dusty climatic conditions.

The application of improved hydraulic oils with a higher viscosity index and enhanced thermal-oxidative stability significantly minimizes internal pressure losses within the hydraulic system. As a result, hydraulic pump efficiency increases, engine power demand decreases, and overall fuel consumption is reduced. Consequently, exhaust emissions are lowered, contributing to improved environmental performance and enhanced operational sustainability of motor graders operating under hot and dusty climatic conditions.

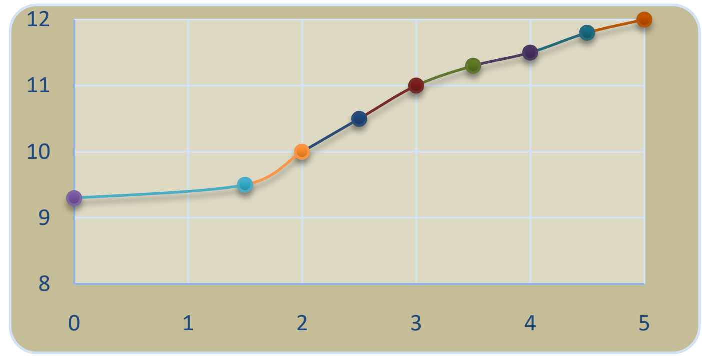

Figure-4: Change in the base number of the oil depending on the additive concentration.

Conclusion

The incorporation of 2.5% PSZn-11 additive into UNO HV (HVLP)-46 hydraulic oil significantly enhances its physicochemical stability and operational performance under hot and dusty climatic conditions. Improved viscosity stability contributes to the reduction of internal pressure losses within the hydraulic system, thereby decreasing engine power demand and lowering overall fuel consumption. Consequently, exhaust emissions are reduced, leading to improved environmental performance and increased operational reliability.

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