Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal, 2026, 20(9), 343–355
https://doi.org/10.12913/22998624/221662
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Received: 2026.03.30
Accepted: 2026.07.10
Published: 2026.08.01

Research on hydraulic oil wear processes in single-bucket excavators operating in rock material mines

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ABSTRACT

The article presents the course and characteristics of changes in the physico-mechanical properties of hydraulic oils used in single-bucket excavators operating in rock material mines. The methodology and results of research into the changes in properties of hydraulic oils of HV quality and VG 46 viscosity are presented. Based on the obtained data from monitoring hydraulic oil wear processes, analysis was carried out on the influence of the time and type of work performed by excavators on the rate of oil degradation. During the conducted research, measurements were taken of hydraulic oil parameters, such as the degree of contamination with solid particles, conductivity, dielectric permeability, and operating temperature, etc. The measurement results formed the basis for identifying changes in the physico-mechanical properties of the oils and determining their causes. The conclusions drawn from the research can be used to optimize hydraulic oil replacement processes and service activities for the hydraulic systems of excavators operating in rock material mines. Apart from regular monitoring of the condition of hydraulic oil and analysis of its physico-mechanical properties, this has a decisive impact on the proper functioning of excavator hydraulic systems and on preventing failures and damage to such systems.

Keywords: rock mining, single-bucket excavators, hydraulic oil, hydraulic oil testing.

INTRODUCTION

Evaluating the characteristic changes in parameters of hydraulic oils operating in the hydraulic systems of working machines is a complex process requiring a thorough investigation of oil degradation. Hydraulic oils ensure the operation of the hydraulic systems of working machines and determine their functionality, durability, and reliability [1,2]. Other important functions of the working medium include cooling hydraulic components, protecting the surfaces of cooperating elements from wear, preventing system contamination, and maintaining the cleanliness of cooperating components (by flushing contaminants and deposits from elements). For these reasons, the main objective of oil degradation research is to determine whether a given hydraulic oil has deteriorated to a degree that prevents it from fulfilling the aforementioned functions. The literature contains numerous studies indicating that the condition of hydraulic oil has a decisive impact on the functioning of hydraulic system components [3,4]. Currently, in the hydraulic systems of most earth-moving machines and equipment, HV-class hydraulic oils compliant with the ISO 6743-4 [5] standard are predominantly used. These oils consist of highly-refined mineral base oils with appropriately selected additive packages that ensure a high level of anti-wear properties and a relatively broad viscosity-temperature characteristic [6]. This has significantly extended the service life of such oils in the hydraulic drives of machines and substantially reduced the wear of friction elements in the components of these systems [7,8]. It is worth noting that these oils are now frequently used in highly-loaded drive systems of working machines, operating at hydraulic pump speeds of around 2500 rpm and working pressures reaching up to approximately 35 MPa [9]. For this reason, the oils used are required to have high-level anti-wear properties and to maintain minimal changes in viscosity despite significant temperature variations in the hydraulic system. Under such operating conditions, the oils may undergo a relatively rapid degradation process (aging process). Oil aging is a process in which the hydraulic oil loses its original physical and mechanical properties, thereby becoming less effective in fulfilling its operational functions and causing negative effects, such as [10,11]:

- deterioration of lubricating properties – aging hydraulic oil may lose its ability to effectively lubricate surfaces and components in the hydraulic system, which can lead to increased wear due to friction and component damage,
- changes in viscosity – a decrease in viscosity can hinder the proper flow of hydraulic oil through the system, which may result in reduced system performance,
- increased contamination of the oil with solid particles – which are products of the aging process,
- reduced thermal stability – which can lead to the formation of deposits, oil oxidation, etc.

As a result of the hydraulic oil aging process, the efficiency and durability of hydraulic systems can be significantly reduced [12]. To prevent the effects of hydraulic oil aging in the hydraulic systems of earth-moving machines and equipment, oil replacement is commonly performed after a predetermined period of use. To ensure proper operation of the hydraulic system, it is important to follow several basic maintenance principles, including [13]:

- regularly checking the level and condition of the hydraulic oil,
- adhering to the oil and filter replacement intervals recommended by the hydraulic oil manufacturer,
- using the appropriate type of hydraulic oil for a given machine, which meets the required standards and specifications of the machine manufacturer,
- monitoring the operating temperature of the hydraulic system, as high operating temperatures can very quickly lead to oil aging (loss of required oil properties).

Currently, a number of oil condition monitoring systems are in practical use in working machines, enabling early detection of signs of degradation in the hydraulic oil that could lead to component damage. These systems facilitate a relatively quick assessment of oil degradation, and thus the implementation of appropriate maintenance actions. The most common hydraulic oil condition monitoring systems include [13,14]:

- laboratory analysis of a given type of hydraulic oil (the tests include parameters such as viscosity, acidity, alkalinity, water content, and the presence of contaminants),
- continuous oil condition monitoring systems. These are special sensors installed within the system that continuously measure oil parameters, such as: temperature, viscosity, pressure, humidity, water content, and the presence of contaminants,
- optical spectroscopy systems. These systems measure the light absorption spectra of hydraulic oil. Spectroscopy facilitates assessment of the oil degradation level and identification of potential problems related to its use,
- filtration-monitoring systems (bypass systems). These systems use special contamination sensors and filters that remove contaminants from the oil.

Modern hydraulic systems used in working machines operate under very demanding operating conditions. This fact significantly increases the risk of hydraulic oil degradation and, consequently, the likelihood of damage to hydraulic components. For this reason, oil quality monitoring systems are extremely useful, as they enable the quick detection of oil aging effects, facilitating preventive actions to avoid damage to the hydraulic system components [15,16]. Modern hydraulic oil condition monitoring systems use various technologies and sensors that allow close monitoring of hydraulic oil parameters, such as viscosity, temperature, pressure, the presence of contaminants, dielectric permeability, and conductivity. These systems are capable of generating warnings or alarms if preset threshold values are exceeded, enabling quick intervention by maintenance personnel to carry out appropriate repair or maintenance actions.

Despite the widespread use of HV-class hydraulic oils in the working systems of construction and mining machinery, the literature still lacks clear, systematic studies of the actual dynamics of hydraulic oil degradation in single-bucket excavators used in rock mining, operating under intense dynamic loads and the frequent use of hydraulic hammers.

In this context, the main aim of the present study, which was of a pilot nature, was a quantitative and qualitative analysis of the aging process of HV-class hydraulic oil with a viscosity of VG 46, used in hydraulic systems of single-bucket excavators operating in hard rock mines, taking into account the machine's operating time, the intensity of hydraulic hammer use, and the nature of the work performed. So far, the issue of hydraulic oil wear in excavators working in hard rock mining has not been the subject of detailed research and analysis.

The scope of the study included monitoring changes in oil cleanliness, moisture content, and elemental composition as a function of operating hours, using portable in-situ diagnostic methods and laboratory analyses. According to the adopted research objective, the results were intended to serve as a basis for developing new oil change intervals for excavators operating in rock mines and methods for diagnosing hydraulic oil condition under real operating conditions.

CHARACTERISTICS OF HYDRAULIC OIL AGING PROCESSES

Currently, single-bucket excavators used in rock material mines are equipped with advanced hydraulic systems that operate at very high working pressures reaching up to 35 MPa. These systems consist of increasingly compact components, which are precisely designed and manufactured. The evolution in the design of hydraulic components – both control-distribution and actuating elements – aims to increase the efficiency of excavators, but, at the same time, these components must work with hydraulic oil of suitable viscosity and properties to ensure the reliable operation of the elements and, consequently, the entire hydraulic system of the excavator.

Hydraulic oils used in single-bucket excavators must possess a range of specific properties [17,18]. They must power the actuating elements of the system and, in addition, provide adequate lubrication, sealing, minimization of component wear, and protection against corrosion. During the operation of an excavator in a rock material mine, the oils are subjected to intense mechanical impacts – especially when using hydraulic hammers – as well as thermal and chemical effects, which gradually reduce their operational parameters and ultimately necessitate their replacement.

The aging process of hydraulic oil is influenced by three primary phenomena [19,20]:
- oil oxidation,
- thermal degradation,
- contamination with solid particles.

Some solid contaminants found in the oil of excavators originate from impurities within hydraulic hoses and lines, or from wear particles on the contact surfaces of rotating components in hydraulic elements. Even dust and dirt particles from the external environment may enter the system. Water droplets can also infiltrate the system, promoting the hydrolysis of additives and accelerating the oxidation of hydraulic oil [1,20]. It is important to be aware that oxidation is the dominant phenomenon in the oil aging process in an operating single-bucket excavator. It causes very serious issues, such as increases in viscosity and acid number, formation of deposits and sludge, depletion of performance-enhancing additives, loss of resistance to foaming, demulsification, and corrosion [9,17]. Oxidized oils can lead to reduced performance of hydraulic systems by degrading the properties of the working medium and lowering the precision of control components. It is important to note that the quantitative assessment of oil contamination is standardized through ISO 4406 [14] and NAS 1638 [21], which classify the number and size of solid particles in the oil. These standards are essential for monitoring oil quality because they allow engineers to identify early signs of wear, predict potential failures, and verify the effectiveness of filtration systems. Online monitoring and laboratory oil analysis provide complementary information [15]: particle counting enables assessment of mechanical contamination, while measurements of physical and chemical parameters – such as viscosity, acid number, water content, and electrical conductivity – reveal the chemical and thermal degradation state of the oil. The selection of these parameters is directly connected to the methodological approach of this study. By tracking both contamination levels and chemical changes, it is possible to:
- identify correlations between the working conditions of hydraulic systems and the degradation of oil properties,
- evaluate the influence of maintenance practices, including filtration and replacement intervals,

- verify the formulated hypotheses that oil degradation follows measurable trends in both mechanical and chemical parameters during operation.

Control elements are susceptible to oil contamination, especially submicron particles that may form sludge or deposits. A sticky layer of these contaminants can further damage cooperating surfaces by attracting other hard particles, such as dust or wear debris from hydraulic components. This may lead to oil filter clogging, reduced cooling efficiency, increased friction between moving hydraulic components, and decreased system precision.

MATERIALS AND METHODS

The research on the aging of oils used in single-bucket excavators operating in rock material mines was conducted using an OPCom Portable Oil Lab analyzer [15]. The main objective of the study was to examine the hypothesis that the physicochemical and particulate properties of hydraulic oil degrade progressively with operating time, affecting the hydraulic system's efficiency and reliability. Specifically, the study aimed to determine the impact of excavator operating time on oil aging rates, assess the validity of manufacturer-recommended oil change intervals and, if warranted, propose revised intervals based on empirical data.

The research focused on HV-class hydraulic oils (ISO 6743-4) [5] of the kinematic viscosity grade VG 46 (PN-ISO 4406) [14], selected for their widespread use in excavators and their relevance to system performance. Parameters of the Orlen Hydrol Oil L-HV 46 tested in single-bucket excavators are shown in Table 1.

Hydraulic oil was used in the hydraulic systems of single-bucket excavators with the following parameters: operating weight: 35 Mg, engine power: 210 kW, working pressure in the hydraulic system: up to 35 MPa, pump capacity: 2×264 dm^3/min.

Oil samples were collected at approximately 200, 400, and 600 engine hours, representing early, intermediate, and extended periods of use. The oil parameters were measured for each engine hour three times, and the average value for each parameter was calculated from the results. These intervals were chosen to capture the progressive effects of mechanical, thermal, and chemical stresses on the oil during normal excavator operation, including the hydraulic hammer impact. Fresh (unused) oil samples were also analyzed for baseline comparison.

Due to the very similar values of the individual parameters obtained during a given series of measurements and the small number of measurements in the series, statistical analysis of the obtained results was not performed, limiting the calculations to the average value of the given parameter.

The OPCom Portable Oil Lab was used as the primary measurement tool due to its ability to perform rapid, on-site analysis of hydraulic oil. It measures chemical changes, such as oxidation and additive depletion, using infrared spectroscopy, evaluates kinematic viscosity using micro-shear sensors, and classifies solid particle contamination via light scattering in accordance with ISO standards. The analyzer is factory-calibrated and provides high accuracy (±2% for viscosity, ±0.5 mg KOH/g for acid number, ±1 ISO degree for particle classification). Limitations include potential interference from certain synthetic oils, the need to cool samples above 60 °C for accurate kinematic viscosity measurements, and the

Table 1. Tested hydraulic oil (baseline properties)

Parameter	Value	Standard / Unit
Kinematic viscosity @40 °C	46 [cSt]	ISO
Kinematic viscosity @100 °C	7.9 [cSt]	ISO
Density	875 [kg/m^3]	15 °C
Flash point	≥ 230 [°C]	COC
Pour point	≤ - 27 [°C]	-
ISO cleanliness (fresh oil)	19/16/14	ISO 4406
Electrical permittivity	2.145	-
Conductivity	350 [ps/m]	-
Relative humidity	26.3 [%]	-

need to dilute samples for heavily-used or very dark oils. During measurement with the OPCom Portable Oil Lab analyzer, the following parameters are determined, as described in more detail in Table 2. Based on these parameters, the results of pilot studies are presented later in the article.

This methodology facilitates a comprehensive assessment of hydraulic oil quality over time, linking operational hours to changes in oil properties, and provides empirical evidence to support recommendations for maintenance and oil replacement intervals in single-bucket excavators.

In rock material mines, three main methods of determining oil change intervals in operating excavators can currently be identified:

1. Oil changes according to the manufacturer's recommendations, which are most often carried out in excavators with a low usage rate of hydraulic hammers (up to 20% of the machine's total operating time).
2. Oil changes based on user experience with a given excavator model, which take into account hammer usage time but do not include oil property testing.
3. Oil changes based on periodic monitoring of the oil's condition, which allows the parameters of the used oil to be determined and the oil change interval to be established based on reaching predefined threshold values.

The growing popularity of the third method results from the availability of portable oil analyzers that enable direct, on-site measurement of oil parameters in excavators operating in rock material mines. Compared to fixed, time-based oil change intervals, condition-based monitoring provides a more accurate assessment of oil degradation under variable mechanical, thermal, and chemical loads, particularly during intensive hydraulic hammer operation. One portable measuring device capable of providing immediate information on the hydraulic oil condition is the OPCom Portable Oil Lab analyzer manufactured by Argo-Hytos [15], as shown schematically in Figure 1a. The analyzer integrates several functional modules that operate on different physical principles. An optical measurement module detects and classifies solid contamination particles, while capacitive and conductive sensors provide information on the oil's chemical condition. Additional sensors measure oil temperature, humidity, and flow rate, enabling compensation for these parameters under changing operating conditions.

The OPCom Portable Oil Lab is a portable oil analyzer that enables the measurement of oil parameters. Sampling directly from a working circuit allows contamination and degradation effects to be captured under real excavator operating conditions.

Figure 1b illustrates the principle of optical particle counting implemented in the OPCom analyzer. As oil flows through the measuring cell, solid particles passing through the laser beam partially attenuate the light. This attenuation is converted into electrical pulses, with their amplitude related to particle size, and the number of pulses corresponding to particle concentration. Based on this signal processing, the oil cleanliness class is determined in accordance with ISO 4406. The OPCom Portable Oil Lab enables measurement of key oil condition parameters, including the oil cleanliness class according to ISO 4406, the number of solid particles per milliliter, dielectric constant, specific electrical conductivity, oil humidity, temperature, and flow rate. The selection of these parameters reflects the dominant oil degradation mechanisms in

Table 2. Parameters used for hydraulic oil condition assessment

Parameter	Standard/Unit	Significance in oil condition assessment
Cleanliness class	ISO code	Assessment of solid particle contamination. Indicates the respective ordinal number according to ISO 4406:21
Concentration	[p/ml]	Indicates the number of particles per milliliter
Relative permittivity	-	The relative permittivity is a parameter for the polarity of the fluid. Oils change their polarity during the aging process.
Electrical conductivity	[pS/m]	Detects contamination and oil degradation. Fresh oils show a characteristic conductivity. Oil change, oil mixtures and oil deposits can be detected by their conductivity.
Temperature	[°C]	Reference condition for measurements. Fluid temperature
Relative humidity of the oil	[%]	Relative humidity between 0 and 100 %
Oil clarity and color	Visual	Preliminary assessment of oil degradation

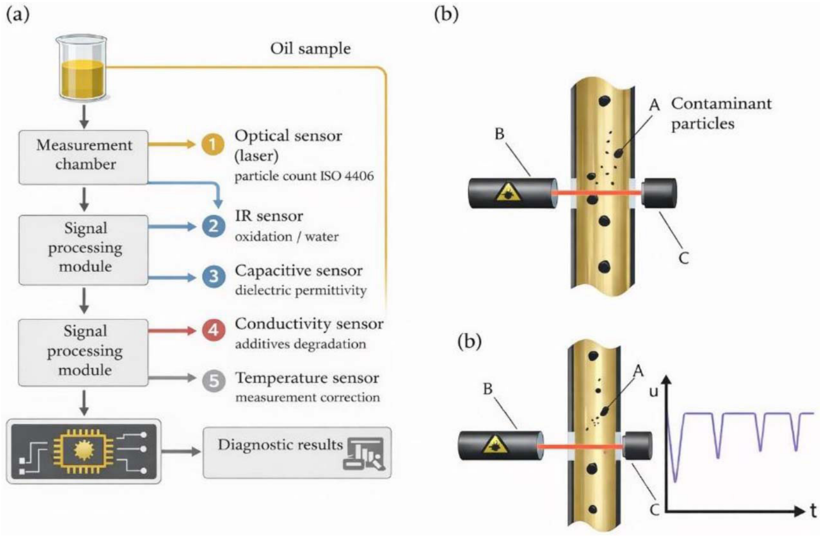

Figure 1. Schematic diagram of the oil condition monitoring methodology using the OPCom Portable Oil Lab analyzer: (a) functional block diagram of the measurement system; (b) schematic illustration of the optical particle counting principle, including light beam interaction with contaminant particles and the corresponding signal response

hydraulic systems. Particle contamination is associated with abrasive wear of precision components; changes in dielectric constant indicate oxidation and depletion of additives; electrical conductivity reflects ionic contamination and chemical aging; and increased humidity accelerates corrosion and oil degradation. Measurement results for each oil sample can be displayed directly on the device, stored in internal memory, or printed as short or extended reports. The analyzer can operate in automatic or manual mode. In automatic mode, measurements are performed continuously, whereas in manual mode a single measurement cycle is completed and the device stops operation. The manufacturer recommends performing three repeated measurements in manual mode to ensure the repeatability and reliability of the results.

It should be noted that the OPCom Portable Oil Lab is intended primarily for condition monitoring and evaluating the quality of hydraulic oil at the excavator's worksite, without the need for laboratory analyses. Figure 2 shows the method for conducting analyses directly on the excavator.

The obtained results provide a repeatable trend, enabling a comparative assessment of oil degradation over time. Extreme contamination levels, air bubbles, or significant temperature variations may affect measurement accuracy; therefore, the results should be interpreted as indicators of oil condition trends rather than absolute values.

The measurement capabilities of the OPCom Portable Oil Lab enable continuous monitoring of oil condition directly under real operating conditions and observation of progressive changes in oil parameters as a function of excavator operating time. This functionality serves as the basis for the adopted research methodology and justifies the use of oil sampling intervals corresponding to successive stages of oil aging during excavator operation.

The study of hydraulic oil degradation in single-bucket excavators operating in rock material mines was carried out in three stages:

- in the first stage, fresh oil samples were taken and tested,
- in the next stage, oil samples were taken from the excavators' hydraulic systems after approximately 200 operating hours (specifically after 200, 400, 600, and 700 engine hours of operation).

At this stage of the research, oil parameters were measured using the OPCom Portable Oil Lab analyzer described above, which was equipped with additional sensors for monitoring oil cleanliness. This analyzer enabled in-situ measurement of oil contamination with solid particles in accordance with the requirements of ISO 4406:2021. In the final measurement stage, oil samples were analyzed using inductively coupled plasma optical emission spectrometry (ICP-OES). The samples were decomposed

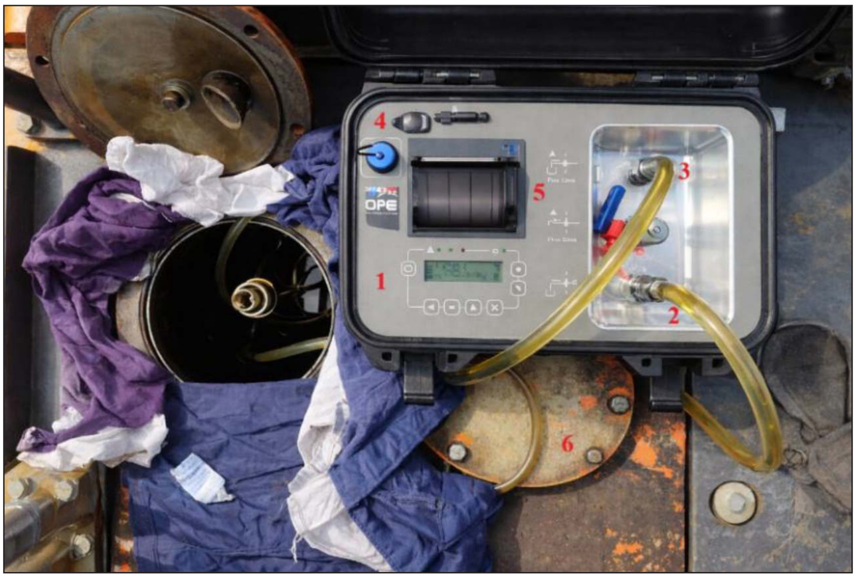

Figure 2. Method of conducting tests directly on the excavator: 1 – top side with control panel, 2 – suction line internal pump, 3 – drainage of oil into the tank, 4 – charger connection, 5 – printer, 6 – excavator oil tank

using a pressurized microwave mineralization system, employing concentrated mineral acids. Thanks to the spectrometer's "Full Frame Imaging" capability, the entire emission spectrum of each oil sample was recorded, also referred to as the "spectral fingerprint" of the sample. The emission signals of the elements present in the oil were analyzed, and a qualitative assessment of the oil condition was conducted. The study used an iCAP 7400 + MFC DUO (Thermo) emission spectrometer, which features Echelle-type optics and a CID (Charge Injection Device) matrix semiconductor detector. It is characterized by an extended spectral range from 166 nm to 847 nm and high resolution. The adopted research methodology made it possible to track changes in oil parameters depending on the number of excavator operating hours. It also enabled ongoing assessment of oil degradation. Thanks to the study, up-to-date information about the condition of the oil used in the hydraulic systems of operating excavators could be provided to relevant mine maintenance departments, ensuring the proper functioning of excavators used in very demanding mining conditions. To standardize the results of oil cleanliness measurements, the ISO 4406:2021 standard was applied to all collected samples. This standard requires cleanliness to be determined by stating the number of solid particles larger than 4 μm, 6 μm, and 14 μm present in 1 ml of the oil sample.

RESULTS

Each oil sample subjected to testing was first carefully inspected visually to determine the oil color, the presence of separate phases, larger contaminant particles, and any sediment. An attempt was also made to visually assess whether the sample contained suspensions related to oil usage (such as emulsions or aqueous solutions). To do this, each tested sample was placed in an upright position for 45 minutes. Figure 3 shows views of tested hydraulic oil samples, which were subjected to visual inspection.

As expected, the tested samples exhibited varying coloration, depending on the number of operating hours accumulated by the oil in each sample. The colors became progressively darker (up to a brownish shade) as the number of operating hours increased. This was, of course, due to the increased oil contamination, resulting from prolonged excavator operation. In one case, a sample exhibited a dark brown color, which was caused by a failure in the excavator's pump assembly. In the examined oil samples, no sediment, large solid contaminant particles, or aqueous solutions were observed. This is not surprising, considering the design of filters used in modern single-bucket excavators.

One of the most important tasks involved in analyzing the condition of hydraulic oil is the assessment of its cleanliness. In this study, the

Figure 3. View of tested hydraulic oil samples (1 – fresh oil, 2 – oil after 200 hours of operation, 3 – oil after 400 hours of operation, 4 – oil after 600 hours of operation)

evaluation of oil contamination levels was performed in accordance with the ISO 4406:2021 [14] standard:

- ISO > 4 μm – fine particles that may affect the wear of precision components in hydraulic systems, such as valves or pumps,
- ISO> 6 μm – medium-sized contaminants that may contribute to mechanical damage and friction within the system,
- ISO> 14 μm – larger particles that pose a threat to the durability of seals and working components,
- ISO > 21 μm – coarse particles that may cause serious damage to hydraulic components and disrupt system performance.

Table 3 presents the results of pilot studies of hydraulic oil used in the hydraulic systems of Doosan 380 LC-5 single-bucket excavators operating in a rock mine. The contamination level, coded according to ISO 4406:2021, and selected physicochemical parameters, such as water content, temperature, and electrical conductivity, were considered. Each of the analyzed samples – including fresh oil and oil after 200, 400, 600, and 700 hours of operation – was subjected to five measurement replicates.

As previously mentioned in the Materials and methods section, due to the very similar values of the individual parameters obtained during a given series of measurements and the small number of measurements in each series, statistical analysis of the test results was abandoned, limiting the analysis to calculating the average value of each parameter. It is worth noting that the limited number of measurements in a given series was also due to the limited time available for their completion, necessitated by the need to take the tested excavator out of service. Even without statistical analysis of the measurement results, the test results indicate clear, repeatable trends in changes in oil parameters during operation, lending credence to the interpretation of oil degradation processes under actual excavator operating conditions.

Figure 4 shows the results of hydraulic oil contamination level studies after approximately 600 hours of system operation. During this period, a significant increase in the rate of solid particle accumulation was observed (particularly in the smallest fractions), indicating an intensification of tribological wear processes and a reduction in filtration effectiveness in the later stage of operation.

After measuring the size and number of contaminant particles in the collected oil samples, the basic parameters of the used oil were then analyzed. Similar to the particle contamination measurements, these tests were conducted for all collected samples in three measurement series and included the measurement of the following parameters:

- temperature of the tested oil (T),
- dielectric constant (ε) and electrical conductivity (C) – indicators of changes in the physicochemical composition of the oil and possible presence of contaminants,
- relative humidity (RH) – a key indicator of water presence in the tested oil (Table 4).

The conducted measurements of the size and number of contaminant particles in the collected hydraulic oil samples enabled an assessment of the degradation of a given oil type in a specific excavator, depending on the number of operating hours. Figure 5 shows an example of the increase in the number of contaminant particles of various sizes in Hydrol L-H 46 oil, used in the hydraulic system of

Table 3. The amount of contamination for different oil operating times

No.	Particle content				IS0 code	Humidity RH [%]	Temperature T [°C]	Conductivity C [ps/m]	Comments
	4 μm [p/ml]	6 μm [p/ml]	14 μm [p/ml]	21 μm [p/ml]					
1.	2610	766.4	76.31	17.1	19/17/14	26.2	26.7	352	Fresh oil – 0 h
2.	2510	632.9	36.99	17.3	19/16/14	26.3	26.1	350	
3.	2412	634.3	45.85	17.5	18/16/14	26.5	26.1	354	
4.	2640	635.1	48.54	18.4	19/16/14	26.6	26.2	355	
5.	2545	636.5	49.26	17.9	19/16/14	26.6	26.5	356	
6.	4488	970.8	106.6	32.93	19/17/14	31.2	26.7	364	200 h
7.	4786	1163	139	33.1	19/17/14	31.3	26.7	378	
8.	4791	1134	125.5	32.98	19/17/14	31.6	26.9	390	
9.	4796	1142	128.4	33.12	19/17/14	31.6	26.8	389	
10.	4825	1139	130.1	33.09	19/17/14	31.8	26.8	391	
11.	7521	2110	133.2	65.88	20/18/14	38.3	28.4	405	400 h
12.	7312	2285	132.1	66.93	20/18/14	38.4	28.1	401	
13.	7523	2265	136.3	66.84	20/18/14	38.1	28.7	403	
14.	7505	2283	137.2	65.95	21/18/14	38.2	28.6	405	
15.	7526	2274	136.9	66.65	21/18/14	38.2	28.7	405	
16.	13111	3155	184.5	73.02	21/19/14	45.3	27.9	415	600 h
17.	13213	3205	179.3	73.05	21/19/14	45.7	27.8	426	
18.	13421	3214	185.2	74.02	21/19/14	44.7	27.8	416	
19.	13468	3211	186.4	73.61	21/19/15	44.8	27.6	418	
20.	13456	3224	188.2	73.50	21/19/15	44.8	27.7	421	
21.	22653	3749	213.6	87.37	22/19/15	56.7	28.3	452	700 h
22.	22522	3732	214.4	88.38	22/19/15	56.8	28.4	463	
23.	23133	3749	213.3	88.53	22/19/15	56.9	28.6	446	
24.	22958	3756	214.8	88.54	22/19/15	56.8	28.3	468	
25.	22895	3757	214.2	88.52	22/19/15	57.0	28.5	472	

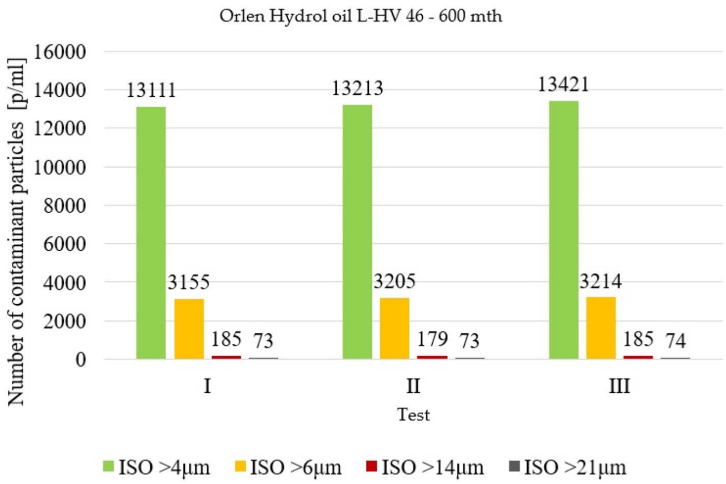

Figure 4. Number of particles by size category in hydraulic oil used over a period of approximately 600 operating hours

a Doosan 380 LC-5 excavator. Upon analyzing this figure, it is important to note that the increase in the number of contaminant particles in the oil pertains only to particles smaller than 4 micrometers and 6 micrometers. No particles larger than 14 or 21 micrometers were detected in the oil. This is due

Table 4. Selected measurement results for the above parameters in oil samples taken from an excavator's hydraulic system after approximately 600 operating hours

Parameter	Sample I	Sample II	Sample III	Unit
Temperature [T]	27.9	27.8	27.8	[°C]
Electrical permittivity [e]	2.227	2.295	2.240	-
Conductivity [C]	415	426	416	[pS/m]
Humidity [RH]	45.3	45.7	44.7	[%]

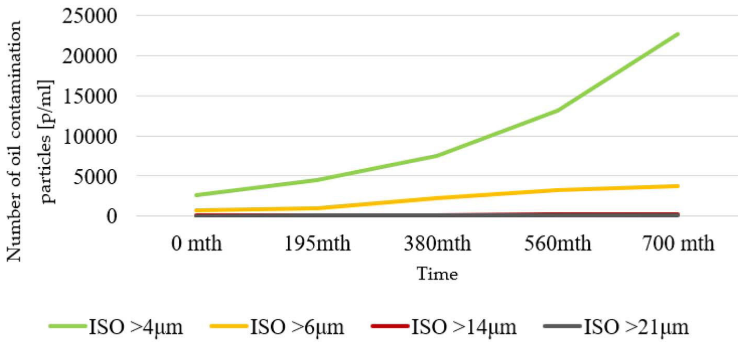

Figure 5. Trend of contaminant particle increase in hydraulic oil used in the Doosan 380 LC-5 excavator

to the efficient operation of the oil filters installed in the excavator's hydraulic system, which effectively clean the oil during its circulation.

The graphs presented above help to understand the recommendation to change the oil in excavators operating in rock material mines after approximately 700–800 operating hours. This is evidenced by a significant increase in the number of particles smaller than 4 micrometers, which occurs after 700 operating hours. The cause of this condition is the fact that excavators are often used as carriers for hydraulic hammers and are exposed to variable dynamic loads during loading of the excavated material onto transport vehicles, as well as during cleaning of the excavation floor and walls. In the final stage of the study, the chemical composition of the oil from the collected samples was analyzed. Sample results of elemental analysis (for micro-contaminants detected in concentrations above 0.0001% w/w of the sample mass) are presented in tabular form (Table 5). The analyses revealed a significant increase in

Table 5. Sample results of the chemical composition analysis of oil from collected samples

Marked parameter	Tested oil sample			
	1 Lab code BAZ-67 / fresh oil – 0 h [ppm]	2 Lab code BAZ-68 / 200 h [ppm]	3 Lab code BAZ-69 / 400 h [ppm]	4 Lab code BAZ-70 / 600 h [ppm]
Sulfur (S)	530	550	540	530
Zinc (Zn)	300	290	290	270
Phosphorus (P)	230	220	220	210
Calcium (Ca)	39	31	48	100
Magnesium (Mg)	30	18	19	19
Sodium (Na)	10	12	10	19
Aluminum (Al)	1.3	1.0	1.6	2.7
Copper (Cu)	6.8	10	10	12
Iron (Fe)	3.1	3.4	4.4	6.6
Potassium (K)	2.5	1.0	1.5	18
Selenium (Se)	1.5	1.9	2.2	2.0
Lead (Pb)	1.1	1.4	1.5	1.5

particles of iron (Fe), copper (Cu), and calcium (Ca), which undoubtedly suggests the possibility of failure after about 600 operating hours of the hydraulic system. Comparing the results obtained with the OPCom Portable Oil Lab analyzer and the ICP-OES spectrometer, iCAP 7400+ MFC DUO (Table 5), the effects of chemical reactions occurring in the oil can also be observed after just 400 operating hours of the hydraulic system.

CONCLUSIONS

The main aim of the research presented in this article was to determine the course and nature of the hydraulic oil degradation process as a function of the operating time of single-bucket excavators used under actual conditions prevailing in rock resource quarries. The values of the hydraulic oil parameters characterizing its degradation process, obtained as a result of the conducted research, allowed a range of conclusions to be drawn and their consistency with the conclusions presented in the literature to be compared. The authors would like to emphasize that the conducted research was of a pilot nature and constitutes the first national attempt to determine the course of hydraulic oil degradation processes in single-bucket excavators operating in rock material mines. In subsequent stages of the research, studies are planned that will allow detailed determination of the course of hydraulic oil degradation in excavators, depending on the nature of their work.

From the conducted research, the following conclusions can be drawn:

1. The process of hydraulic oil degradation in the hydraulic systems of single-bucket excavators used in underground mining is nonlinear. Under the examined excavator operating conditions, a noticeable acceleration of the hydraulic oil degradation process (increase in the amount of solid contaminants) was observed after approximately 600 hours of excavator operation, as indicated by the change in parameters characterizing oil wear.
2. The dominant factor affecting the degradation time of hydraulic oil is the increase in its contamination with solid particles smaller than 6 μm. The number of these particles increases with the excavator operating time, from a value of 2412 p/ml for fresh oil to 23133 p/ml after 700 h of operation of the excavator’s hydraulic system. This indicates relatively intensive tribological wear of the components of the excavator’s hydraulic system and has a key impact on the deterioration of hydraulic oil properties. The significant increase in the number of solid contaminant particles observed in the studies, particularly those smaller than 6 μm.
3. In the tested hydraulic oil, no significant increase in contamination by solid particles larger than 14 μm was observed during the entire excavator operation period. This fact indicates that the standard filtration systems used in excavator hydraulic systems effectively retain solid contaminants of larger sizes. Unfortunately, their effectiveness against contaminant particles smaller than 6 μm is completely ineffective.
4. Based on the conducted research, a significant increase in the water content in the hydraulic oil was observed, from about 26% for fresh oil to 57% for oil after 700 hours of hydraulic system operation. Such a substantial increase in water content may result in intensified oil oxidation processes, deterioration of the oil’s lubricating properties, and an increased risk of hydraulic system component corrosion.
5. The increase in the electrical parameters of hydraulic oil, defined by its conductivity and permittivity, constitutes an important indicator of the degradation of the oil being examined. The increase in the electrical conductivity of the oil observed as a result of tests by about 30%. It is worth emphasizing that the values of the electrical parameters of hydraulic oil are treated as a sensitive indicator of the increase in oxidation products of the oil components and the degradation of its performance additives.
6. The analysis of the elemental composition of the oil, especially regarding the presence of Fe and Cu elements does not indicate the occurrence of emergency conditions after approximately 600 h of the excavator’s hydraulic system operation. The amounts of Fe and Cu particles indicate that they correspond to the processes of normal wear of the tribological elements of excavator hydraulics.
7. The operating conditions of single-bucket excavators used in rock mining have a significant impact on the acceleration of the oil degradation process in their hydraulic systems. Dynamic loads acting on the excavator during ore loading, wall breakage, floor leveling, and frequent use of the excavator as a carrier for hydraulic hammers, cause a considerable

acceleration of the hydraulic oil degradation process compared to the hydraulic oil degradation process in single-bucket excavators used for standard earthworks. Additionally, it should be noted that the speed of the oil degradation process in excavators used in rock raw material mines is also influenced by variable mining and geological conditions, the nature of the deposit occurrence and the method of its exploitation, as well as the technological routes along which the excavator moves. In this regard, it should be stated that stone mining operations, in which single-bucket excavators are used, should be considered particularly unfavorable from the perspective of the hydraulic oil degradation process. This means that it is necessary to use shortened intervals for hydraulic oil replacement and to implement monitoring of its condition during excavator operation.

8. Based on the assessment of the hydraulic oil cleanliness class according to ISO 4406, its deterioration was noted from a level of 19/17/14 to 22/19/15 after 700 hours of hydraulic system operation. This change, as previously mentioned, indicates a significant increase in the number of contaminant particles in the oil, particularly in the range of the smallest fractions (<6 μm).
9. According to the authors, the optimal oil change interval under the operating conditions of the tested excavator should be a maximum of 700 operation hours, which is considerably shorter than the operating time of the oil recommended by the hydraulic oil manufacturer, which is 1200 hours. This is another confirmation of the guidance that can be found in the literature, indicating that under so-called severe duty conditions, the service life of hydraulic oil may be significantly shorter than the value recommended by the manufacturer of the work machine.
10. From the perspective of the efficiency of research on the oil degradation process under actual machine operating conditions, short-term monitoring of the oil condition constitutes a more reliable method for assessing the current state of hydraulic oil than an approach based on fixed time intervals. This method of studying the condition of hydraulic oil, referred to as a condition-based maintenance (CBM) strategy, enables the precise time for oil change to be determined.

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