

Results of motor oil quality indicator evaluation during operation of mining dump trucks

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Abstract: The primary objective of this study is to investigate the operational characteristics of motor oils used in the engines of mining and transportation equipment. Experimental research was conducted on the performance of SAE 15W-40 motor oil employed in QSK-60 diesel engines operating under heavy-duty conditions. BELAZ-75310 and BELAZ-75307 mining dump trucks are designed for transporting loosened rock mass along technological roads in open-pit mining operations under various climatic conditions. The study focused on key physicochemical properties of the oil—such as viscosity, total base number, and flash point—which directly affect its operational performance. To determine the characteristics of used oil, spectral analysis was carried out. Laboratory physicochemical and spectral analyses were performed according to standardized methodologies. The results revealed that the used oil primarily contains wear products, with specific elements indicating the wear of corresponding engine components: aluminum (Al) reflects piston wear, chromium (Cr) indicates wear of chromium-coated piston rings, iron (Fe) corresponds to cylinder liner wear, and lead (Pb) signifies bearing wear. Silicon (Si) represents atmospheric dust, while molybdenum (Mo) is associated with the degradation of additives. Elevated iron concentrations indicate an intensification of wear processes. To achieve the research objective, SAE 15W-40, API CI-4 oil samples were collected from QSK-60 engines installed in BELAZ dump trucks operating at the Navoi Mining and Metallurgical Combine. These samples were analyzed for key quality indicators.

INTRODUCTION

BELAZ mining dump trucks, as the primary mode of transport within open-pit working zones, are particularly exposed to increasingly complex mining and geological conditions as the depth of extraction grows. These dump trucks are designed for transporting loosened rock mass along technological roads in open-pit mines under a wide range of climatic conditions.

During engine operation, the condition of motor oil is influenced by numerous factors, including climatic and road conditions, speed and load regimes, driving quality, fuel system calibration, the technical state of the cylinder-piston group, and the efficiency of filtration elements. All these factors act simultaneously, leading to the accumulation of oxidation products and mechanical contaminants in the oil. The buildup of impurities accelerates the depletion of additives, which in turn causes the deterioration of oil performance and reduces engine durability [1-2].

Understanding the behavior and changes in the operational properties of motor oil allows for its more efficient use in engines and provides a scientific basis for determining optimal oil change intervals. This becomes particularly critical for motor oils used in heavy-duty mining and transport equipment operating in high-dust environments.

BELAZ dump trucks are specifically engineered to transport rock mass in challenging geological and technical conditions of deep open-pit mines, along technological roads, and under diverse climatic conditions, with ambient temperatures ranging from -50°C to $+50^{\circ}\text{C}$. Studies have shown that engine failures account for approximately

29% of the total downtime of BELAZ dump trucks, directly increasing operating costs and reducing productivity. Since their power units lack redundancy, the failure of a single component or assembly can result in the complete shutdown of the vehicle [3-5].

The physicochemical properties of in-service oil can serve as diagnostic parameters that make it possible to evaluate the technical condition of the engine without disassembly, as well as to assess the potential for further reliable operation over a given service period.

Therefore, the general approach to selecting the most significant oil quality indicators involves determining their capacity to assess the intensity of impurity accumulation and additive depletion.

The key criteria for evaluating the suitability of used engine oil for continued operation are its influence on wear rate, lacquer and deposit formation inside the engine. The most critical factors affecting the wear rate of major engine components and deposit formation are the concentration of insoluble contaminants, the depletion of detergent-dispersant additives, and the accumulation of oxidation products.

MATERIALS AND METHODS

The purpose of this study is to investigate the operational characteristics of API CI-4, SAE 15W-40 motor oil used in diesel engines operating in heavy-duty mining and transport equipment. Compliance with API CI-4 requirements ensures that this oil is suitable for use in high-speed, four-stroke diesel engines functioning under severe operating conditions in BELAZ mining dump trucks and other specialized machinery. It is specifically formulated to withstand the harsh operational environments and demanding load conditions of such equipment.

When the oil is used at elevated ambient temperatures exceeding +40 °C, specific failures are observed, primarily caused by the deterioration of its physical and mechanical properties due to increased crankcase oil temperatures. Once the oil temperature in the crankcase exceeds 120 °C, its viscosity decreases, and it can no longer form a reliable lubricating film on friction surfaces or maintain hydrodynamic lubrication in bearings. This leads to accelerated wear of engine components. Furthermore, with every additional 10 °C increase in oil temperature, the oxidation rate doubles, and oil consumption due to evaporation rises significantly. When oil temperatures exceed 190–200 °C, flash and combustion may occur, posing a serious operational hazard [6-8].

To establish a reference baseline, fresh API CI-4, SAE 15W-40 motor oil used in diesel engines of heavy-duty mining equipment was analyzed. Laboratory physicochemical and spectral analyses were performed in accordance with standardized methodologies. Experimental data on the quality indicators of the fresh API CI-4, SAE 15W-40 motor oil are presented in Table 1

TABLE 1. Quality Indicators of Fresh Motor Oil—API CI-4, SAE 15W-40

Oil Brand	Density at 20°C, kg/m ³	Kinematic Viscosity at 100 °C, cSt	Flash Point (Open Cup), °C	Total Base Number, mg KOH/g
SAE15W-40, API CI-4	886,0	15,3	224	10,2

RESULTS AND DISCUSSION

Analyzing the causes of changes in individual physicochemical indicators of used motor oil reveals that each parameter responds sensitively and consistently to specific external malfunctions in the engine's components and systems.

Many of these indicators are closely interrelated. For example, an increase in the content of insoluble residues leads to a rise in oil viscosity. A low flash point indicates dilution of the oil with fuel, which in turn results in decreased viscosity. An increase in iron and other metal concentrations in the oil causes higher acidity and a greater amount of mechanical impurities, which again leads to increased viscosity, among other effects.

For engine diagnostics, it is generally recommended to determine the following oil parameters: kinematic viscosity, flash point, total base number (TBN) and total acid number (TAN), water content, impurity levels, density, and oil color. A comprehensive analysis of these indicators enables relatively quick and reliable assessment of the engine's technical condition without the need for disassembly [9-10].

During the operation of monitored vehicles, samples of fresh, in-use, and used oil were collected and analyzed with recorded mileage. For diagnostics of individual components and assemblies, oil samples of 0.3–0.5 liters were taken. The study focused on key physicochemical properties — kinematic viscosity, total base number, moisture content, and flash point (open cup) - which have the greatest influence on the operational performance of the oil [11-12].

As can be seen from the table, deviations in the quality indicators—such as viscosity, total base number, and flash point—became significant once the operating time of the dump truck exceeded 200 engine hours. Viscosity represents the ability of oil to adhere to internal engine surfaces and retain its key physical and chemical properties. For this reason, it is one of the primary parameters used to assess oil quality. Viscosity is temperature dependent: if it becomes too low at elevated temperatures, the strength of the oil film between friction pairs and the pressure in the lubrication system will be insufficient, resulting in increased wear of friction surfaces. Conversely, excessive viscosity at low temperatures may prevent the starter from cranking the engine.

TABLE 2. Experimental data on the quality indicators of used motor oil — SAE 15W-40, API CI-4

Dump truck operating time, h	Oil operating time, h	Flash point, °C	Kinematic viscosity at 100 °C, cSt	Total base number, mg KOH/g	Fe concentration, ppm
6620	50	213	14,87	9,29	7,56
6765	125	214	14,38	9,14	8,38
6870	198	210	14,34	9,11	8,53
6938	278	209	14,04	8,86	9,84
Oil change at 278 engine operating hours					
6955	17	214	14,49	9,05	9,25
7105	167	207	14,40	8,97	9,29
7212	274	205	14,24	8,96	9,14
Oil change at 274 engine operating hours					
7270	58	213	14,18	8,79	11,79
7490	228	206	14,10	8,27	12,24
7501	298	203	14,24	7,91	12,78
Oil change at 298 engine operating hours					
7540	39	214	13,64	9,11	12,90
7660	159	210	14,10	8,86	13,56
7765	264	201	13,93	8,01	15,30
Oil change at 264 engine operating hours					
7805	40	213	14,68	8,27	5,01
7963	128	210	14,57	8,69	7,56
8120	285	205	14,40	7,14	8,38
Oil change at 285 engine operating hours					
8398	55	215	14,34	8,76	8,53
8556	125	212	14,25	8,48	10,15
8668	278	204	13,14	8,42	12,84
Oil change at 278 engine operating hours					
8720	48	214	14,14	7,28	5,01
8850	153	210	14,26	6,89	9,56
8930	295	195	13,15	6,56	10,38
Oil change at 295 engine operating hours					

During operation, the viscosity of the oil decreased to 13.15 cSt. This change affects the oil's performance, increases wear in the cylinder-piston group, and indirectly reflects the level of organic contamination. Such behavior is typically caused by changes in the structural-group composition of the oil and fuel dilution. The accumulation of oxidation products also significantly impacts the viscosity characteristics of lubricating oils.

Flash point is an important indicator of the presence of distillate fuel fractions in the oil. It decreases when unburned fuel enters the lubrication system due to leakage or incomplete combustion. For in-service oils, the critical

flash point limit is 170–180 °C. For high-viscosity oils with an initially higher flash point, the allowable decrease is 40–50 °C. The entry of just 1% gasoline into the oil lowers the flash point from 200 °C to approximately 170 °C, while 6% gasoline nearly halves it. Dilution of oil with fuel sharply reduces its anti-wear properties, accelerating deposit and lacquer formation on pistons.

In this study, the flash point dropped to 195 °C, approaching the rejection threshold, indicating the need for oil replacement to prevent reduced engine reliability.

Another critical parameter of oil quality and performance is total base number (TBN)—a key indicator of additive depletion. TBN reflects the oil's capacity to neutralize acids formed during fuel combustion and base oil oxidation. Alkalinity, provided by basic additives, is consumed at varying rates during acid neutralization. The end of oil service life is often defined as the point when TBN equals the total acid number (TAN). The permissible TBN value is typically 1.5–2.0 mg KOH/g, corresponding to 50% of the TBN of fresh oil.

Operating an engine with oil below this TBN threshold accelerates piston ring and cylinder wear and can intensify lacquer and deposit formation. A low TBN also increases the risk of corrosion and failure of vulnerable engine parts, especially crankshaft bearing shells. TBN also provides insight into additive depletion and the oil's ability to resist corrosive attack.

In long-term use, initially added additives may be fully depleted during the neutralization of acids such as carboxylic acids. However, their neutralization products (salts) continue to contribute to the oil's alkalinity, sometimes temporarily increasing TBN.

Motor oil must maintain sufficient alkalinity to preserve detergent properties, neutralize acids, and suppress corrosion. The higher the TBN, the more acidic by-products can be neutralized during oxidation and combustion. Otherwise, these acids accelerate corrosion and deposit formation. In this study, TBN decreased from 9.31 to 6.56 mg KOH/g during operation.

The service life of the oil is determined primarily by its detergent properties, which are crucial in preventing contamination due to oxidation on hot engine surfaces. Under steady-state diesel operation, the depletion rate of TBN is proportional to fuel consumption [9].

The key criteria for assessing the suitability of used oil for continued engine operation remain its effect on wear rates, lacquer and deposit formation. As shown above, the most influential factors are the concentration of insoluble contaminants, depletion of detergent-dispersant additives, and accumulation of oxidation products.

An analysis of lubricant aging patterns shows that the concentration of mechanical impurities reaches its critical limit faster than other parameters. The level of contamination depends on external factors, such as dustiness of the work site. Mechanical impurities accumulate in the oil as a result of airborne dust ingress through the intake system or crankcase leaks, as well as through the formation of insoluble oxidation and wear products [10].

The most intensive accumulation of mechanical impurities typically occurs during the first 100–150 engine hours, after which the process stabilizes as an equilibrium is reached between contamination and removal through filtration systems (filters, centrifuges).

To study the effect of air dust concentration on engine component wear, an experimental investigation was conducted on three BELAZ dump trucks (models 7513, 75307, and 75310) operating in open-pit conditions. The sampling interval corresponded to approximately 1800–2000 kg of consumed fuel. From each warmed-up engine, 150 ml of oil was periodically collected for analysis.

A widely used diagnostic technique for assessing engine wear involves determining iron concentration in the oil. Spectral analysis was performed to evaluate the Fe content in API CI-4, SAE 15W-40 motor oil from BELAZ dump trucks with QSK-60 engines over time (Fig. 1).

The degree of wear of engine components can be monitored by analyzing the concentration of wear products in the oil. Figures 1, 2, and 3 present the results of the spectral analysis of the elemental composition of wear particles in SAE 15W-40 oil as a function of operating time in the dump truck engines.

The analysis of the research results shows that the average concentration of iron in the oil increases over the course of operation. Elevated iron content indicates an intensification of wear processes. As the iron concentration in the oil rises, the frictional, anti-wear, antioxidant, and detergent properties of the oil deteriorate. This degradation is a direct consequence of disruptions in the lubrication regime of friction pairs, which leads to increased loads and temperatures in contact zones.

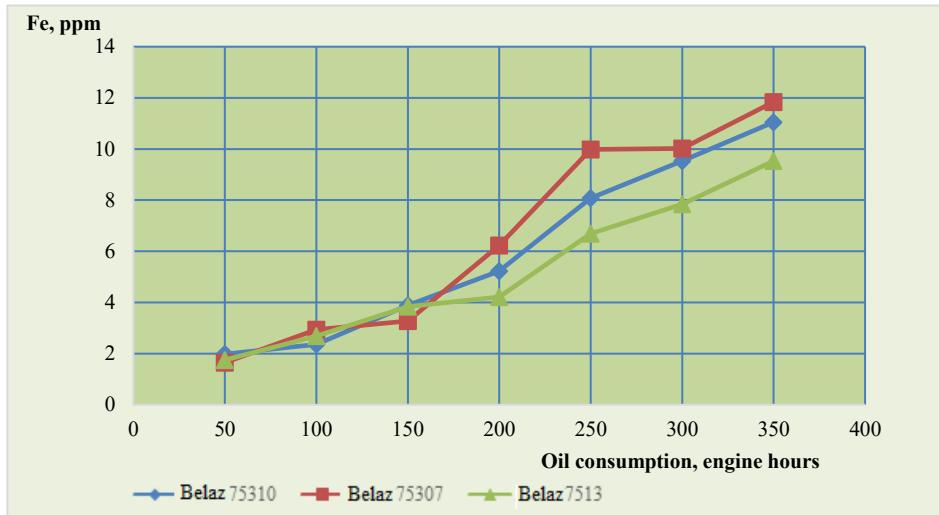


FIGURE 1. Dependence of iron (Fe) concentration in used motor oil on the operating time of dump trucks (engine hours).

The elevated iron content not only reflects intensified wear but also has a negative impact on the reliability, efficiency, and durability of engine performance. Iron concentration is an important indicator of the oil's anti-wear characteristics, their changes over time, the wear resistance of engine components, and the efficiency of filtration and cleaning systems integrated into the lubrication circuit.

As the iron content increases, the oil's functional properties—such as its ability to reduce friction, prevent wear, resist oxidation, and keep engine components clean—deteriorate further. This is the result of inadequate lubrication in high-friction zones, leading to increased mechanical and thermal stress on components.

The detergency and dispersancy of modern oils—the ability to remove and hold contaminants in suspension—are among their most critical functional properties. Reliable long-term engine operation is possible only when internal components remain clean. In particular, the piston ring grooves must remain free of deposits to preserve ring mobility; the pistons themselves must stay clean to ensure effective heat transfer; and the oil channels, valve train, camshaft lobes, and other friction surfaces must remain free of sludge and varnish.

To identify the most failure-prone components, used SAE 15W-40 motor oil from QSK-60 engines of BELAZ-75310, BELAZ-75307, and BELAZ-7513 dump trucks was subjected to spectral analysis. This made it possible to evaluate the elemental composition of wear products and assess which components were contributing most to iron accumulation in the oil.

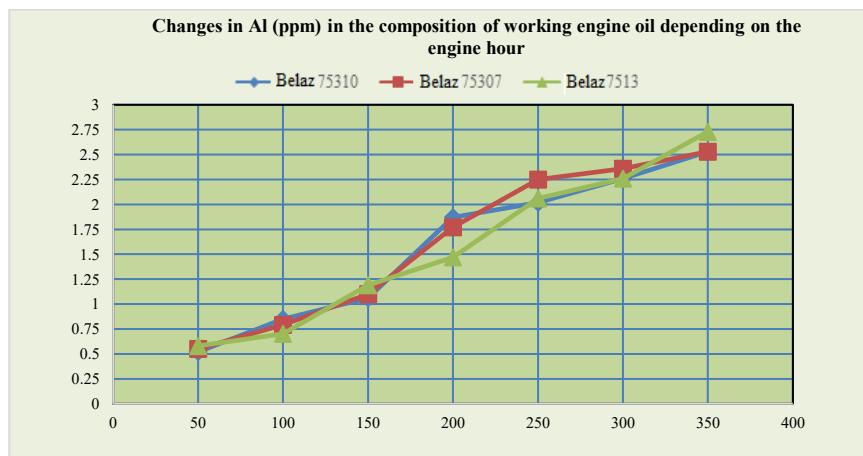


FIGURE 2. Results of spectral analysis of aluminum (Al) content in used motor oil — API CI-4, SAE 15W-40.

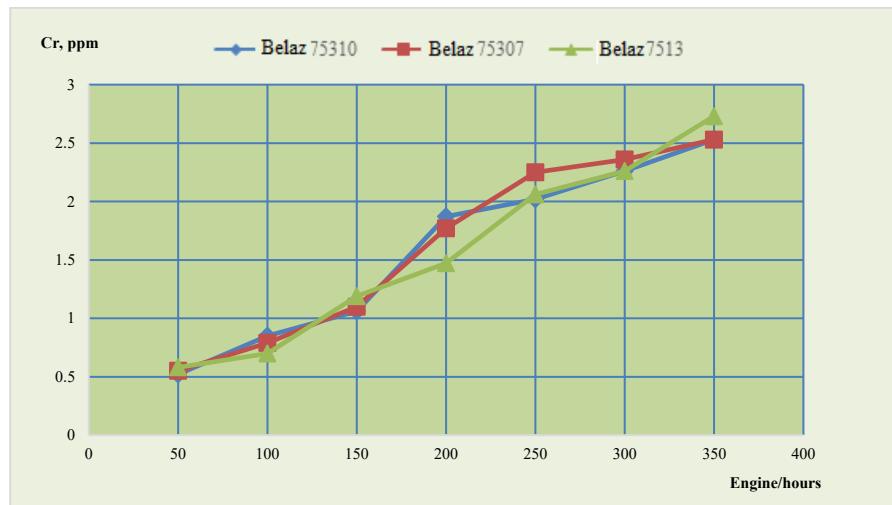


FIGURE 3. Dependence of chromium (Cr) concentration in used motor oil — API CI-4, SAE 15W-40 — on the operating time of dump trucks (engine hours).

A significant increase in the concentration of a particular element in the oil indicates intensive wear of the engine components associated with that element.



FIGURE 4. Dependence of lead (Pb) concentration in used motor oil — API CI-4, SAE 15W-40 — on the operating time of dump trucks (engine hours).

The concentration of specific elements in the oil provides valuable diagnostic information about engine component wear. In particular, aluminum (Al) indicates piston wear, chromium (Cr) reflects the wear of chromium-coated piston rings, and lead (Pb) corresponds to bearing wear.

The intensive accumulation of mechanical impurities during the initial period of oil operation is primarily caused by the oxidation of low-stability hydrocarbons throughout the lubrication system. According to experimental data, mechanical impurities have the most significant impact on engine component wear rates. When their concentration reaches 0.016%, the wear rate is, on average, four times higher compared to operation with clean oil.

The main factor contributing to the formation of high-temperature deposits in engines is oxidation, which occurs both within the oil volume and on metal surfaces. These deposits negatively affect engine reliability, efficiency, and service life.

Currently, further research is being conducted on the effect of the type and concentration of additives on the performance of motor oils used in heavy-duty mining equipment operating under conditions of high airborne dust concentration.

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