**Results of Evaluating the Quality Indicators of Motor Oils during Operation in the Engines of Quarry Dump Trucks**

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Abstract: The purpose of this research is to analyze the performance properties of engine oils applied in mining transport machinery engines. Experimental investigations were carried out on the 15W-40 lubricating oil employed in QSK-60 diesel power units operating under severe mining conditions. The BELAZ-75310 and BELAZ-75307 quarry dump trucks are engineered to haul loose rock materials on technological routes within open-pit mining sites, functioning efficiently across diverse climatic environments. The study focused on evaluating the key physicochemical parameters of the lubricant—such as viscosity, total base number, and flash point—which determine its performance behavior. Investigations of lubricating oil degradation under high-temperature and dust-intensive conditions have revealed that oils are rapidly polluted by solid particles, moisture, fuel residues, and oxidation products, resulting in accelerated aging processes. To accomplish the research objectives, samples of SAE 15W-40 motor oil (API CI-4), applied in QSK-60 engines of BELAZ trucks operating at the “Navoi Mining and Metallurgical Combine,” were collected and analyzed for their primary quality indicators. To evaluate the condition of the used lubricant, the motor oil samples underwent spectral examination. Laboratory investigations, including physicochemical and spectrometric analyses, were performed in accordance with standardized procedures.The obtained results demonstrated that the degraded oil contained several metallic wear elements: aluminum (Al) corresponding to piston wear; chromium (Cr) associated with deterioration of chrome-coated piston rings; iron (Fe) linked to cylinder liner abrasion; and lead (Pb) indicating bearing erosion. Additionally, the presence of silicon (Si) reflected atmospheric dust ingress, while molybdenum (Mo) signified additive degradation products. An elevated concentration of iron suggested an acceleration in engine wear processes.

**Keywords:** motor oil, oxidation, lubricating oil contamination, deposit formation process, high-temperature deposits, oxidation products, durability, air dustiness.

# INTRODUCTION

BELAZ dump trucks, operating as the primary transport vehicles within quarry work zones, are exposed to increasingly challenging mining and technical conditions that intensify with greater excavation depth. These heavy-duty trucks are engineered to move fragmented rock material along technological routes in open-pit mining environments characterized by variable climatic influences.

During engine operation, numerous factors contribute to the alteration of oil condition, including environmental and road factors, variations in engine load and speed, driving habits, fuel system calibration, the state of the cylinder–piston assembly, and the effectiveness of filtration components [1]. The combined effect of these influences promotes the build-up of oxidation by-products and solid contaminants within the lubricant. Such accumulation depletes additive reserves, thereby degrading the oil’s functional properties and ultimately shortening engine service life.By understanding the regularities of the behavior and change of the operational properties of motor oil, it is possible to use it more effectively in engines and scientifically justify the intervals for its replacement. Special attention is given to the operating conditions of motor oils in engines of heavy-duty mining transport equipment in environments with high air dust levels [2,3].

BELAZ quarry dump trucks are engineered to transport rock materials under demanding mining and technical conditions characteristic of deep open-pit operations. These vehicles function on technological haul roads within mineral extraction sites and maintain efficiency across a wide range of ambient temperatures, from −50 °C to +50 °C. Studies indicate that engine-related failures of BELAZ dump trucks account for approximately 29% of the total downtime, directly increasing maintenance expenses and decreasing overall productivity. Since the power units of these trucks lack redundant subsystems, the malfunction of even a single component can result in the complete inoperability of the machine [4,5].

The physicochemical parameters of in-service lubricants can act as diagnostic criteria, enabling the assessment of engine condition without the need for disassembly. Such diagnostics make it possible to evaluate not only the current technical state of the equipment but also its projected reliability over continued operation [6].

Therefore, the comprehensive method for identifying the most informative oil quality indicators focuses on their capability to characterize impurity accumulation and additive depletion rates.

Table 1 presents the lubricant performance indicators used to evaluate these changes. As shown, oil contamination and additive degradation can be quantified through several parameters; hence, it is essential to determine those with the greatest diagnostic significance.

**TABLE 1.** The preliminarily selected oil quality indicators.

|  |  |
| --- | --- |
| Reasons for changes in oil quality. | Oil quality indicators. |
| Oil contamination with mechanical impurities (C). | Silicon content (Si). |
| Insoluble impurities (IP). |
| Optical density (A). |
| Ash content (3). |
| Content of wear products (Si). |
| Additive wear (Sp). | pH value (pH). |
| Dispersing ability (DS). |
| Contamination with oxidation products of the oil. | Kinematic viscosity (v). |
| Density (ρ). |

Studies of lubricant contamination in engines powering heavy-duty mining machinery operating under hot climatic conditions—where summer temperatures can exceed +50 °C and airborne dust concentrations are high—have revealed that motor oils become rapidly polluted with solid particles, moisture, unburned fuel residues, and oxidized organic compounds. Such contamination accelerates oil degradation and leads to premature deterioration of its functional characteristics [7,8].

The elevated thermal loads on turbocharged engine components exposed to motor oil, combined with the infiltration of combustion gases into the crankcase (reaching temperatures of about 500–700 °C during compression), significantly aggravate operating conditions.

The primary criteria determining the continued serviceability of lubricants in internal combustion engines include their influence on component wear, varnish film formation, and deposit accumulation. Among the most critical factors affecting wear intensity and deposit generation are the concentration of insoluble contaminants, depletion of dispersant additives, and accumulation of oxidation by-products [9, 10].

# MATERIALS AND METHODS

The aim of this work is to study the operational characteristics of motor oil API CI-4, SAE 15W-40, used in diesel engines of heavily loaded mining transport equipment. Compliance with the API CI-4 requirements is intended for use in high-speed four-stroke diesel engines operating under heavy-duty conditions in BELAZ quarry dump trucks and special equipment. It has been developed with consideration for their harsh operating conditions and working regimes.

When the oil is used in high ambient temperatures (above +40°C), specific failures occur, caused by the deterioration of the physicochemical properties due to the increase in oil temperature in the engine crankcase. When the oil temperature in the crankcase exceeds 120°C, the oil loses its viscosity and is unable to form a reliable film on the friction surfaces, as well as provide hydrodynamic lubrication in the bearings, which also leads to increased wear. Furthermore, a further increase in oil temperature by 10°C doubles the oxidation rate, and significantly increases oil consumption due to burning. An increase in oil temperature above 190-200°C can provoke its flash and combustion.

To achieve the stated goal, samples of motor oil API CI-4, 15W-40 from the QSK-60 engine of the BELAZ-75307 dump truck operating at the "Navoi Mining and Metallurgical Complex" were collected and analyzed based on the main quality indicators.

The main criteria for determining the quality of oils and their suitability for use in automotive transport and technological equipment were:

• No emergency stoppages during the operation of vehicles and technological equipment using the tested oil throughout the entire testing period.

• No negative impact of the oil on the operation and condition of the internal combustion engine (determined through spectral and physicochemical analysis).

• The actual oil service life corresponds to the established regulated oil change interval in the internal combustion engine.

Preliminary testing was conducted on fresh motor oil API CI-4, 15W-40, used in diesel engines of heavily loaded mining transport equipment. Laboratory physicochemical and spectral analyses of the oils were conducted according to the established methodology. Experimental data on the quality indicators of fresh motor oil API CI-4, SAE 15W-40 are presented in Table 2.

**TABLE 2.** Quality indicators of fresh motor oil API CI-4, SAE 15W-40

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Oil brand | Density at 20°C, kg/m³ | Kinematic viscosity at 100°C, cSt | Flash point in an open cup, °C | Alkaline number, mg KOH/g |
| SAE15W-40, API CI-4 | 886,0 | 15,3 | 224 | 10,2 |

Results of spectral analysis (elemental composition) of active elements in fresh motor oil SAE 15W-40 from the QSK-60 engine of the BELAZ-75307 dump truck.

**TABLE 3.** Spectral analysis of fresh motor oil API CI-4, SAE 15W-40

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Sample name | Al | Cr | Fe | Pb | Cu | Ni | Si | Sn | Mo |
| Motor oil SAE 15W-40, API CI-4 | 0.52 | 0.16 | 0.13 | 0.22 | 0.05 | 0.05 | 2.38 | 0.14 | 75.30 |

According to the results of spectral analysis, the oil grade API CI-4, SAE 15W-40 contains anti-wear additives of molybdenum (Mo). In modern diesel engines, molybdenum disulfide dispersions are added to improve the anti-wear properties of motor oils under increased loads. By adding 1% molybdenum disulfide to the oils, friction and wear of the rubbing parts are reduced, primarily under boundary lubrication conditions.

**RESULTS AND DISCUSSION**

Analyzing the causes of changes in individual physicochemical indicators of the quality of working oil, it can be noted that each indicator responds adequately to the manifestation of external disturbances in the operation of engine components and systems.

At the same time, many indicators are interconnected. For example, an increase in the content of insoluble sediment leads to an increase in the oil viscosity, a low flash point indicates that the oil has been diluted by fuel, which in turn leads to a decrease in viscosity; an increase in the content of iron and other metals in the oil causes an increase in acidity and the content of mechanical impurities, and, consequently, viscosity, etc.

For engine diagnostics, it is generally recommended to determine the kinematic viscosity, flash point, alkalinity and acidity numbers, water and contamination content, density, color of the oil, etc. A comprehensive analysis of the results of these indicators allows for diagnosing the engine's condition with minimal labor input and a certain level of accuracy.

During the operation of the monitored vehicles, studies of fresh, working, and used oil samples are conducted with mileage tracking.

To diagnose the condition of individual units and aggregates, oil samples were taken in quantities of 0.3–0.5 liters. The main physicochemical properties (kinematic viscosity, alkalinity number, moisture content, flash point in an open cup) that affect the operational characteristics of the oil were studied.

**TABLE 2.** Quality indicators of fresh motor oil API CI-4, SAE 15W-40

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Dump truck operating time, engine hours | Oil operating time, engine hours | Flash point temperature, °C | Kinematic viscosity at 100 °C, cSt | Total base number (TBN), 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 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 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 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 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 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 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 hours | | | | | |

As seen from the table, deviations in quality indicators (viscosity, total base number, and flash point) became noticeable after the dump truck reached 200 m/h and beyond.

Viscosity is the ability of the oil to adhere to the surfaces of internal engine parts and maintain its fundamental chemical and physical properties. Therefore, this parameter is also selected for assessing the quality of the oil. Viscosity can change depending on the ambient temperature. If it is too low at high temperatures, the strength of the oil film between the friction surfaces and the pressure in the lubrication system will be insufficient. This will lead to increased wear of the friction pairs. Excessively high viscosity at negative temperatures can prevent the starter from turning the crankshaft. During operation, the oil viscosity decreased to 13.15. It also affects the performance of the oil and has a significant impact on the wear of the cylinder-piston group (CPG) components, as well as indirectly evaluates the contamination of the oil with organic impurities. This is related to changes in the structural-group composition and the ingress of fuel. The accumulation of oxidation products also affects the viscosity properties of the oils.

The flash point of the oil is an indicator of the presence of fuel distillate fractions in it. It changes when unburned fuel enters the oil, as well as due to fuel leaks. For operational oils, the flash point's critical value is between 170–180°C, and for high-viscosity oils with a high flash point, a decrease of 40–50°C is considered critical. When 1% gasoline enters the oil, the flash point decreases from 200°C to 170°C, and the presence of 6% gasoline in the oil reduces it by almost half. The thinning of the oil due to fuel causes a sharp deterioration in its anti-wear properties, accelerates the formation of carbon deposits, and slag formation on the pistons. As seen from the table, the flash point of 195°C is close to the rejectable value, which indicates the need for oil replacement and makes further use of this oil impossible without compromising the engine’s operational reliability."

Very important indicators of oil quality and its performance are the alkalinity and hydrogen index – the main criteria for assessing the effectiveness of additives. The total base number is a conditional measure of the oil's ability to neutralize acids formed from the combustion products of fuel and the oxidation of the oil base. Alkalinity, determined by the presence of alkaline additives, is consumed at varying rates for neutralizing acids. The limit of oil performance is often considered to be the equality of the total base number to the total acid number. The acceptable value of the total base number is limited to 1.5–2.0 mg KOH/g, or 50% of the base number of fresh oil. Operating an engine with oil having a base number lower than the limit leads to accelerated wear of the piston rings and cylinders, and sometimes intensifies lacquer and carbon deposit formation. A low base number leads to corrosion and the destruction of the most vulnerable engine components, particularly the crankshaft bearing inserts. The total base number provides useful information about the washing out of additives and shows the ability of engine oils to resist corrosion.".

In long-operating oils, initially introduced additives can be completely consumed, for example, in neutralizing carbonic acids; however, their salts (neutralization products) become carriers of alkalinity in the working oil, and the base number increases.

Motor oil must have a certain alkalinity to maintain its cleaning properties, ability to neutralize acids, and suppress corrosion processes. The higher the base number, the more acids formed during the oxidation of the oil and fuel combustion can be converted into neutral compounds. Otherwise, these acids cause corrosive wear of engine components and intensify the formation of deposits.

From the table, it can be seen that the base number during operation decreased from 9.31 to 6.56. The main criteria for the suitability of operating oil in automotive engines for further use should be its influence on the rate of wear, lacquer formation, and deposit buildup in the engine. As discussed earlier, the concentration of insoluble impurities, the effectiveness of the cleaning-dispersing additives, and the accumulation of oxidation products have the greatest impact on the rate of wear of engine components and the formation of lacquer and deposits.

By analyzing the aging patterns of lubricants during operation, it can be concluded that the concentration of mechanical impurities in motor oils reaches its limiting value the fastest."

Factors influencing the concentration of mechanical impurities in the engine oil of the engine have been identified (dustiness of the area where the equipment is operated). Mechanical impurities accumulate in the motor oil as a result of dust being drawn in with the intake air or through leaks in the crankcase, as well as due to the formation of insoluble oxidation products and the wear of cylinder-piston group components. It is believed that mechanical impurities accumulate most intensively in the motor oil during the first 100-150 engine hours of operation, after which the process stabilizes. During this period, the amount of mechanical impurities accumulating in the oil and retained by the cleaning components (filters, centrifuges) becomes constant, which determines the equilibrium state.

To study the impact of air dustiness on the operation of engine components, an experimental study was conducted on three dump trucks (BelAZ-7513, BelAZ-75307, BelAZ-75310), which were operated in a quarry for hauling rock and subjected to analysis based on key quality indicators. The dump trucks had varying operational hours. The sampling frequency was on average every 1800-2000 kg of fuel consumed. From the lubrication system of each heated engine of the dump trucks, 150 ml oil samples were regularly taken for analysis. Laboratory physicochemical and spectral analyses were conducted according to the established methodology.

Based on the results of the spectral analysis, graphs were constructed showing the dependencies of changes in insoluble mechanical impurities in the motor oil API CI-4, SAE15W-40 from the QSK-60 engine of the BelAZ dump trucks, depending on the duration of operation (Fig. 1).

**FIGURE 1.** Variation of insoluble mechanical impurities (IMI) as a function of oil operating time in engine hours.

An analysis of the research results shows that during the study period, the average content of insoluble impurities increased (Fig. 1). This has a negative effect on the reliability, efficiency, and durability of engine operation. The results showed that under relatively similar operating conditions of dump trucks, the rate of increase in insoluble impurities varied. This is explained by the fact that the rate of sedimentation of contaminating impurities differs among engines. The intensive accumulation of mechanical impurities during the initial period of oil operation is due to the oxidation of low-stability hydrocarbons throughout the entire lubrication system.

According to the results of experimental studies, mechanical impurities have the greatest impact on the rate of engine component wear. For instance, when their concentration in oil reaches 0.016%, the wear rate is, on average, four times higher compared to operation with clean oil.

To monitor the engine wear process, the method of determining iron content in the oil is widely used. Increased levels of iron indicate the intensification of wear processes. The iron content reflects the anti-wear properties of the oil and their changes during operation, the wear resistance of engine components, and the effectiveness of the filtration systems integrated into the lubrication system.

As the iron content in the oil increases, the oil’s frictional, anti-wear, antioxidant, and detergent properties change. This is a consequence of a disruption in the lubrication regime of frictional components, which in turn leads to an increase in load and temperature at contact surfaces.

For this purpose, a spectral analysis was conducted to determine the iron (Fe) content in API CI-4, SAE 15W-40 engine oil from QSK-60 engines of BELAZ dump trucks, depending on the duration of operation (Fig. 2).

**FIGURE 2.** Dependence of iron (Fe) content in used engine oil on the operating time of dump trucks (in engine hours).

An analysis of the research results shows that the average iron content increased over the study period. Elevated levels of iron indicate the intensification of wear processes. As the iron content in the oil increases, the oil's frictional, anti-wear, antioxidant, and detergent properties deteriorate. This is a consequence of the disruption in the lubrication regime of frictional components, which in turn leads to increased load and temperature at contact surfaces.

The main cause leading to the formation of high-temperature deposits in engines is oxidative processes occurring both within the oil volume and on metal surfaces. Such deposits negatively affect the reliability, efficiency, and durability of engine operation.

The ability to remove contaminants from within the engine is one of the most important characteristics of modern engine oils, as the reliable long-term operation of the engine is only possible if all of its components remain clean. The piston ring grooves must be kept clean to prevent the rings from losing mobility, the pistons themselves must remain clean to ensure proper heat dissipation, and the oil channels, valve mechanism, camshafts, and other frictional components must also be free of deposits.

To identify the most unreliable element of the system, a spectral analysis was performed on used SAE 15W-40 engine oil from the QSK-60 engine of BELAZ dump trucks models 75310, 75307, and 7513. Engine component wear can be monitored by tracking the concentration of wear products in the oil. Figures 3, 4 show the results of spectral analysis (elemental composition) of wear products in SAE 15W-40 oil depending on the duration of its operation in dump truck engines.

**FIGURE 3.** Results of spectral analysis of Al elements in used API CI-4, SAE 15W-40 engine oil

**FIGURE 4.** Dependence of Cr content changes in used API CI-4, SAE 15W-40 engine oil on the operating time of dump trucks in engine hours.

A significant increase in the concentration of a particular element in the oil indicates the intensity of wear of the components associated with that element. The concentration of aluminum (Al) serves as an indicator of piston wear, the presence of chromium (Cr) reflects wear of the chromium-plated piston rings.

# CONCLUSION

Currently, research is on going on the effectiveness of the nature and concentration of additives on the performance indicators of engine oils operating in engines of heavy-duty mining transport equipment under conditions of high air dustiness.

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