

DUST CONTROL IN THE MINERAL TRANSPORTATION INDUSTRY

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Abstract: Dust control during open pit mining operations presents significant challenges in both summer and winter. However, colder temperatures impose additional requirements for dust suppressants. This study proposes preventive compositions utilizing light and heavy gas oils derived from catalytic cracking and delayed coking as base components. Incorporating heavy fractions increases the flash point, enhancing the safety of dust suppressants, while also improving adhesion properties through higher levels of polyaromatic hydrocarbons and reducing overall product costs. To further enhance the low-temperature and adsorption characteristics of the developed dust suppressants, varying concentrations (2-10 wt.%) of heavy oil residues (such as cracking residue and tar) are added. Additionally, alternative dust suppressants are created through the water emulsification of vinylated alkyd oligomer, with an examination of its ability to form robust films on dusty surfaces. The study demonstrates the effectiveness of an aqueous solution of vinylated alkyd oligomer as a summer dust suppressant. The findings include the development of new preventive compositions with improved low-temperature properties, validated by performance tests conducted in a laboratory setting.

Key words: open pit mining; dust formation; dust suppressants; plant polymers; oil products; heavy oil residues

Introduction. This study focuses on the development of mining technology and safety protocols for operations conducted in extremely low temperatures, where adherence to high environmental standards is essential. In Russia, open pit mining—especially in ore deposits—constitutes approximately 70% of total production. The industry is seeing deeper excavations, reaching up to 400 meters (and potentially 450-600 meters in the future), which complicates ventilation in quarries and worsens working conditions due to increased gas and dust exposure. The Russian coal industry is also growing, with production projected to reach 410 million tons by 2030. The State Register of Mineral Reserves indicates that the Neryungri and Syllakh deposits in the Far Eastern Federal District contain 47% of explored coal reserves in Eastern Siberia and the Far East, although only about 7% have been developed. For example, a subsidiary of Tigers Realm Coal Limited in the Beringovsky coal basin reported a 131% increase in production, reaching 576,000 tons. Despite the rising demand for coal and its derivatives, challenges remain in its handling. Extracting over 1,000 tons results in more than 100 m³ of enrichment waste, creating risks to human health due to technical dust. Drilling and blasting contribute approximately 35% of harmful emissions, with loading and transportation operations accounting for 40%, leading to significant dust accumulation in quarry areas. These fine dust particles cause considerable air pollution, threatening the safety and health of workers in both open pit and underground mining operations, where the use of environmentally friendly compositions is recommended.

Problem Statement: The harsh climate, particularly in regions like Kemerovo and Kuzbass, presents challenges for dust control in open pit mines during low temperatures. This paper

suggests reducing the pour point of dust suppressants by adding depressants such as cracking residue and tar. This reduction occurs because resinous-asphaltene compounds can adsorb onto the surfaces of paraffin crystals, which are involved in lowering the pour point. Differential scanning calorimetry indicates that these paraffin crystals significantly contribute to the effectiveness of any depressants used, including heavy oil residues. Research from China highlights similar dust control issues, showing that surfactant formulations can enhance the ability of water to suppress coal dust. Field tests in the Erdos coal mine demonstrated that a surfactant solution significantly outperformed water alone in reducing dust concentrations.

Purpose: This paper aims to develop preventive agents (PAs) that combine oil products with heavy oil residues to enhance their low-temperature properties and dust suppression capabilities in winter. Additionally, it explores the use of plant polymers as an alternative base for summer dust-suppressing compositions. Summer formulations based on aqueous dispersions are both environmentally friendly and effective.

Methodology: Comparative tests were conducted on preventive agents using both water-based and organic (oil) bases. The organic PAs included catalytically cracked light and heavy gas oils, as well as light and heavy coker gas oils, in a 1:1 ratio. Additives like cracking residue and tar, known for their strong adhesion properties, were incorporated to improve low-temperature performance. The water-based PA was created through the emulsification of vinylated alkyd oligomer (VAO).

Test results for the dust-suppressing compositions are summarized in Table 1. The findings indicate that water-based PAs generally outperformed organic ones in key parameters such as fire safety and environmental impact. However, VAO's low frost resistance (with a pour point of 0 °C) limits its use during winter months. #### Method for Evaluating the Resistance of Preventive Compositions. To evaluate the resistance of the proposed preventive compositions to wind erosion, a chamber was designed to simulate dust formation in a quarry (Fig. 1). This chamber consists of a

Table 1

Parametr	VAO	Organik-based PAs			
		CCLGO:CCHGO		LCGO:HCGO	
		5 wt.% CR	5 wt.% T	5 wt.% T	5 % CR
Pour point, °C	0	– 52	– 48	– 53	– 46
Flash point °C	-	100	80	79	83
Engler viscosity according to the viscometer of type V3-246, E	10-20	13.5	12.5	13.7	14
Organic content, %	3-7	100	100	100	100

Physical properties of dust-suppressing compositions

container holding a soil sample and a cyclone that mimics wind. The cyclone is securely connected to the chamber containing the samples. The effectiveness of dust suppression was measured by weighing the amount of dust particles dislodged from the surface treated with various preventive compositions. Samples analyzed included sand, coal, and urtite, the latter being specifically tested to determine the ability of the preventive compositions to mitigate dust from fine materials.

Method for assessing dust-binding properties of preventive agents. The dust-binding properties of the preventive agents (PAs) were evaluated through a method involving the vibration mixing of dust with the PA, followed by a sieve analysis that simulates the degradation of road surfaces. In this sieve analysis, 50 grams of dust within a specific fraction ($d = 0.15\text{--}0.08\text{ mm}$) were mixed with a dust-binding agent at a rate of 1 dm^3 per square meter of roadway. The mixing process lasted for five minutes. Afterward, the mixture was screened through a series of sieves with mesh sizes of 1 mm, 0.3 mm, 0.2 mm, 0.15 mm, and 0.08 mm. The percentage of the fraction greater than 1 mm (wt.%) served as a measure of the dust-binding effectiveness of the PA.

Discussion. Preventive agents were developed using catalytically cracked gas oil fractions with boiling points ranging from $200\text{--}340\text{ }^{\circ}\text{C}$ and $320\text{--}470\text{ }^{\circ}\text{C}$, as well as delayed coker gas oils with boiling ranges of $220\text{--}359\text{ }^{\circ}\text{C}$ and $340\text{--}480\text{ }^{\circ}\text{C}$. A mixture of light and heavy gas oils was created in a 1:1 ratio, to which cracking residue or tar (heated to $50\text{--}70\text{ }^{\circ}\text{C}$) was added at a concentration of 2 wt.%. This mixture was then stirred until it reached a uniform consistency. The physical and chemical properties of the developed PA compositions are detailed in another paper. The

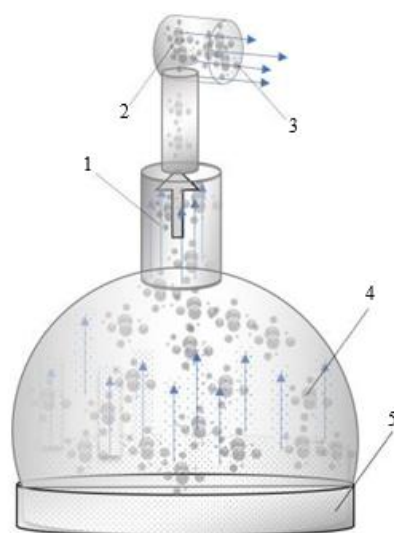


Fig.1. An installation for measuring dust entrainment

- 1 – an off-take with the flow of entrained particles;
- 2 – a collector of dust particles;
- 3 – a flow of entrained particles; 4 – a sphere, where the cyclone simulates wind entrainment;
- 5 – a container with the examined dusty material.

preventive compositions that include heavy oil residues, such as cracking residue and tar, at concentrations of 2-10 wt.%, conform to modern technical standards (TUs), specifically TU 38.1011322, TU 38.1011142, TU 0258-001-48899100-2004, and TU 0258-020-38519207-2012. The inclusion of heavy oil residues increases the system's viscosity and density, yet these parameters remain within acceptable limits defined by the TUs, ranging from 2.68 to $3.12\text{ mm}^2/\text{s}$. Enhanced viscosity leads to reduced consumption of the preventive agent during application. Additionally, the flash point rises from 82 to $103\text{ }^{\circ}\text{C}$ with the addition of heavy fractions, including those from delayed coker and catalytically cracked gas oils, thereby improving safety. The flash point of gas oils and heavy oil residues rises from 82 to $103\text{ }^{\circ}\text{C}$, which helps to enhance the flame resistance of the preventive agent. The pour point of the compositions decreases from -45 to $-50\text{ }^{\circ}\text{C}$ for those based on catalytically cracked gas oils, while for those derived from delayed coking gas oils, the pour point drops from -35 to $-46\text{ }^{\circ}\text{C}$. It has been found that the mechanism by which heavy oil residues (HOR) act as depressants in preventive agent mixtures is linked to their ability to reduce surface tension (ST) at the liquid-solid

interface. Both the surface tension and pour point (PP) are influenced by the concentration of

active HOR components and the viscosity of the oil dispersed systems (ODS). Thus, it is essential to compare the dependence curves of ST and pour points against HOR concentration. These curves for ST and PP at a temperature of -10°C in CCLGO:CCHGO and LCGO:HCGO fractions in a 1:1 ratio are illustrated in Fig. 2.

When heavy oil residues are added to the base fractions, the resinous-asphaltene substances they contain create adsorption layers on the surfaces of growing crystals of solid paraffinic hydrocarbons. This action slows crystal growth and hinders the formation of an ideal three-dimensional crystal structure. The interaction between the resinous-asphaltenes and the solid hydrocarbon crystals reduces the strength of the coagulation structures, thus lowering the pour point of the mixture at a 5 wt.% HOR concentration (point B in Fig. 2a).

Specifically, adding cracking residue to the CCLGO:CCHGO mixture at a 5 wt.% concentration decreases the pour point by 18°C , changing it from -35 to -53°C . In the same medium, tar at a 5 wt.% concentration reduces the pour point by 11°C (Fig. 2). For mixtures based on CCLGO:CCHGO, the optimal concentrations of cracking residue (CR) and tar (T) are both 5 wt.%. The degree of pour point depression correlates with the amount of solid paraffinic hydrocarbons in the oil fraction; catalytically cracked gas oils contain half as much of these hydrocarbons compared to those in LCGO:HCGO mixtures. Exceeding the maximum allowable concentration of cracking residue in the mixture results in coagulation bonds forming among the

supramolecular structures throughout the system. To further investigate the surface properties of the developed preventive agents, their wetting ability was assessed by measuring contact angle (CA) values on a metal plate (Fig. 3). The contact angle decreases with an increase in HOR concentration from 2 to 10 wt.%. However, adding more HOR thickens the ODS, causing the CA to rise. Following the analysis of changes in surface tension and contact angle of the lab PA samples at varying ambient temperatures, a study was conducted on the relationship between adhesion work and HOR concentration in PA mixtures based on both CCLGO:CCHGO and LCGO:HCGO at -10°C , with the results shown in Fig. 4.

When heavy oil residues (both tar and cracking residue) are added to the preventive agent composition, the adhesion work only increases when the concentration exceeds 10 wt.%. This is attributed to enhanced intermolecular interactions between the heavy oil residues and the metal surface. At a 5 wt.% concentration, the surface tension and contact angle change significantly and non-linearly, supporting the idea of competing adsorption processes at the liquid-solid interface and on solid paraffin crystals, particularly at negative temperatures.

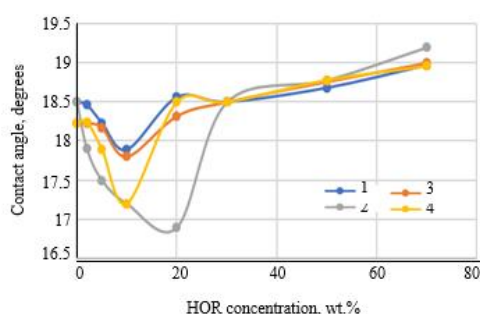


Fig.3. Dependence of changes in PA contact angle on HOR concentration

1 – CCLGO:CCHGO+CR; 2 – LCGO:HCGO+CR; 3 – CCLGO:CCHGO+T; 4 – LCGO:HCGO+T

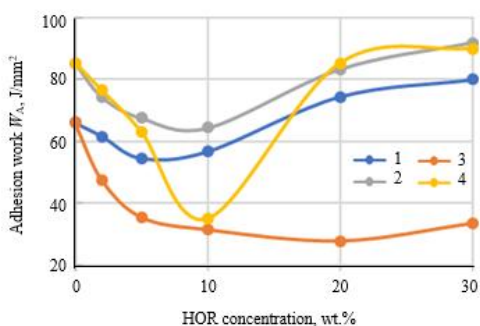


Fig.4. Dependence of changes in adhesion work on HOR concentration in PA mixtures based on CCLGO:CCHGO and LCGO:HCGO (1:1) at -10°C

1 – CCLGO:CCHGO+CR; 2 – LCGO:HCGO+CR; 3 – CCLGO:CCHGO+T; 4 – LCGO:HCGO+T

In the case of delayed coker gas oil mixtures, adding tar at a concentration of 10 wt.% leads to a sharp decrease in adhesion work, followed by an increase. This change is linked to the hydrocarbon composition of the delayed coker gas oils, which have a higher resin content—twice that of catalytically cracked gas oils. The increased adhesion work is due to interactions between the densely packed hydrocarbons in LCGO:HCGO and the resinous-asphaltene substances (RAS) in tar, resulting in a notable thickening of the oil dispersed system (ODS). The extreme dependencies observed confirm that mixtures of CCLGO:CCHGO and LCGO:HCGO in a 1:1 ratio, with CR and tar concentrations ranging from 2 to 10 wt.%, exhibit good wetting properties, particularly at 5 wt.%. The lubricating properties of the preventive agents were evaluated by measuring the average wear scar diameter (WSD) of steel balls using a four-ball friction machine, following GOST 9490-75. The addition of cracking residue at concentrations up to 5 wt.% does not enhance the lubricating properties of the delayed coked gas oil mixtures. Instead, an increase in WSD from 0.665 to 0.689 mm is observed. This can be attributed to the larger size of RAS macromolecules and a decrease in intermolecular interactions among the liquid components and with the solid surface, leading to weakened supramolecular structures, reduced film thickness, and ultimately poorer lubrication performance. Therefore, optimal compositions contain cracking residue concentrations between 2 and 10 wt.%.

With the addition of tar at concentrations up to 2 wt.%, the wear scar diameter (WSD) decreases from 0.807 to 0.762 mm, but as the concentration increases to 5 wt.%, it rises again to 0.803 mm. Conversely, adding 2 wt.% of cracking residue (CR) improves the lubricating properties of the base mixtures of catalytically cracked gas oils, reducing WSD from 0.807 to 0.685 mm. This improvement occurs because the resinous-asphaltene substances (RAS) in CR form a thin and uneven film on the surfaces of the friction pairs (steel balls) that interact with each other. From

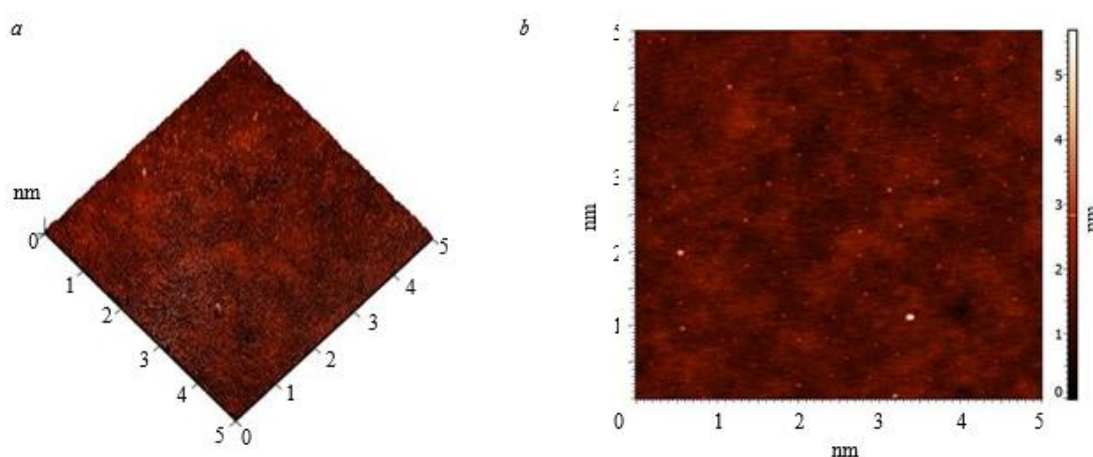


Fig.6. Image of an irregular surface of the film, formed by a water-based preventive agent:
 α – at a scan angle of 45° , b – top view

this analysis, it can be concluded that the optimal compositions for low-temperature, surface, adsorption, wetting, and lubricating properties are mixtures of CCLGO:CCHGO (1:1) and LCGO:HCGO (1:1), both with CR and tar concentrations ranging from 2 to 10 wt.%.

VAO	1,200	1,17 8.2	1.81	1,200	1,15 7.88	3.51	1,200	1,14 6.5	4.50
HCGO:LC GO+CR(5%)	1,200	1,15 4.4	3.80	1,200	1,146	4.50	1,200	1,14 0.4	4.95
HCGO:LC GO+T(5%)	1,200	1,15 5.4	3.71	1,200	1,14 7.8	4.35	1,200	1,14 2.8	4.76
CCHCGO:CC LGO+CR(5%)	1,200	1,15 4.4	3.80	1,200	1,146	4.50	1,200	1,14 0.6	4.95
CCHCGO:CC LGO+CR(5%)	1,200	1,15 4.4	3.69	1,200	1,14 8.04	4.33	1,200	1,14 3.1	4.74

Alternative summer dust suppressants were created by emulsifying vinylated alkyd oligomer (VAO) in water. The resulting dispersion was evaluated for its ability to form strong films on dusty surfaces. VAO was synthesized through a multi-step process involving oil alcoholysis with a trihydric alcohol in the presence of lithium hydroxide (LiOH), followed by the esterification of monoglyceride with phthalic anhydride and subsequent post-vinylation with ditertiary butyl peroxide, culminating in polyesterification. This process was conducted in a laboratory setting using standard equipment for alkyd synthesis, including a three-necked flask, stirrer, refrigerator, and thermometer. Analysis of the 3D polymer content in films made from aqueous VAO dispersions showed that films made with sunflower oil contained 45-50% 3D polymer, comparable to the solvent-borne analogue. In contrast, films made with soybean oil had 35-37% 3D molecules. Using a scanning atomic-force microscope (Ntegra Prima), the structure of VAO dispersion films on a mica surface was examined. Images of the VAO film taken from various angles revealed that the films were homogeneous, with only minor irregularities of 1-2 nm, likely representing compacted spheres of VAO molecules formed under the influence of van der Waals forces.

Table 2

Entrainment of dust particles, produced by wind erosion, before and after preventive agent treatment

PA	Sand			Coal			Urtite		
	Before treatme nt, g	After treatme nt, g	Share of entrain ment, %	Before treatme nt, g	After treatme nt, g	Share of entrain ment, %	Before treatme nt, g	After treatme nt, g	Share of entrain ment, %

Studies have demonstrated that dust suppressants made from aqueous dispersions of vinylated alkyd oligomer (VAO) offer numerous advantages, including increased hardness, faster drying times, the ability to be applied via pneumatic or airless spraying, compatibility with standard alkyd synthesis equipment, the absence of organic solvents, and enhanced environmental safety. To assess the resistance of the proposed preventive agents (PAs) to wind erosion, a chamber was designed to replicate the dust formation process (see Fig.1). Dust suppression efficiency was measured by weighing the dust particles removed by a cyclone from surfaces treated with the PA. The preventive agent was applied to the dust material using a spray gun at a rate of 0.5 L per m². The dusty materials analyzed included sand, coal, and urtite. Table 2 presents the results of dust particle entrainment before and after PA treatment. The experiments evaluated both oil-based and aqueous VAO-based dust suppressants.

The treatment with PAs effectively reduced dust entrainment (Table 2). For instance, sand treated with a VAO-based composition showed an entrained dust percentage of 1.81%, the lowest recorded. In contrast, sand treated with oil-based compositions exhibited entrainment values between 3.69% and 3.80%, which is still a positive outcome for dust control. Oil-based compositions proved particularly effective on sand and coal, while aqueous dispersions performed better on fine dust materials like urtite due to their smaller particle sizes, which can envelop dust particles. These findings align with research by P. Wang et al. The efficiency of dust suppression through spraying was linked to the wettability of coal dust and the size difference between droplets and D50 dust particles. Initially, as coal dust particle sizes increased, dust suppression efficiency improved but then declined. Experimental results indicated that smaller particle sizes led to a decrease in hydrophilic oxygen-containing functional groups, resulting in reduced dust wettability, as shown in Table 2. A comparison of the developed dust suppressants with existing agents revealed that the proposed oil composition is competitive, meeting the required physical, chemical, and technological properties of PAs. The cost of the new oil composition is 25 rub/l, comparable to the existing product "Universin," priced at 28 rub/l. A market analysis of domestic and imported products, such as Dustclean (Russia), ArcticLine (Poland), Dustex (Germany), and ArenaKleen (USA), shows prices ranging from 250 to 755 rub/l, making them less favorable for domestic industries focused on import substitution. The market analysis for summer dust suppressants highlights the economic efficiency of the developed VAO-based compositions, with a diluted cost (solution concentration up to 10 wt.%) of only 4 rub/l, compared to similar products like DustControl LQD (Russia) and potassium salt-based suppressants, which range from 55 to 620 rub/l.

In conclusion, to address dust formation during the extraction, processing, and transportation of mineral resources, universal oil- and water-based preventive compositions have been developed. These compositions enhance the efficiency of solid bulk material handling by mining and transport equipment while improving environmental conditions by reducing dust in quarries and on highways. Key findings from the studies on the physical and chemical properties of various composite PA compositions include:

1. PAs were formulated using a mixture of light and heavy gas oils from catalytic cracking and delayed coking in a 1:1 ratio, incorporating 2-10 wt.% of heavy oil residues (HOR) like cracking residue and tar. The mechanisms for depressant and thickening effects of the oil residues were confirmed. Prototypes meeting existing technical standards were produced.

2. Investigations into the impact of ambient temperature and HOR concentration on surface properties (surface tension, contact angle, adhesion work) validated the unified adsorption mechanism of RAS from cracking residue and tar on solid paraffinic hydrocarbons and metal surfaces, resulting in significant decreases in surface tension, contact angle, adhesion work, and pour point. RAS from cracking residue was found to be more effective than that from tar.
3. The lubricating properties of the developed PAs were evaluated by measuring wear scar diameter on a four-ball friction machine (FBFM). Adding tar at 2 wt.% to CCLGO:CCHGO mixtures reduced WSD, while a higher concentration increased it. Optimal mixtures for low-temperature, surface, adsorption, wetting, and lubricating properties were identified.
4. Environmentally friendly summer dust suppressants were developed from alternative raw materials based on aqueous dispersion of VAO.
5. A comparative analysis of the physical, chemical, and performance characteristics of PAs based on aqueous VAO dispersion and oil was conducted, demonstrating that VAO-based PAs offer superior fire prevention and environmental properties. They also adhere to finely dispersed surfaces significantly better than organic PAs. However, due to their high water content, these compositions are best suited for summer or warm periods, while oil-based agents are more effective for treating coal and coarse dusty materials during winter. Thus, both types of compositions serve distinct applications without direct competition.

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