Investigation of the adhesion properties of organic dust suppressants

I. S. Ilyashenko, *S. V.* Kovshov

Industrial Safety Department,St. Petersburg Mining University, St.Petersburg, Russia

Abstract: The authors of the article have developed and proposed for use a new environmentally safe organic dust suppressing compound. The article presents an overview and analysis of the most common organic dust suppressants , describes their features and characteristics. Methods for determining the adhesive properties of solutions have been studied, a proprietary technique has been proposed, and a stand has been developed for assessing the adhesive properties of dust-suppressing solutions applied to dusty surfaces of highways. The adhesion ability of environmentally safe dust control solutions, which have a natural basis and are used for dedusting linear and area sources of dust formation, was evaluated and analyzed. It was found that ginger oil has the lowest adhesion capacity (225.8 Pa), the highest is an aqueous solution of beet molasses (414.9 Pa).

1 Introduction

The air environment surrounds humans throughout their life, which means almost constant direct contact with atmospheric air. For various reasons, the quality of air inhaled by a person often does not meet the comfortable and safe conditions of human's life, which, in its turn leads to the development of serious diseases with severe consequences [1,2,3].

This problem is particularly relevant for enterprises of the mineral resource complex [4]. Increased air dustiness at entrprises engaged in open-pit mining has a significant negative impact on the employees engaged in production, on the population living near the enterprise, as well as on air quality and the environmental situation as a whole [5]. Herewith, the most intensive source of dust is technological access roads [6].

At the same time, measures to reduce dust emission from quarry roads often do not give a positive effect due to their low efficiency for various reasons [7]. In this regard, different dust suppressants and binding compounds can be used, which contribute to the formation of dust conglomerates and dust surface fixation.

The authors of the article developed a new organic dust-collecting compound that does not harm the environment and workers employed in high dust conditions. The purpose of the study is to determine the possibility of using the developed solution by analyzing and comparing it with various dedusting organic compounds.

2 Dust suppression. General information and features

2.1 Overview of means and methods of dust suppression

Dust suppression is a set of measures and means used to reduce the intensity of dust formation and, as a consequence, to reduce the airborne industrial load on workplaces (in terms of labor protection), as well as on the population living close to the dust source and on the atmospheric air (in terms of ecology and environmental protection).

Today, according to statistical data, the issue of air quality in residential and industrial zones is quite acute. For example, the load on the earth's atmosphere is characterized by an annual intake of more than 150 million tons of various clouds of dust and aerosols [8]. All this indicates the need for measures to reduce dust emission to improve the quality of the air environment. In this regard, a significant number of scientists around the world are searching for solutions to the problem of increased air dustiness. One line of this study is the development and improvement of available means and methods of dust suppression.

Russian and international experience in the implementation of measures for dedusting and dust suppression shows that there are many ways to reduce dust formation, but the most common method is hydro-dusting [9,10].

Industrial water is often an affordable and cheap resource at many enterprises, e.g., at organizations operating in the mineral resource complex, which allows it to be used for various purposes, including dedusting. However, the effectiveness of hydro-spraying depends on many factors, which often leads to the absence of any positive effect from the measures taken. When the distributed water dries out completely, the dedusting effect disappears, and the movement of air and vehicles only contributes to evaporation of the liquid [10]. For this reason, in most cases, hydro-spraying becomes costly and impractical.

In addition to water for dedusting, surfactants of various chemical compositions and origin are also used. Surfactants are solutions and emulsions of active substances that, when interacting with a dusting material, drying, or being exposed to any external factors, lead to the bonding of dust conglomerates and the formation of a strong coating or film that prevents soil erosion and dust emission [11,10]. However, in some cases, dedusting with surfactants becomes impractical for economic reasons, since often the cost of such dedusting chemical compositions is high, and the payback period for their implementation may exceed the planned life of the mining enterprise.

Some surfactants pose a relatively serious environmental threat and hazard to the health of workers since they contain ammonium, chloride, carbide, and other compounds that can emit harmful and dangerous gaseous products when interacting with water or under certain external conditions. For example, a dust suppressing solution is known, which is a compound of calcium carbide and sodium salt of carboxymethyl cellulose in a ratio of 3:1 and dissolved in water to a concentration of 5% [12]. However, it is also known that in this case, the reaction of interaction of calcium carbide with water is active, as a result of which gaseous acetylene is released, which forms an explosive mixture with air.

Therefore, a special area of research and development of dust-suppressing compounds and surfactants concerns the use of organic and semi-organic dedusting solutions, which have a lower cost compared to chemically synthesized solutions and are slightly inferior to them in efficiency. The organic composition of these solutions means their rapid decomposition in nature, which, in its turn, contributes to improving the efficiency of recultivation of disturbed land during the open-pit mining of a mineral deposit. Moreover, rapid decomposition not only leads to the filling of the soil with nutrients but also means minimal damage to the environment and workers directly in the zone of influence of the applied dedusting compound.

2.2 Analysis of organic dust suppressants

The authors of the article developed and proposed for use a dust-suppressing organic solution consisting of an aqueous solution of flax and starch prepared by a special method. To determine the possibility of using sprinklers without changing the entire watering process and purchasing new equipment in the case of using the proposed solution, the main characteristics and parameters that determine this possibility were analyzed.

The defined parameters were:

– The density of the developed solution of different concentrations of components using the hydrometer ANT-2

– The viscosity of the developed solution of different concentrations at different temperatures using the Engler viscometer for drop liquids VU-M-PHP

– The adhesive strength of the solution using a modified DOSM-3 dynamometer.

The results of measurements of these characteristics are shown in Table 1.

Table 1. Characteristics of the developed solution of different concentrations.

Defined parameter	Developed solution with varying component concentrations			
	1%	2%	3%	5%
Density of the solution ρ, $kg \cdot m^{-3}$	931.5	932.3	933.1	934.6
Kinematic viscosity of the solution ν*, 10^6 $m^2 \cdot s^{-1}$	9.74	17.49	29.88	36.01
Adhesion of the solution, $kg \cdot m^{-2}$	32.84	33.09	33.59	34.08

*At room temperature Θ = 25°C.

Relatively small values of the density and viscosity of the solution, as well as the purity and absence of solid impurities, confirm the possibility of using sprinklers for watering quarry roads with the developed compound. However, in addition to the possibility of using technological watering systems, it is necessary to compare this solution with analogs to justify its competitive advantages. The authors of the article have analyzed the characteristics of some of the most widely applied organic and semi-organic solutions offered for dust suppression.

One of the advantages of the proposed solution is its effectiveness in comparison with water. The low cost of raw materials for the production of the solution, as well as a decrease in the frequency of watering when replacing hydro-dusting, provides the company with annual savings of over 20 thousand U.S. dollars (more than 1.5 million rubles) on activities related to dust removal.

However, the disadvantages of this solution include a short storage life due to the purely organic composition, which plays an important role for many industrial enterprises. Therefore, the next step in improving the composition will be to develop an additive that reduces the rate of deterioration of the solution.

Another most common and well-known organic compound is a solution of lignosulfonate, which is a product of wood processing in pulp and paper production. In addition to its use in the production of concrete, drilling fluids, dyes, and fertilizers, lignosulfonate and its solutions are also widely used for dedusting various surfaces. In its composition, dust-suppressing solutions of lignosulfonate can also contain animal and vegetable fats, as well as other wastes from various production cycles. Lignin, which is the main building material in trees, is discharged into wastewater as a result of the sulfite process, which is why the resulting emulsion is called lignosulfonate.

The resulting solutions for dedusting have relatively high efficiency and ease of manufacture. When it is used, the solution glues together dust particles, forming their strong conglomerates. Moreover, as a waste product of paper production, raw materials for the production of dust suppressing solutions become cheap and affordable [13]. However, a significant disadvantage of this composition is its solubility in water, so its use depends on climatic conditions [10].

There are works related to the study of the possibility of using glycerin as a dust suppressant. Scientists consider glycerol, a by-product of biodiesel production, as a new method of dust suppression. For these purposes, a pure aqueous solution of glycerol can be used, as well as more complex compositions that include chloride compounds and fatty acids [14]. For example, one of the proposed compounds [15] includes 80% glycerol, 10-11% water, 7% sodium chloride, and 1-2% fatty acids and methyl esters. This solution can significantly increase the wettability of dust particles, provide the formation of strong dust aggregates, and a strong coating on the dusty surface. Moreover, reducing the freezing point of the solution due to the use of glycerin can allow the use of this solution in the pre-winter cold period.

3 Adhesion of dust suppressing compounds

3.1 Theoretical study of the adhesive ability of the solution

Most of the compounds intended for reducing dust emission are based on the effect of the adhesion of dust particles and the formation of a solid coating on the dusting surface, which prevents soil erosion and dust generation. Therefore, the cohesion and adhesion of dust particles play a significant role in the effectiveness of dust suppression measures with the use of such solutions.

In this case, cohesion is the ability of small dust particles to stick together, forming heavier complexes, and is due to the so-called "attraction" forces between the molecules of substances [8]. The cohesion force between two particles is directly proportional to the diameter of these particles (see Equation 1), and the breaking force of the resulting aggregate (for example, gravity) – to the cube of the diameter of the particles [16]. Therefore, when the diameter of particles changes, the breaking force will change to a greater extent, and due to that conglomerates of smaller particles will be more difficult to destroy by the same forces. The cohesion strength is calculated using Equation 1:

$$Fcoh=2\pi\delta*d \quad (1)$$

where δ = surface tension at the boundary between the solid body and air; and d = diameter of particles.

Moreover, the adhesion of dust particles of various origins depends on their dispersion, plasticity of the source material, and dust humidity. If the surface of the particles is wetted with a liquid, their adhesion will also be affected by the capillary effect, which means that the surface tension of this liquid will pull the particles together [16].

According to the classification of dust by particle adhesion [8,16], quartz dust SiO_2 belongs to the group of non-adhering dust with a value of the dust layer's tensile strength P < 60 Pa.

Adhesion, in its turn, characterizes the strength of the reinforced layer formed after dust suppression and reducing dust emission; its destructibility is a result of external influence on the coating. The adhesion parameter also reflects the capacity of the solution to bond dust particles together and form a strong coating on the treated surface.

Therefore, to increase the adhesion of dust and provide high efficiency of dust suppression, it is recommended to use various surfactants and solutions that enhance the wettability and adhesion of dust particles. The effectiveness of their application can be confirmed by studying the adhesive properties of the solution to study the strength of the created coating and the adhesion degree of particles.

3.2 Overview of methods for determining the adhesion of the solution

As mentioned above, the value of adhesion of a dedusting solution is a criterion for the effectiveness of dust suppression with the use of this substance. The authors of the article have analyzed existing approved methods for determining the adhesion of the solution, as well as the equipment used for this purpose. Such a review is necessary to select the most rational and affordable method for determining the separation force to compare the dedusting solutions by their efficiency.

As a result of the analysis, methods for determining the adhesion of various building solutions (for example, concrete), paints, and coatings, as well as the necessary equipment were studied. According to regulatory documents, to assess the adhesion of solutions and coatings, the most commonly used tools are tensile and other pull-ff adhesive testers for determining the breaking force, single-blade and multi-blade cross-cut adhesive testers for applying a grid of cuts, as well as other variations of these instruments. Several methods approved by standards were selected for determining the adhesion of paint materials, due to the identity of the use of these substances with dust suppressing solutions.

One of the selected methods is approved by ISO 2409:2013 [17]. This method consists of the use of single-blade and multi-blade cutting tools for making incisions on the studied coating. Incisions are made in the form of a grid using appropriate templates for their uniformity and correctness. Hence, this technique is called the lattice cut method (or cross-cut method). An adhesive tape with an adhesive strength of 2.4 - 4.0 N/m is applied to the cut grid, and then smoothly torn off at an angle of 60° to the surface. Then the adhesive ability of the coating is evaluated on the principle of "passes/does not pass" or on a scale from 0 to 5, depending on the degree of damage to the incised mesh.

The second method is also used to evaluate the adhesive properties of coatings made of paint materials, glues, primers, and other materials. All aspects of the methodology are approved by the ISO 4624:2016 standard [18]. This method consists of the use of glues and is called the separation method (or pull-off method). If this method is used, the studied product is applied to homogeneous plates with the same surface. After the coating has dried, cylindrical blanks are glued to it using special adhesives. After the glue has solidified, the workpieces are tested for separation to determine the breaking force required to destroy the coating layer. Thus, the result of the measurement is the separation force that must be applied to break the adhesive or cohesive bonds in the coating.

To study the adhesive properties of dust suppressing compounds, the authors of the article have selected the second of the presented methods. Determination of the adhesion value by the separation method is most suitable for studying both the adhesive properties of the solution and for determining the cohesive bond between the dust particles that make up the protective coating. Besides, the presented method is a universal way to determine the adhesion ability of the applied product, regardless of the dusting surface and material.

3.3 Method for researching the adhesion ability of the dust suppressing solution

To study the adhesive properties of solutions, a series of experiments was carried out on a specially assembled model of a technological quarry road, which consists of two sections of a road modeled on a scale of 1:40: horizontal and inclined (to study the fluidity of applied solutions).

Following the similarity theory [18] and the method developed at the Center of Geomechanics and Mining Problems of St. Petersburg Mining University, the road surface was made of SiO_2 sand, ED-20 epoxy resin, and PAP hardener in a certain ratio.

To prepare the test bench for the experiments, a dusting material, such as fine silicon dioxide and coal dust, was distributed on the surface of the roadbed. Then, at a certain flow rate, the studied dust suppressing solution was spread on the model road surface and remained there until the coating completely dried out without any additional external influences.

The study of adhesive properties consisted in determining the force of separation of the slab from the surface of the road model, i.e., in determining the breaking force required to destroy the formed coating. For this, a modified DOSM-3 dynamometer was used (see Figure 1): the elastic element of the measuring device was connected to a plate having a uniform smooth surface, with an area of S = 401.94 cm^2. It should be noted that for the accuracy and correctness of the experimental results, the initial value of the parameter, reflected on the reference scale of the device, was registered before each measurement due to the influence of the plate and fasteners, while the device during measurement reflects the degree of compression/stretching of the elastic element in units of length (mm).

Consequently, to convert the measured value of the deformation (in mm) into the value of the separation force, the dynamometer was calibrated, and the resulting data was then compiled into a calibration table. For this, 2 tests were performed on the load and discharge of the elastic element of the measuring device in the range of 0-2 kg with a step of 0.2 kg and recording the corresponding value of its deformation.

Fig. 1. Modified DOSM-3 dynamometer on the experimental stand.

The plate of the measuring device was placed on a stand with a newly applied solution and left until the liquid dried out completely and a protective coating formed. Then the device was lifted in the direction perpendicular to the surface of the roadbed model while observing the dynamometer reading scale at the same time: when a certain force was applied to the device at the point of separation, a threshold parameter value was observed, after which a certain decrease in the measured value of deformation occurred. 10 measurements were made for each studied solution, and the average value of the threshold deformation was determined. Then the difference between the defined maximum and initial values was calculated, and the value of the separation force, which characterizes the adhesive properties of the solution, was determined using the calibration table data and the linear interpolation method.

For example, when studying the properties of a dust suppressing solution made of water and beet molasses, the average threshold value of the elastic element deformation was 0.98 mm, the initial reading of the dynamometer was 1 mm, i.e., the difference in readings was $x_3 = 0.02$ mm. This deformation value, according to the data of the calibration table, falls within the range between the forces $m_2 = 1.6$ kg and $m_1 = 1.8$ kg, which correspond to deformations of 1.23 mm and 1.25 mm with a difference between the maximum value of 1.26 mm – $x_2 = 0.03$ and $x_1 = 0.01$ mm. Then, the expression for calculating the separation force using linear interpolation will look like Equation 2:

$$m_{ad} = m_{ad} + \frac{(m_2 - m_1)\cdot(x_3 - x_1)}{x_2 - x_1} \quad (2)$$

where m = separation force; and x = deformation value.

Thus, the separation force for this solution will be:

$$m_{ad} = 1.8 + \frac{(1.6 - 1.8)\cdot(0.02 - 0.01)}{0.03 - 0.01} = 1.7 \text{ kg}$$

The adhesion, which characterizes the work of this force, can be determined by the division of the received force (the separation force in kg) by the area of its action according to Equation 3:

$$W_{ad} = \frac{m_{ad}}{S\cdot 10^{-4}} \quad (3)$$

where S = plate area.

Then the adhesion force value will be:

$$W_{ad} = \frac{1.7}{401.94\cdot 10^{-4}} = 42.3 \text{ kg}\cdot\text{m}^{-2}$$

or

$$W_{ad} = 42.3 \cdot 9{,}81 = 414.9 \text{ N}\cdot\text{m}^{-2}$$

Table 2 summarises the data of determining the adhesion ability of studied organic dust suppressing solutions.

Table 2. Adhesion properties of dust suppressing compounds.

Determined parameter	Developed solution with components concentration				Aqueous solution of lignosulfonate	Aqueous solution of beet molasses	Ginger oil
	1%	2%	3%	5%			
Separation force, kg	1.32	1.35	1.37	1.37	1.51	1.70	0.93
Adhesion, $N \cdot m^{-2}$	322.1	324.6	329.4	334.3	3680.5	414.9	225.8

3.4 Summary

The described method for determining the strength of adhesion allows determining the relative effectiveness of any applied dust suppressing solution, in particular, the developed organic composition.

This, in its turn, makes it possible to compare different compounds basing on their efficiency, since the value of the adhesion determines the strength of the created coating when applying the solution on the dusting surface, and the strength of the dust conglomerates themselves, formed as the result of dust suppression. Thus, the strength of adhesion can serve as a criterion for the effectiveness of certain dust suppression measures associated with the watering surfaces with binding and adhesive compositions.

4 Results and discussions

Analysis of existing methods of dust suppression using organic compounds has shown that most of the methods are based on resource conservation and the use of waste from various industries to produce dedusting compounds. Besides, most organic solutions also contain 1-3 inorganic additives that improve the wettability and adhesion of dust particles, which increases the effectiveness of the solution itself, but under certain conditions can pose a threat to humans and the environment. Moreover, the production of these solutions often is associated with wastes from various industrial processes, which are either not common in the world or have a relatively high cost.

The study of the characteristics and properties of various organic compounds and substances showed that the proposed solution has a lower efficiency value in comparison with solutions of lignosulfonate or beet molasses; however, processing of dusting surfaces with the developed composition is much more effective than hydro-dusting, which also affects the economic effect. Inexpensive and available raw materials for the production of the composition, which is a short-term and not labor-intensive process, makes the proposed solution not only effective for use but also economically attractive. The proposed developed compound does not contain any harmful, hazardous components. It is also proposed to produce and prepare organic concentrate in-house. When the concoction has cooled down, the water solution should be made and applied to the dusty surface.

Nevertheless, there is a significant disadvantage of the proposed solution consisting of its short storage life, which is due to the purely organic composition. The solution to this problem through the development and introduction of additives is a further direction of research.

5 Conclusion

The problem of reducing the increased dustiness of atmospheric air in residential and industrial zones is acute for scientists and engineers. The solution to this issue is complicated because of such limiting factors as economic feasibility and environmental and sanitary safety. In this regard, the development of organic binding compounds for dust suppression is actively developing.

The developed method for determining the adhesion ability of dust suppressing solutions and a test bench for simulation makes it possible to estimate the value of adhesion of dedusting compounds, which is an important criterion for the correct selection of the most effective method of dust suppression and suitable components of the corresponding technological solution.

The developed organic dust suppressing compound allows to significantly reduce the aerotechnogenic load on the atmospheric air and does not present any environmental threat and danger to human health. Besides, the use of this solution allows an enterprise to save money on activities related to dedusting. Therefore, due to the efficiency, safety, and economic attractiveness of the proposed compound, it is recommended to use it for dust suppression on the technological roads of enterprises associated with the open-pit development of mineral deposits.

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