Master thesis

# Development and substantiation of technical solutions for dust suppression during mining operations at the open pit mines of the Kirovsk branch of JSC "Apatit"

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## Declaration of Authorship

„I declare in lieu of oath that this thesis is entirely my own work except where otherwise indicated. The presence of quoted or paraphrased material has been clearly signaled and all sources have been referred. The thesis has not been submitted for a degree at any other institution and has not been published yet."

# Abstract

The graduation paper is devoted to the development of measures focused on improving the working conditions of the personnel by the dust factor at the Koashva quarry of the Kirov branch of Apatit JSC. The subject of the study is the process of magnetization of aqueous media to provide greater efficiency of dust suppression in open pit mining. As a part of the study, the effect of a permanent magnetic field on the reduction of respirable dust fractions during dust suppression was determined on a self-manufactured laboratory model, and recommendations on the potential industrial implementation of the proposed measures were given. As a part of the risk-based approach, a model for comprehensive risk assessment of pneumoconiosis development was suggested for the open pit mine personnel.

The proposed methods to improve the working conditions have shown their effectiveness in terms of the occupational and industrial safety. The conducted risk assessment has allowed to identify the most harmful working zones, which require additional measures to be implemented for provision safe working conditions.

# Zusammenfassung

Die Abschlussarbeit widmet sich der Entwicklung von Maßnahmen zur Verbesserung der Arbeitsbedingungen des Personals durch den Staubfaktor im Steinbruch Koashva der Kirower Niederlassung von Apatit JSC. Gegenstand der Studie ist der Prozess der Magnetisierung wässriger Medien, um eine höhere Effizienz der Staubbekämpfung im Tagebau zu erreichen. Im Rahmen der Studie wurde der Einfluss eines Permanentmagnetfeldes auf die Reduktion von lungengängigen Staubanteilen bei der Staubunterdrückung an einem selbst hergestellten Labormodell ermittelt und Empfehlungen zur möglichen industriellen Umsetzung der vorgeschlagenen Maßnahmen gegeben. Als Teil des risikobasierten Ansatzes wurde ein Modell zur umfassenden Risikobewertung der Pneumokoniose-Entwicklung für das Tagebaupersonal vorgeschlagen.

Die vorgeschlagenen Methoden zur Verbesserung der Arbeitsbedingungen haben ihre Wirksamkeit im Hinblick auf den Arbeits- und Arbeitsschutz unter Beweis gestellt. Die durchgeführte Risikobewertung hat es ermöglicht, die schädlichsten Arbeitszonen zu identifizieren, die zusätzliche Maßnahmen zur Gewährleistung sicherer Arbeitsbedingungen erfordern.

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# 1 Introduction

**Relevance of the research topic.** Nowadays the human safety is an essential part of any sphere of human activity. For a long time, the safety and health of employees have been one of the most important priorities in all areas of activity, especially in such potentially dangerous and perilous areas as the mineral resource complex. And with the continuous development and scientific and technological progress, the negative impact of various industrial factors is only becoming more considerable. Thus, according to Rospotrebnadzor (The Federal Service for Surveillance on Consumer Rights Protection and Human Wellbeing of the Russian Federation) data from 2020, the share of occupational diseases in the spheres of economic activities for mining equals 40%, while 90% of all occupational diseases are associated with imperfection of technological processes and constructive shortcomings of labor tools. Hence, the issue of maintaining working conditions at the level at which it is possible to guarantee the preservation of the life and health of each employee is becoming more acute.

Today, there are many production factors that can cause harm to the health of personnel of industrial facilities, but the increased dustiness of the air of working areas remains one of the most significant factors in the industry. High concentrations of aerosols in the workplace can lead to irritation of the eyes and other mucous membranes, skin damage, the development of respiratory diseases such as asthma, bronchitis, pneumoconiosis, fibrosis and others. In addition, high dust concentrations can reduce visibility in the hazardous working area, which increases the risk of injury while operating, and can also act as an abrasive material and significantly accelerate the wear of equipment operating in conditions of high dustiness of the air (Su et al., 2020).

At the enterprises of the mineral resource complex, solid aerosols are formed at all stages of production, and the dust concentrations in the workplace can be several times higher than the maximum permissible concentration (MPC). For example, in open pit mining all stages of the technological process may be determined as the sources of intense dust emission: from large scale blast, excavation of rocks and their transportation by dump trucks to processing and storage in dumps and tailings. At the same time, the resulting dust cloud can travel considerable distances from the place of formation, thereby affecting not only personnel, but people and ecosystems even outside the sanitary protection zone (SPZ). Obviously, it is difficult to overestimate the importance of solving the problem of intense dust emission at all stages of production.

Today, the science has a goal not only to solve the problem of intensive dusting, but also to make the proposed solution economically feasible and not harmful for other systems and spheres, for example, ecology. Therefore, despite the wide variety of ways to reduce the dustiness of the air in the workplace, not every one of them is currently applicable or requires further development. The low efficiency of most of the modern proposed solutions to reduce air dust concentration is due to the large number of limitations and requirements for dust suppression means or is related to the focus on the total dust load, and not on the fine respirable fraction (Huang et al., 2019). Moreover, the process of dust formation is complex and involves the interconnection of many dependencies and processes, which leads to the impossibility of using a single solution and the need to select and develop unique methods in each individual case (Johann-Essex et al., 2017).

A significant contribution to the intense dust emission problem was made by such scientists as Azarov V.N., Beresnevich P.V., Dremov V.I., Zinoviev A.P., Kovshov V.P., Kovshov S.V., Kornev A.V., Korshunov G.I., Romanchenko S.B., Shuvalov Yu.V., Wang H., Zhang Z., Zhou Q., Xu G., Trechera P., Omane D., Johann-Essex V., Keles C., Mo J., Ma W. Rezaee M., Scaggs-Witte M. and others.

The scientific works of these and many other scientists are aimed at studying the properties of dust and dust-emitting materials that can affect the effectiveness of dust suppression and dust collection measures, at developing dust suppressing and binding agents for fixing dusty surfaces and reducing the intensity of dust emission, as well as at developing various tools and devices to increase the effectiveness of ways to reduce dustiness of the air.

The degree of knowledge on the properties of dusty materials does not allow us to state with complete certainty that these studies are sufficiently deep to be used as a scientific foundation for the further research of a broader profile. The developed dust suppressing and binding compounds are currently ineffective in reducing the respiratory fractions or their application is economically impractical due to the high cost of manufacture. And the means of increasing the efficiency of dust suppression are also insufficiently studied in the aspect of the possibility of their practical application in industrial conditions, which requires additional research both in the laboratory and in the field. In this regard, the development of new means to improve the efficiency of dust suppression and the study of the potential effectiveness of their implementation is an urgent and important modern task (Liu et al., 2021).

**Scientific novelty:**

- the dependence of the concentration of fine respirable dust formed in a floating cloud in the course of its movement along the wind flow on the model is determined.

- the dependence of the dust concentration of the respirable fraction on the magnetic characteristics of water during hydro-spraying on the model is established.
- a model for comprehensive risk assessment of the respirable pathology development was proposed for the workers of the open pit mines.

**The research purpose** is the improvement of working conditions of personnel engaged in open-pit mining by reduction of increased dustiness of the air. **The idea of the research** is to reduce the high dust load on personnel by treating dust-suppressing compounds and water-based products with magnetic fields to reduce their surface tension and improve wettability, which should lead to an increase in the effectiveness of the dust suppression measures.

**Research tasks:**

- To analyze the studies of the relationship between the properties of the dusting material and the deposition efficiency of the formed dust masses by existing dust suppression methods.
- To analyze existing approaches to improving the efficiency of dust suppression by means of the influence of magnetic and electromagnetic fields on water-based dust suppression agents.
- To formulate a hypothesis about the influence of permanent and non-permanent magnetic fields on the physicochemical properties of dust suppressants and their effectiveness.
- To make a laboratory stand simulating the ground surface on the territory of the open pit mine, using equivalent materials.
- To conduct experimental studies on the self-made laboratory stand to determine the effectiveness of dust suppression by hydro-spraying with ordinary water and magnetized water;
- To process the obtained experimental data and summarize the results of the study, including the possibility of using the proposed problem solutions in industrial conditions.
- To propose a risk assessment model for determination of the risks of respiratory diseases development in the open pit mine and perform the risk assessment as a part of the risk-based approach.

**Research methodologies.** The work was carried out using a set of methods, including: analysis of scientific literature sources of Russian and foreign scientists studying the issues of dust formation and dust suppression in open pit and underground mining; laboratory methods for studying the processes of dust emission and dust suppression; analysis of the dispersion of dust material using the laser diffraction and the optical method of dynamic image analysis. The research was carried out on the basis of the Center for Geomechanics and Problems of Mining Production of St. Petersburg Mining University, and using laboratory equipment of the Department of Industrial Safety. Up-to-date software was used to process and mathematically analyze the results of the experimental studies.

**Practical significance of the research:**

1. A laboratory stand has been developed to assess the dustiness of the air, considering the roughness of the profile of a linear dust source, and to assess the effectiveness of hydro-spraying for dust suppression.
2. Recommendations have been given for improving the efficiency of dust suppression due to the magnetization of aqueous media and increasing their wetting ability.
3. A risk assessment model has been proposed for evaluation of risks of respiratory diseases development for the workers of the open pit mines.

The possibility of conducting further research on the use of non-constant electromagnetic fields to increase the efficiency of dust suppression based on the obtained empirical data.

# 2 Theoretical and methodological fundamentals of the research

## 2.1 Statistics of professional morbidity

Modern conditions of human activity are characterized by a constant increase in the amount of resources consumed, in the volume of their extraction and production, thus an increase in the intensity of the impact of harmful and dangerous production factors on employees of enterprises is also observed and, as a result, the risk of developing of professionally caused diseases increases (Korshunov et al., 2012; Nosatova, Semeykin, 2018).

The analysis of statistical data on occupational morbidity of workers of industrial enterprises and, in particular, enterprises of the mineral resource factor allows not only to understand the general state of occupational morbidity of personnel, but also to identify the main problems related to occupational and industrial safety at work, as well as to substantiate the relevance of the problem being solved and the importance of its solution.

Thus, to indicate the urgency of the problem of increased air dustiness and occupational respiratory diseases, a number of scientific papers devoted to the study and compilation of statistical data on occupational morbidity, in particular, at mining enterprises, were analyzed, and official reporting documents of state bodies were considered as well.

First of all, it is important to refer to official sources of statistical information, among which the Ministry of Labor of the Russian Federation, the Federal Service for Supervision of Consumer Rights Protection and Public Welfare (Rospotrebnadzor) and the Federal State Statistics Service (Rosstat) are the most important in the field of labor conditions and safety.

The report of the Ministry of Labor of the Russian Federation "Results of monitoring of labor conditions and safety in the Russian Federation in 2020", the state report of Rospotrebnadzor "On the state of sanitary and epidemiological welfare of the population in the Russian Federation in 2020", as well as the data from Rosstat "Information on occupational injuries and occupational diseases" for 2021 were selected for analysis.

According to the data of the Ministry of Labor of the Russian Federation on professionally caused diseases in 2020, the number of jobs and employees who, as a result of a special assessment of working conditions, were assigned to a class of working conditions 3.1 (harmful, 1$^{st}$ degree) decreased, and the number of determined jobs with a class of working conditions 3.2 – 3.4 (harmful, 2$^{nd}$ – 4$^{th}$ degrees) increased by about 3% in 2020 compared to 2019.

Taking into account the distribution of harmful and (or) hazardous production factors at mining enterprises, every third workplace at mining facilities is exposed to aerosols of predominantly fibrogenic action (APFA), which is the industrial dust that can cause fibrosis and pneumoconiosis development in personnel. Thus, the share of workplaces exposed to APFA is 6.77% and ranks 3rd among all other factors of the production environment (Fig. 1).

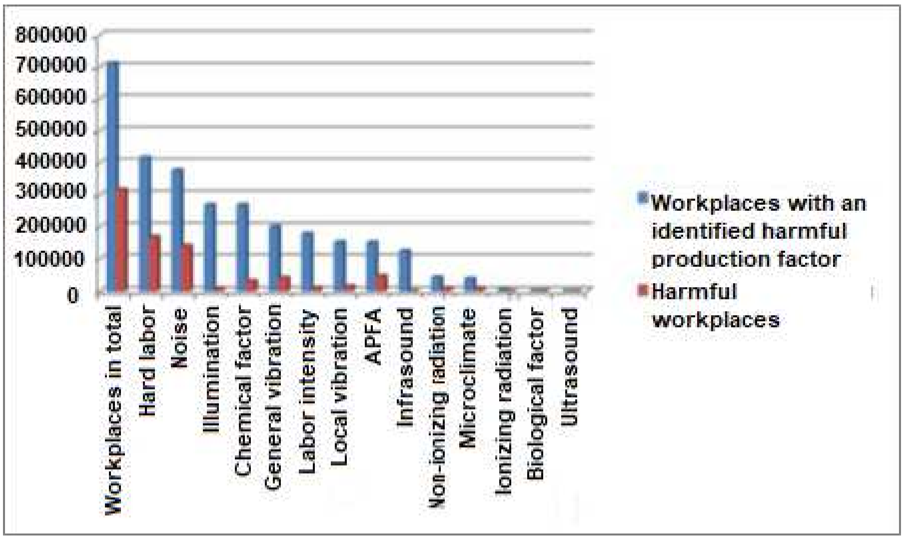



**Figure 1: Distribution of production factors in the workplaces of mining enterprises (according to the Ministry of Labor of the Russian Federation)**

Nevertheless, according to the official data, in 2020, a decrease in the share of occupational diseases in the mining industry was registered in comparison with 5 other most hazardous areas of economic activity and amounted to 40.44% (Fig. 2). It is worth noting that 40.44% is still a very high level of occupational morbidity, especially considering that in the processing industry, characterized by a very large release of dispersed systems, toxic substances, etc., the share of professional diseases (PD) was only half of the number of professionally caused diseases in the field of mining (22.16% of the total number of PD out of the 6 most harmful and dangerous spheres of economic activity).

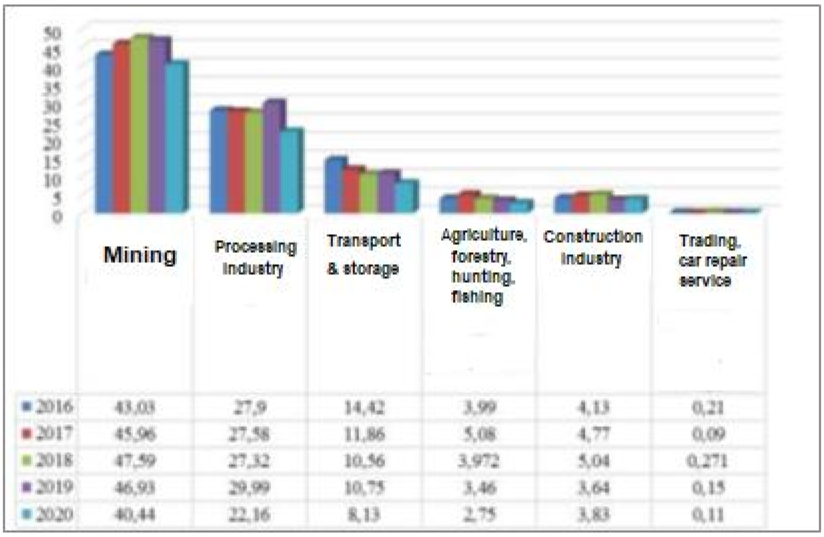



**Figure 2: The share of PD in the most harmful and dangerous types of economic activity (according to the Ministry of Labor of the Russian Federation)**

Taking into account the data presented in the state report of Rospotrebnadzor in 2020, the occupational morbidity in Russia in 2020 decreased in comparison with the previous year of 2019 and in general amounted to 0.78 per 10,000 employees, including 0.61 per 10,000 employees for occupational diseases, and 0.17 – for acute occupational poisoning (Fig. 3).

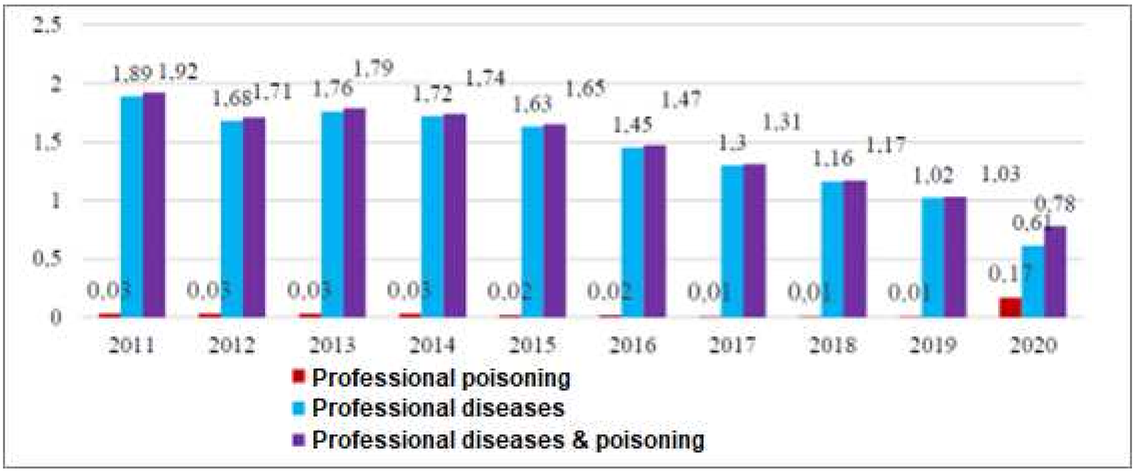



**Figure 3: The distribution of PD in the time scale (according to Rospotrebnadzor)**

At the same time, the presented data indicate that in the structure of occupational pathology for 2020, the morbidity associated with the effects of APFA ranks only 4th and accounts for 10.91% among the other causes of the development of PD (Fig. 4).

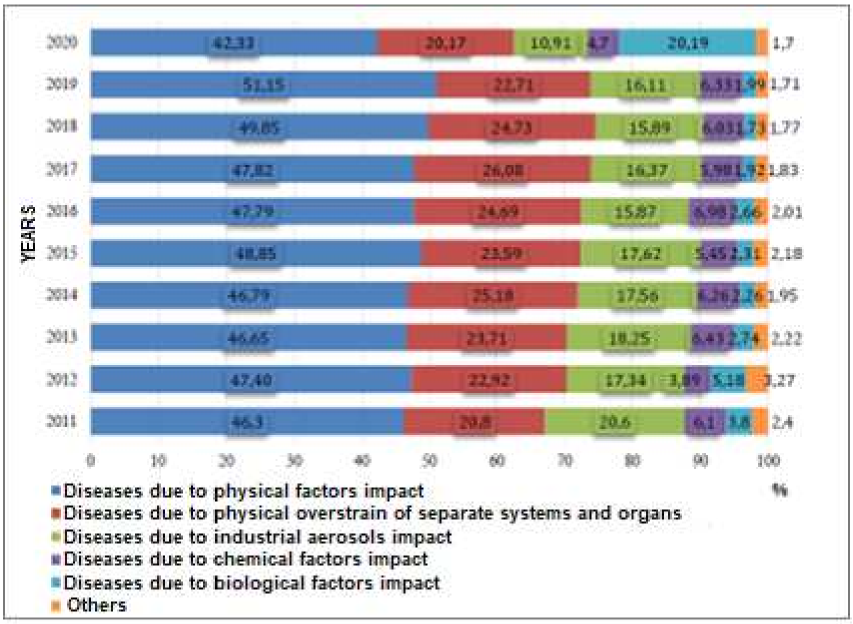



**Figure 4: The structure of occupational morbidity of personnel according to the affecting production factors (according to Rospotrebnadzor)**

It is important to note here that in comparison with 2019, there is a 20% increase in the share of biological factors in the structure of the main factors that led to the development of occupational pathology (20.19% in 2020), which is obviously related to the COVID-19 pandemic. Nevertheless, these statistics do not take into account how the action of certain production factors, including industrial aerosols, could affect the development and consequences of coronavirus infection in this case, as well as whether production factors could provoke the development of infection in an employee whose body could safely resist the diseases before the exposure to any factor.

Moreover, the issue of concealing the fact of the establishment of occupational diseases in employees remains significant. A number of factors and reasons can force the staff or the employer to conceal the fact that an employee has received an occupational disease, and in this case, there even may be cases not of concealment, but of substitution of established diseases with coronavirus infection, since 2020 has become one of the peak years in terms of morbidity worldwide. For example, exposure to industrial aerosols on an employee can cause the development of pneumonia in the same way as COVID-19. Moreover, the lungs of an employee who has been under the influence of APFA for a long period of time change their structure as a result of the development of fibrosis, pneumoconiosis and other diseases caused by the fibrogenic effect of aerosols. This leads to an "illuminated" image on X-ray and tomographic medical examination of the lungs, similar to studies of lung tissues after diagnosis of coronavirus infection in patients. An analysis of the causes of such circumstances of concealment and substitution of the facts of occupational diseases, as well as examples of studies devoted to this problem, are given below in this section of the Master's thesis.

The analysis of the structure of respiratory professionally caused diseases shows that the development of about 87% of all respiratory diseases in workers is caused by exposure to industrial aerosols (Fig. 5).

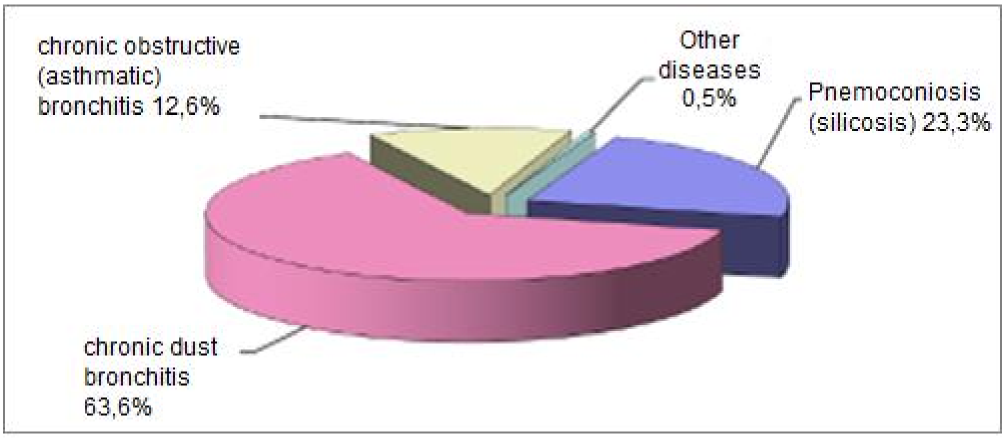



**Figure 5: The structure of respiratory occupational diseases (according to Rospotrebnadzor)**

This can be explained by the fact that the only significant proportion of diseases in the presented diagram (12.6%) are chronic obstructive bronchitis, which in most cases can be provoked by the action of viruses and infections. Such a significant proportion of respiratory diseases due to the impact of APFA (86.9%) confirms the importance and relevance of the problem of increased dustiness in the workplace of enterprises, and also emphasizes the need for the implementation of effective measures to reduce dust load.

It is also noteworthy that the statistics of occupational morbidity in the spheres of economic activity from the Ministry of Labor of the Russian Federation does not coincide with the same statistics from Rospotrebnadzor. Thus, according to Rospotrebnadzor, the share of professionally caused diseases in the field of mining was 46.93%, and not 40.44% for the data from the Ministry of Labor of the Russian Federation (Fig. 6).

After careful analysis of the data, it can be concluded that the statistics of Rospotrebnadzor on occupational morbidity for 2020 coincide with similar statistics of the Ministry of Labor of the Russian Federation, but for 2019.

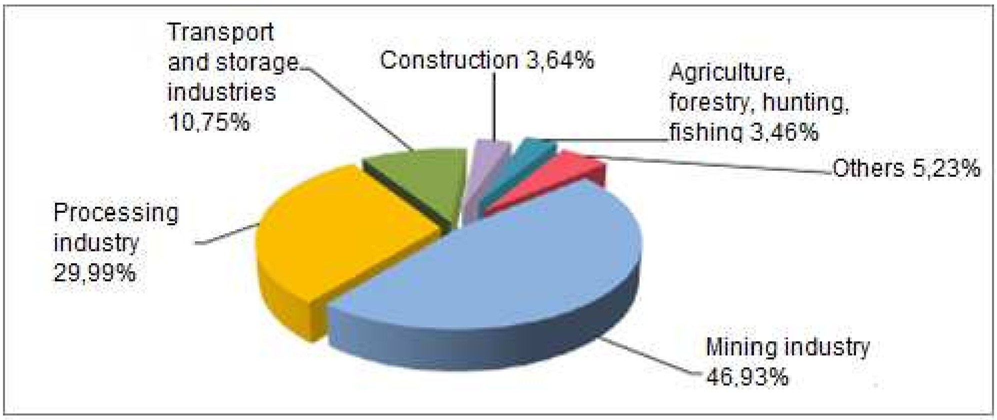



**Figure 6: The distribution of occupational diseases by spheres of economic activity (according to Rospotrebnadzor)**

Separately, it can be noted that, according to Rospotrebnadzor, the indicator of occupational morbidity per 10,000 employees in some subjects of the Russian Federation exceeded the same indicator but averaged across Russia for 2020 (0.78 per 10,000 employees). The list of these territories also includes the Murmansk Region (2.96 per 10,000 employees), on the territory of which the Koashvinsky apatite-nepheline quarry is located, in relation to which this study was conducted.

It is also important to emphasize that, according to the analysis of the causes of the development of occupational pathology in industrial personnel conducted by Rospotrebnadzor, more than 90% of all occupational diseases are due to imperfection of technological processes (45.04%) and constructive shortcomings of labor tools (45.17%), which indicates the necessary focus of research and development of measures to reduce occupational morbidity exactly due to these causes of occupational diseases (Fig. 7).

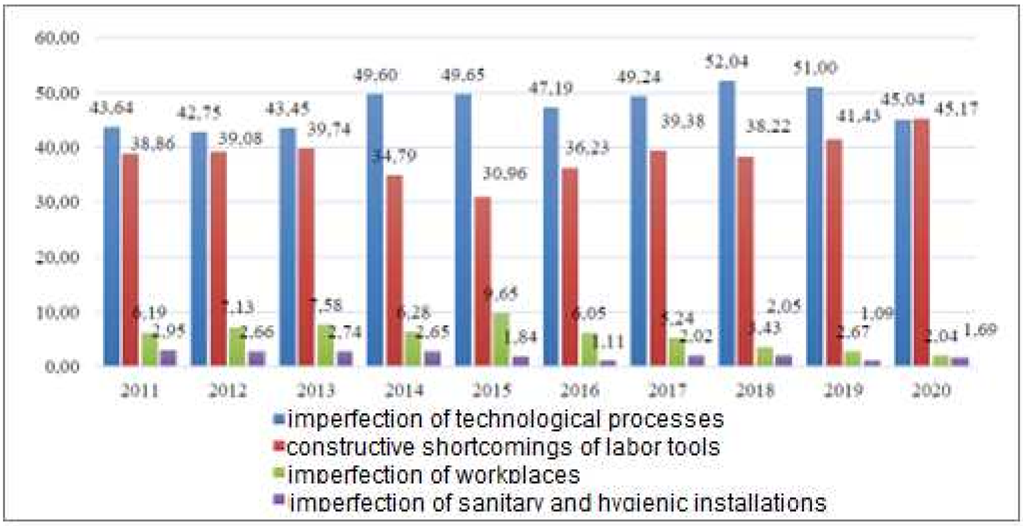



**Figure 7: Causes of the development of PD in personnel (according to Rospotrebnadzor)**

In addition to the official sources of statistical information concerning the occupational morbidity of personnel, it is also important to consider studies devoted to the investigation of occupational pathology in employees of enterprises, the causes of its occurrence and the circumstances of intentional reduction in the reliability of official statistical information.

Thus, the study of N.V. Vadulina and co-authors is devoted to identifying problems that can lead to an increase in occupational morbidity at mining enterprises, as well as problems related to the discrepancy between statistical and forecast data on occupational morbidity of employees (Vadulina et al., 2020).

First of all, the authors note a significant difference between the official statistics on professionally caused diseases and their predicted number. According to scientists, there is a low interest of both the employer and the employee to disclose the fact of the establishment or occurrence of a case of injury or occupational disease due to several factors, and thus the official statistics of personnel diseases as a result of the impact of factors of the production environment is significantly underestimated. As an example, the authors provide statistics on occupational morbidity of workers in the United States, where, according to the official data, more than 500 thousand confirmed cases of occupational diseases are registered annually, whereas, according to the authors, 12-13 thousand annually diagnosed cases of PD are officially confirmed in the Russian Federation (Vadulina et al., 2020).

Among the reasons for concealing and substituting the fact of establishing an occupational disease in employees, the authors of the study identify a number of such:

- The lack of interest of the employer in the officially confirmed case of PD among the personnel, since in this case there is a need for compensation payments to the employee for his treatment and rehabilitation, the insurance rates paid to the Social Insurance Fund (FSS) are increased (up to 40% of the surcharge), which in turn significantly reduces the employer's profit. Thus, the employer's investments in labor protection are due to legislative necessity, and not motivation to improve working conditions and workplaces.
- The employee's low interest in the official registration of the fact of occupational disease due to the risk of transfer to a safer, but less paid job, as well as the risk of complete loss of either working capacity (justified by medical examinations) or the loss of the place of work (dismissal of a "problem" employee by the employer for some fictitious reason).
- Low interest of a medical organization in establishing an occupational disease due to the possible loss of an important client in the future (Vadulina et al., 2020).

In the scientific work by Chebotarev A.G., the author analyzes the state of working conditions at workplaces of enterprises engaged in both underground and open pit mining according to a wide list of factors of the production environment (Chebotarev, 2018). In particular, the author of the study points out that increased dustiness of the air remains one of the most significant factors of the production environment, leading to the development of occupational pathology in workers. As an example, A.G. Chebotarev speaks about the state of the dust factor in underground conditions, where in some places, during mining operations, dust concentrations can be 2-10 times higher than the maximum permissible concentrations (MPC). At the same time, the scientist notes that sometimes even the most advanced engineering systems and solutions at the moment are unable to reduce the dust load on employees of the open pit and underground mining enterprises. Also, an interesting remark of the author of the study is that dustiness of the air can be a much more harmful and destructive factor of the production environment in combination with other factors, for example, noise, illumination and microclimate. According to the scientist, the combined effect of these production factors can have a more pronounced harmful effect on the worker’s health.

Another scientific work by E.A. Alshits and I.A. Kulkova is devoted to evaluating the effectiveness of measures to reduce occupational morbidity and injury in workplaces funded by the employer (Alshits, Kulkova, 2018). The authors carried out a comparative analysis of the volume of investments in occupational safety with the effectiveness of funded activities on the example of the Sverdlovsk region. Separately, scientists emphasize that the occupational pathology of the respiratory organs in this region for the year under study was in third place (22 cases) after diseases of the musculoskeletal system (48 cases) and hearing loss (28 cases) in terms of the number of established cases. According to the authors, the number of policyholders in the Sverdlovsk region has decreased, but the amount of funding for preventive labor protection measures, on the contrary, has increased. At the same time, a comparative analysis of the volume of costs and the number of cases of injuries and occupational diseases conducted by the authors of the study shows a negative correlation between the studied parameters, which means that with an increase in the cost of financing of preventive measures, there is a decrease in the number of cases of occupational diseases and injuries at work.

## 2.2 Analysis of the technological process by the dust factor

The research, presented in the Master's thesis, was partially carried out in the conditions of the Koashvinsky apatite-nepheline quarry belonging to the Vostochy (Eastern) mine of the Kirov branch of Apatit JSC. An important stage of the research and preparation of the graduation paper is the analysis of the technological process taking place at the Koashva open pit from the point of view of the dust factor and its potential harmful effect on the workers of the mining facility.

According to the project, the contour of the Koashvinsky quarry is stretched between the south-western and north-eastern directions. The extraction of the deposit is carried out by ledges with a height of 10 m – from the surface to the horizon of 100 m, below the horizon of 100 m – it is worked out by ledges with a height of 12 m. Table 1 shows the geometric parameters of the Koashvinsky quarry.

Such geometric parameters primarily characterize the quarry as a significant areal source of dust load. Moreover, such a depth of the quarry (more than 500 m) it can contribute to the appearance of recirculation of air descending into the quarry, thereby leading to the accumulation of hazards and, in particular, an increase in the concentration of dust in the workplace.

| Parameter | Units | Value |
|---|---|---|
| Dimensions on surface: | | |
| – length | m | 3700 |
| – width | m | 2170 |
| Dimensions on bottom: | | |
| – length | m | 470 |
| – width | m | 90 |
| Maximum depth: | | |
| – including the mountain part | m | 960 |
| – by closed contour | m | 580 |
| Lowest bottom elevation | m | - 290 |

**Table 1: General geometric parameters of the Koashvinsky quarry**

At the same time, 2 sites are conditionally allocated at the Koashvinsky field itself: mountain and valley. The upland area is characterized by a significant difference in elevation (from 900 m to 300 m above sea level). The valley site is located in the river valley of the Vuonnemjok River and therefore it is characterized by small changes in the elevation of the surface (from 280 m to 300 m).

Upon reaching the design contour of the quarry and establishing the technological process in terms of the operation of quarry equipment and its use, since 2020, the productivity of the Koashva quarry has reached 3.7 million tons of ore per year.

The following operating time schedule and mode were adopted for mining operations at the Koashvinsky quarry:

- stripping, mining and drilling operations at the quarry are carried out for 340 working days a year, in 2 shifts of 12 hours a day.
- blasting operations at the quarry are carried out only during daylight hours.
- the work of support services and IT is carried out according to an intermittent work schedule in one shift for 8 hours a day, 5/2.

At the moment, the scheme of transport communications on the territory of the Koashva quarry is presented in the form of systems of automobile pit exits, technological roads on the surface, providing transport links between mining operations and the ore transshipment warehouse. In addition, there are 2 operational dumps and an industrial site of the Vostochny mine located outside the quarry.

Technological automobile quarry roads on the surface, designed to move overburden rocks to existing dumps, as well as extracted ore to an ore warehouse, are located along the perimeter of the Koashva quarry.

Technological highways located along the perimeter of the quarry have a very long length and represent a large-scale linear source of dust formation, making the greatest contribution to the dust situation at the quarry (Kovshov et al., 2019).

The transport connection between the mining and overburden horizons of the quarry with the ore transshipment warehouse and dump No. 2 is provided by a system of stationary exits, which is located on the southern part of the quarry and runs along the non-working side. The overburden faces at the quarry with dump No. 3 are connected by a system of temporary automobile exits, the exit system itself is located on the northern side of the quarry.

Stationary automobile ramps, subject to the technology of their laying, do not represent a potential intensive source of dusting, whereas temporary ramps, on the contrary, are characterized by low soil strength, increased potential for wind erosion and dust removal.

The parameters of exits and permanent transport berms up to the horizon of 130 m are taken into account the use of dump trucks with a capacity of 218 tons in the future, below – for dump trucks with a capacity of 130 and 136 tons.

At the Koashvinsky deposit, overburden rocks consist of strong and medium-strength rocks, loose quaternary deposits (moraine) and secondary overburden.

The ore deposit, which in turn consists of 11 ore bodies, is characterized by an alternation of formation-like bodies of apatite-nepheline ores and massive urtites.

The entire volume of rock mass, including secondary overburden rocks, as well as 10% of loose sediments must be destroyed (loosened) by drilling and blasting.

The development of the Koashvinsky deposit is carried out using a transport system with the use of excavators-mechanical shovels, hydraulic excavators, as well as motor transport. Overburden rocks, according to the accepted scheme, are placed on external dumps and stacked with the help of bulldozers.

EKG-10 excavators and hydraulic excavators CAT-6018 (RH-90C), CAT-6030 (RH-120E), whose equipment is presented in the form of both "forward" and "reverse" shovels, were taken as the main mining equipment for the development of rock overburden, loose quaternary (moraine) rocks and ores.

The gradual increase in the annual productivity of the mining operations carried out is also taken into account, in connection with which it is also decided to purchase and replenish the mining equipment, including EKG-10 excavators, Caterpillar CAT-6030 (RH-120E) diesel-hydraulic excavators, of the "reverse" and "face shovel" type with bucket capacity, respectively, 13.6 and 15 $m^3$.

Moreover, taking into account the increasing production volumes during the transportation of rock mass, the project assumes the replacement of the used dump trucks with BelAZ-75131 and CAT-785C with a load capacity of 130 and 136 tons.

Drilling operations on boreholes with a diameter of 250 mm are carried out using drilling rigs SBSH-250MNA-32 and D-75KS. The creation of the slope of the ledge after the explosion is carried out using the FlexiROC D65 drilling rig. At the same time, the diameter of the contour boreholes for blasting is 180 mm.

Blasting operations are carried out with the use of emulsion explosives. According to the project, blasting operations at the Koashvinsky open pit are carried out once a week.

Secondary destruction and crushing of oversized pieces of rock boulders formed as a result of blasting and insufficient explosive loosening is carried out with a hydraulic hammer H120Ss equipped on a CAT-320DL quarry excavator.

At the moment, the storage of recoverable overburden at the Koashva quarry is carried out at external dumps: No. 2, No. 3 and No. 4, which are located along the perimeter of the Koashva open pit mine. Dumping at the Koashva quarry is carried out with the help of bulldozers T-35.01, T-500, CAT-D10T.

From the working ore faces, the extracted minerals are transported to the ore transshipment warehouse. The transshipment point is designed for loading the delivered ore using EKG-12.5 excavators into 2BC-105 railway dumpcars. After loading, dumpcars are transported by electric locomotives to the ANOF-3 processing plant.

## 2.3 Measures for air protection

The described technological process and each of its stages make a significant contribution to the overall dust load on personnel and the environment. To reduce emissions of pollutants in the form of solid aerosols into the atmosphere and to reduce the negative impact of open pit mining on personnel and on the environment, the company provides a number of measures to protect the atmospheric air.

At the Koashvinsky quarry, the following methods are used to reduce the intensity of dust formation:

– drilling of boreholes with rolling cutter bit using dust suppression with a water-air mixture. The dust suppression efficiency is 95-97%.

- hydro-spraying of the blasting block with dust suppression efficiency up to 90%;
- humidification in the face of the loosened rock mass with dust suppression efficiency up to 85%;
- irrigation of highways in the warm season with dust suppression efficiency up to 70%.

In turn, measures to protect atmospheric air due to the pollution from the external waste rock dumps include:

- humidification of the material within the limits allowed by the technological process, with dust suppression efficiency up to 90%;
- irrigation of the surface of dumps, roads in the warm season.

## 2.4 Reclamation of the disturbed lands

In addition to the operational control measures and reduction of dust emissions into the atmospheric air during the operation of the Koashva quarry, the organization also provides for the reclamation of disturbed lands as a result of open pit mining.

The main sources of violation of land resources during the development of the Koashvinsky quarry are:

- quarry.
- waste rock dumps and off-balance ore warehouses.
- system of water-lowering and hydro-observation wells.
- highways and ground facilities of engineering infrastructure.
- drainage ditches of clean and dirty waters.

The general list and characteristics of the objects of the Koashvinsky deposit, which are the sources of impact on land resources and soil cover in the area of the location of the mining object are given below:

1. Quarry excavation with a depth of up to 960 m, taking into account the upland part and up to 580 m in a closed contour, with a total surface area of 578 hectares.

2. Overburden dump No.2. The area of the dump on the earth's surface is 566.1 hectares. The total area of the recultivated surface of the dump is 626 hectares.
3. Overburden dump No.3. The area of the dump on the earth's surface is 156.8 hectares. The total area of the recultivated surface of the dump is 172.2 hectares.
4. Off-balance non-feasible ore warehouse No. 2, formed after the end of operation of the dump No. 3.
5. Overburden dump No.4. The area of the dump on the earth's surface is 200.3 hectares. The total area of the recultivated surface is 207.6 hectares.
6. Overburden dump No. 5. The area of the dump on the earth's surface is 323.2 hectares. The total area of the recultivated surface of the dump is 352.2 hectares.
7. Off-balance non-feasible ore warehouse No. 1 formed after the end of operation of the dump No. 4.
8. The system of water-lowering and hydro-observation boreholes. At the end of the quarry development, the actual number of water-lowering boreholes will be 24 pieces, the total number of hydro-observation boreholes will be 19.
9. Drainage ditches of clean and dirty waters.
10. Highways built during the construction and operation of the quarry.

According to the regulatory documentation approving the norms for the implementation of measures for the reclamation of lands disturbed due to the extraction of minerals by open pit mining, the following requirements must be met when implementing these measures:

- preliminary removal and storage of the fertile soil layer, selective development of potentially fertile overburden rocks in the volumes necessary to create a cultivation layer.
- creation of dumps and quarry recesses taking into account their reclamation and accelerated return of uncultivated areas for use in the national economy.

- formation of dumps and quarry recesses resistant to landslides and scree, protected from water and wind erosion by afforestation, laying and (or) treatment with special chemical and other materials.
- carrying out measures to organize the concentrated runoff of stormwater and industrial waters by installing special hydraulic structures.
- cleaning or harmless removal of drained water from dumps containing toxic substances.
- provision of measures to regulate the water regime in the cultivation layer of rocks with unfavorable water-physical properties.
- creation of a screen made of capillary-breaking or neutralizing materials (sand, stone, gravel, film, etc.) in the presence of toxic rocks at the base of the reclamation layer.
- formation of dumps with combustible rocks, according to technological schemes, excluding their spontaneous combustion.

There are no agricultural, environmental, recreational, historical and cultural lands on the territory of the Vostochny (Eastern) Mine facilities, therefore, taking into account the natural conditions and location of the disturbed site, as well as the economic and socio-economic conditions of the enterprise's location area, the company has adopted the following direction of reclamation of disturbed lands:

- “sanitary and hygienic” – for land used for mining complex facilities, construction sites of new mine facilities and overburden dumps (type of land use – abandonment of land for self–healing);
- “water management” – for the quarry site (type of land use – reservoirs).

## 2.5 Reclamation measures at Koashvinsky open pit mine

After the full development of the mineral reserves of the deposit, the technical liquidation or conservation of production facilities: buildings, structures, engineering communications should be performed. The liquidation or conservation of the facility is carried out according to projects, in compliance with the requirements of industrial safety, protection of mineral resources and the environment.

The service life of the Koashvinsky quarry, according to the approximate calculated data of the enterprise and taking into account the operational ore reserves, will be 66 years.

After the completion of mining operations and the termination of the operation of the quarry drainage system natural filling of the quarry is provided by the groundwater and precipitation.

In accordance with the requirements of the regulatory documentation for the liquidation of spent mining facilities, the company provides for the installation of fencing of the developed space, recultivated as a reservoir. Fencing is carried out along the top around the quarry to prevent people and animals from entering the territory of the spent quarry.

According to an approximate estimate of the time of the flooding of the quarry performed at the enterprise, the restoration of groundwater levels to static levels will occur in 23-24 years. The calculation of the rate of recovery of levels in the quarry when the drainage system is turned off is based on the value of the actual water inflow into the quarry due to groundwater in winter (from November to April inclusive), which is 3400 m3/hour.

The analysis of the climatic and economic conditions of the area allows us to draw the following conclusions on the choice of the direction of reclamation:

- there are no agricultural, environmental, recreational, historical and cultural lands on the territory of the Vostochny (Eastern) Mine facilities.
- the soil and vegetation layer on the territory of the Vostochny (Eastern) Mine is poor in organic and nutrient elements (its thickness in the areas of the territory under consideration is less than 0.1 m). According to the normative documents regulating measures for the preservation of the fertile layer and the classification of unproductive lands for land use, such soils are not previously removed from the territory, and a separate warehouse of the soil layer is not organized.

Recultivation works in open-pit mining also provide for the implementation of measures to prepare the lands that are released after construction work and after the development of the deposit for subsequent use and include:

- earthworks to restore disturbed lands.

- filling of drainage channels, irrigation and terracing of slopes of overburden dumps, filling and leveling of dips.
- rough and fine leveling of the surface of disturbed lands.
- biological reclamation.

Earthworks for the restoration of lands disturbed during the construction of new facilities and sites under the objects of the mining complex include work on filling the formed recesses, pits and trenches with soil extracted on site or imported soil from nearby dumps to the marks of natural relief, cleaning the territory from cluttering with waste, planning and leveling of recultivated surfaces.

Borehole liquidation is carried out by plugging, which includes dismantling of the borehole equipment and isolation of exploited aquifers by pumping cement mortar into the well in order to exclude possible chemical and bacteriological contamination of aquifers from the surface.

Thus, the main volume of reclamation works provided by the enterprise falls on overburden dumps.

In the conditions of dump formation at the Koashva apatite-nepheline quarry, there is no need to carry out special measures to remove and store the fertile, which is due to the low capacity and depletion of the soil and vegetation layer and the recommendations of regulatory documents. In this regard, the application of a layer of fertile land to the surface of rock dumps is not carried out.

Recultivation of overburden dumps provides for:

- carrying out the mining stage of recultivation.
- carrying out a biological stage in order to improve landscape and aesthetic criteria and reduce wind erosion of dumps.

Reclamation works should ensure:

- prevention of activation of hazardous geomechanical processes.
- intensification of the process of formation of a sustainable biocenosis.
- prevention of pollution of water basins.
- prevention of failure of people and animals, fencing of dangerous areas.

The mining and technical stage of reclamation provides for the implementation of measures to prepare the lands that are released after the development of the deposit for subsequent use.

The technical stage of recultivation of overburden dumps at the Koashvinsky quarry includes the following types of work:

- excavation work to restore disturbed lands.
- terracing of slopes of dumps.
- rough and fine surface layout.

The application of a fertile layer to the surface of rock dumps is not carried out due to the low power of the soil and vegetation layer depleted of organic and nutrient elements (its thickness in the areas of the territory under consideration is less than 0.1 m).

The main volume of the mining and technical stage of recultivation for the period of completion of work at the Koashvinsky quarry is carried out in the process of forming dumps and provides for the following complex of works:

- terracing of slopes of dumps.
- carrying out work on leveling the surface of the upper tier of dumps and berms.

The main task of the levelling is to bring the technogenic relief into a condition suitable for the intended use. All small recesses, sinkholes, collapse zones are filled in, and if necessary, an additional set of measures is carried out to ensure safe operating conditions of the restored sites.

In accordance with the regulatory documentation, land leveling is divided into rough and fine. Rough leveling of the land is the preliminary leveling of the surface with the execution of the main volume of earthworks. The final leveling of the land is the final leveling of the surface and correction of the microrelief with insignificant amounts of excavation work.

Poor quality of land leveling leads to uneven soil moisture, disturbance of surface runoff and stagnation of water in low-lying areas. All this reduces the efficiency of the use of reclaimed land and often requires large amounts of repair work.

In turn, the irrigation and terracing of the slopes of the dumps are carried out in order to increase stability, prevent local destruction and eliminate harmful effects on the environment. Steep slopes are more prone to landslide phenomena, water and wind erosion. Landscaping and effective use of steep slopes (slopes) is significantly difficult.

In the light of modern knowledge about the role of the Earth's soil envelope in maintaining a stable state of the biosphere and the global nature of man-made impacts on natural complexes, restoration of disturbed lands at the present level is considered primarily as restoration of ecosystem (soil-ecological) functions of the territory to preserve the stable state of the biosphere.

The location of the Eastern Mine overburden dumps in combination with meteorological factors determines the volume and type of biological reclamation. Vertical zoning determines the temperature regime and general properties of the soil cover, which is characterized by a decrease in power and an increase in skeletal composition with elevation. Up to the level of 405 m, the soil and vegetation layer of the territory is represented by shrubby forest vegetation (dwarf birch, berry bushes, mosses), higher up the slope vegetation is represented by mosses and lichens.

These circumstances determine the volume of biological reclamation: biological reclamation according to climatic conditions can only be carried out on tiers located up to the 405 m mark. On the upper tiers located above 405 m, biological reclamation by sowing or planting any plants is difficult: only self-infestation of rocks with mosses and lichens growing at a given height of the mountain can occur here, and measures for surface reclamation will consist in creating favorable conditions for this process.

According to most of the factors determining the process of the self-resoration of land on the dumps of the Koashvinsky quarry, the conditions for restoring vegetation cover are good and satisfactory, including the content of fine-grained soil in overburden rocks, the average width of disturbed areas, the general characteristics of the surrounding landscape and its proximity to natural landscapes, the presence of organic matter in the surface layer, the general appearance of the surface relief. In addition, a significant content of coarse-grained material in rocks prevents water and wind erosion of the surface.

Taking into account all these factors, it can be assumed that the natural recovery process will be protracted, multi-stage and long in duration due to harsh edaphic conditions. However, the species composition will be enriched as the biotope is formed, and zonal and climatic conditions will prevail.

Biological recultivation of overburden dumps at the Koashva quarry consists in sowing perennial grasses –grasses Leymus arenarius, widely growing on the coastal dunes of central and northern Europe. On the Kola Peninsula, it grows along the entire coast, as well as on the shoals of large lakes, which indicates good stability of this vegetation in the meteorological conditions of the Murmansk region and the Arctic Circle.

Biological reclamation works should be carried out in the summer.

The sowing of Leymus arenarius on the surface of the slopes of the dump is carried out with the help of hydraulic sowing, that is, a mixture of seeds and liquid media. To apply a hydraulic mixture consisting of seeds, water, fertilizers and film-forming substances, a watering machine UMP-1 is used on the slope surface. The consumption of the hydraulic mixture during irrigation measures is 15 $m^3$/ha.

It is possible to intensify the process of self-restoration of the surface of dumps by creating favorable conditions for the accumulation of products of geochemical destruction of rocks by eliminating water and wind erosion, conducting agrochemical reclamation through the introduction of organic and mineral fertilizers and the formation of a relief that promotes the consolidation of seeds and spores of plants included in the succession of this territory. This is achieved by applying film-forming reagents to the surface together with a complex of mineral fertilizers.

The surface treatment of the slopes of the dumps using the described hydraulic mixture is carried out 1 time.

These measures make it possible to reduce the intensity of atmospheric air pollution with solid aerosols in order to reduce the negative impact on personnel and the environment not only during the operation of the Koashva quarry, but also after the end of mining operations. This, in turn, will avoid a significant deterioration of the environmental situation in the conditions of the mining region and exclude the possibility of negative consequences caused by the technogenic factor.

## 2.6 Influence of the dust factor on the health of the employee

In addition, it is also necessary to describe the physiological effect of dust on the human body to indicate the importance of solving the problem of increased dustiness of air in the workplace, since the action of APFA is characterized by a number of features that determine the importance of the dust factor for society.

Recently, the direction of research devoted to a deeper study of the properties of dust particles and the source of dust masses has been gaining popularity, since knowledge of certain dust parameters, as well as the correlation of these parameters with the physicochemical properties of dust, can make it possible to better understand the features of the impact of the dust factor on the worker's body, as well as determine the most effective way to reduce dust. The question of the dependence of the properties of dust and the effectiveness of suppressing it is discussed in chapter 3 of the Master's thesis.

If the physiological effect of dust on the worker's body is to be considered, in this case it is also important to know certain characteristics of dust particles. For example, softer and longer dust particles can settle on the mucous membranes of the upper respiratory tract and have a greater potential for the development of tracheitis and bronchitis. Moreover, a higher solubility of dust leads to its entry into the blood and increased harmful effects (Kasymov, 2021).

Also, the harmful effects of industrial aerosols are mainly determined by the depth of dust particles entering the respiratory tract, since part of the dust particles linger in the nose and nasopharynx, part of them – linger in the upper respiratory tract, trachea and bronchi, and the rest of them – get deep into the lungs, damaging the pleura and alveoli. Dust in the latter case, capable of penetrating so deeply into the lungs, has the most disastrous effect on the worker's body. Such aerosols lead to the development of severe pneumoconiosis and massive fibrosis, which are characterized by fouling of the lungs with connective tissue due to their damage and healing. As a result, the efficiency of the lungs' function decreases in direct proportion to the volume of the lesion, the oxygen saturation of the blood decreases, the employee experiences cough, shortness of breath, heavy breathing and, as a result, a decrease in working capacity up to complete disability. At the same time, the depth of dust penetration into the human body is affected by its characteristics such as particle shape, particle size, dust material density, electric charge, and more (Voroshilov, Fomin, 2019). Also, according to a number of studies, including the work of Katola V.M. and colleagues, electrically charged dust is able to linger on the mucous membranes of the upper respiratory tract for many times longer, thereby exacerbating the harmful effects on the human body (Katola, Komogortseva, 2018).

In addition, depending on the shape, dispersity and chemical composition of dust, in addition to fibrogenic, it can have an irritating, sensitizing and cauterizing effect on the mucous membranes of the upper and lower respiratory tract of a person. At the same time, even a short contact with dust with such properties is sufficient for the occurrence and development of abnormalities in the functioning of the respiratory, nervous, cardiovascular and other functional systems of the body (Gazizov, 2014). Moreover, the diagnosis of pneumoconiosis or fibrosis established as a result of dust exposure does not respond to any treatment, which leads to a complete or partial loss of working capacity and the inability to continue working under the influence of the dust factor. At the same time, it is only possible to introduce the disease into the remission stage by the prompt exclusion of the impact of the factor on the employee and ensuring proper rehabilitation measures for his/her recovery. Thus, in the case of diseases caused by exposure to dust on an employee, preventive measures aimed at reducing and eliminating the risk of developing incurable occupational diseases in personnel become especially important.

## 2.7 Conclusion on Chapter 2

The analysis of statistical data on occupational morbidity of industrial workers caused by exposure to increased dustiness in the workplace suggests that the dust factor remains one of the most significant harmful production factors in many areas of economic activity and, in particular, at enterprises of the mineral resource complex.

At the same time, official statistics on occupational morbidity of workers in modern conditions can often be much lower than the actual condition, since none of the parties to the interaction (employer – employee – medical organization) is interested in the official establishing of the fact of occupational disease in the employee, which requires significant work in improving the culture of occupational safety at enterprises and requires implementation of additional control measures.

In the mining industry, which is the most harmful sphere of human activity in terms of the negative impact of production factors, the dustiness of the air sometimes plays a fundamental role in the planning and implementation of occupational safety measures both in underground and open pit mining. Dust concentrations in the air of the working area can exceed the maximum permissible concentrations by tens and hundreds of times in the most intensive technological processes, which inevitably leads to an increase in the risk of developing occupational respiratory pathology. Each of the stages of the technological process, both in open and underground mining, contributes to the overall dust load, which characterizes the importance of implementing engineering solutions and financing preventive measures at each of these stages in order to reduce the risk of developing occupational respiratory diseases in workers.

In order to reduce the negative impact of the solid aerosols emitted as a result of open pit mining, enterprises implement dust suppression measures throughout the operation of quarries. However, the effectiveness of these measures is not always sufficient to ensure safe working conditions for open pit mining personnel. In addition, the Koashvinsky quarry provides for measures for the reclamation of disturbed lands and man-made technogenic sources of intense dust formation by creating a protective cover of vegetation that prevent wind erosion and the emission of dust.

The analysis of scientific works devoted to the study of the physiological effects of the factor of increased air dustiness on the health of workers, as well as depending on the properties of dust, also reflects the importance of preventive measures to reduce the intensity of the impact of the dust factor on personnel and to prevent the development of such incurable respiratory pathologies as fibrosis and pneumoconiosis.

Consequently, the relevance of the research topic is confirmed by the high prevalence of the problem of increased dustiness of the air, the high level of occupational morbidity of personnel exposed to industrial aerosols, the almost continuous formation of dust at all stages of the technological process of mining, as well as by the importance of preventing the development of respiratory diseases, such as fibrosis and pneumoconiosis, which are not amenable to outpatient and inpatient treatment.

# 3 The state of knowledge on the problem

## 3.1 Significance of the theoretical research on the issue

The basis for the development of methods for reducing the dust content of the working area air is a deep understanding of the dust formation process and the properties of the dusting material, on which the parameters and features of dust emission may depend (Su et al., 2020; Zhou et al., 2020). Therefore, part of modern research works is devoted to the study of a wide range of parameters of dust, solid materials that serve as a source for intensive dust formation, as well as the processes underlying the dusting of certain materials. Among them, for example, the porosity of solid materials and minerals, their adsorption capacity, physicochemical features of the formation of nano-sized dust particles, as well as their further unification into larger agglomerates are studied.

The results of such experiments make it possible to identify the root cause of the formation of dust of a certain dispersity and chemical composition: it is known that the respiratory dust with particles ranging in size from 1 to 10 microns and having a needle shape has the most harmful effect on the human body. Consequently, the ability to explain the grinding of solids to such fractions and may allow to reduce the release of these fractions, for instance, by developing additional measures to improve the technology of drilling or crushing rocks, and effectively solve the problem of increased dustiness, significantly reduce the level of occupational morbidity of workers with respiratory diseases.

Moreover, a comprehensive study of the features of the formation of dust of respirable fractions can make it possible to develop dust suppression measures aimed at dust of a certain dispersed composition. Thus, understanding the dependence of the chemical composition and shape of dust particles formed as a result of a particular process of rock destruction makes it possible to determine such properties of particles and materials as wettability and sorption ability.

Knowledge of these properties of the dusting material makes possible the most effective selection of dust suppressing compositions or the dispersion degree of steam formed by atomizers or water mist generators to ensure better adhesion and settling of floating dust particles. (Li et al., 2022).

However, the knowledge of the processes that occur during the destruction of rocks and the formation of floating aerosols is not enough to solve the problem of increased dustiness of the working area air and reduce the risks of the development of occupational respiratory diseases. Therefore, a significant part of modern research, devoted to the search for a solution to the problem of intensive dust formation, is engaged in the development of dust suppressing compositions and devices designed to precipitate dust floating in the air and prevent it from being blown up again.

The development of environmentally friendly and safe surfactants or other components that form the basis of dust suppressing solutions is currently one of the most extensive and promising areas of research. The correct selection of components affects the effectiveness of reducing the concentration of floating dust, improving working conditions at workplaces, as well as the economic effect of the implemented measures: if the selected composition does not react, bind and precipitate dust particles, the solution itself, its production and storage will bring significant costs for enterprises, and the losses associated with its use will greatly exceed the expediency. The creation of environmentally friendly and safe solutions is relevant, since this approach avoids additional harmful effects on the environment and workers who may potentially be exposed to dust suppressing solution and its vapors, as well as reduce the cost of environmental fines and compensation to affected workers.

In addition, there is another separate research subtopic, which is devoted to the development of dust suppressing and binding compounds based on the wastes from other industries. For example, the practice of using binding organic components as part of a dust suppressing solution, such as a decoction of linseed cake, beet molasses, or guar gum is becoming widespread at the moment (Liang et al., 2022; Zhang et al., 2018). Such compositions allow not only to carry out dust suppression on linear and areal sources without significant harmful effects on the environment, but also to increase the fertility of the treated areas due to the organic components. The use of organic rapidly decomposing solutions contributes to the potential growth of vegetation in treated "fertilized" areas, and the root system of grasses and plants will fix the dusty surface and significantly reduce dust removal associated with wind erosion. However, a significant disadvantage of such solutions is that the organic composition leads to rapid fermentation and spoilage of the dust suppressing solution, and it is necessary to take this into account when preparing and storing these substances.

In addition to the study of the properties of dusting materials and the development of dust suppressing compounds, the development of devices for dust suppression in various technological processes at enterprises is also in active development: design of nozzles with different spray parameters, creation of misting devices that allow to control the dispersion of water mist and others (Lee et al., 2022; Li et al., 2022). In addition, in underground mining and at stationary sources of dust formation, for example, warehouses of rocks and ores, scientists often propose a solution in the form of coating dusty surfaces with foam (Wang et al., 2019a).

Recently, scientists around the world have been interested in the possibility of using magnetic fields to increase the efficiency of dust suppression and improve the binding of dust particles. The use of magnetic fields and the magnetization of water and surfactants can change the physical properties of water, reducing surface tension and contact angle, thereby improving wettability (Wang et al., 2019b). However, many studies have noted that the decrease in the surface tension of water after treatment with a magnetic field is insignificant, which led to an expansion of the direction and a change in the attention of scientists to the magnetization of not only water, but also the surfactants.

This direction is a promising vector of research devoted to the search for solutions to the problem of increased dustiness of the working area air, since it does not require significant technical and financial resources to modernize the equipment used, but a deeper and more comprehensive study of the influence of magnetic fields on the physical properties of water and dust suppressing solutions of various chemical compositions is necessary to substantiate the possibility and effectiveness of the implementation of such solutions.

Taking into account all of the above, it can be concluded that the problem of increased air dustiness in the workplaces of industrial enterprises, especially at the facilities of the mineral resources sector, is complex, requiring a multifaceted approach to its solution and the joint work of scientists around the world. In each of these scientific areas, there are still many unresolved scientific problems that hinder the full implementation of a particular technology and its effective application. Therefore, it is important to investigate and evaluate the possibility and effectiveness of using the proposed solutions, to make correct and accurate conclusions that contain the weaknesses of each, and to develop their own solutions to the problem of increased air dustiness based on global practices and experience.

## 3.2 Research tasks

The purpose of the scientific research that formed the basis of this Master's thesis is to improve the working conditions of personnel engaged in open pit mining, according to the factor of increased dustiness of the air. The idea of the study is to reduce the dust load by treating water and water-based surfactants with magnetic fields to reduce their surface tension and improve wetting ability. According to the accepted hypothesis, this approach is able to increase the efficiency of the use of water and water-based dust suppressing agents, which in turn will reduce the occupational morbidity of mining workers due to the dust factor.

To achieve the stated goal, it is necessary to solve the following tasks:

- To analyze the studies of the relationship between the properties of the dusting material and the deposition efficiency of the formed dust masses by existing dust suppression methods.
- To analyze existing approaches to improving the efficiency of dust suppression by means of the influence of magnetic and electromagnetic fields on water-based dust suppression agents.
- To formulate a hypothesis about the influence of permanent and non-permanent magnetic fields on the physicochemical properties of dust suppressants and their effectiveness.
- To make a laboratory stand simulating the ground surface on the territory of the open pit mine, using equivalent materials.

- To conduct experimental studies on the self-made laboratory stand to determine the effectiveness of dust suppression by hydro-spraying with ordinary water and magnetized water;
- To process the obtained experimental data and summarize the results of the study, including the possibility of using the proposed problem solutions in industrial conditions.
- To propose a risk assessment model for determination of the risks of respiratory diseases development in the open pit mine and perform the risk assessment as a part of the risk-based approach.

As a part of the solution of the first and second tasks, it is planned to conduct a systematic analysis of relevant scientific literature, in particular, highly cited scientific articles devoted to these areas of scientific research. To do this, it is supposed to use the capabilities of various resources and library systems, including the scientific library system eLibrary and the scientific database Scopus, providing access to the most up-to-date scientific works of scientists all over the world on the subject of research.

As a part of the manufacture of the laboratory stand, it is planned to use the capabilities of the Center for Geomechanics and Mining Problems to create a model of a conditionally isolated system in order to assess the dustiness of the air and the effectiveness of dust suppression measures.

At the stage of laboratory surveys, it is planned to conduct a comprehensive study of the properties of dust from samples taken at the Koashvinsky quarry of JSC Apatit, in particular, the shape of particles and the dispersed composition, as well as a study of the effectiveness of hydro-spraying with ordinary water and magnetized water on the laboratory stand.

## 3.3 Analysis of up-to-date research on the problem

The problem of increased air dustiness in the workplace is widespread all over the world, but due to the very high level of industrialization, the most urgent issue is observed in China, so the review presents many works by Chinese colleagues. In addition, scientists from the USA, India, and a number of European countries, such as Poland and Germany, are actively trying to solve the problem of high dust concentrations. At the same time, the approaches to solving this problem are different for each side, since the mining, geological, technical, hydrological and other conditions of mining operations differ, and there are also differences in general in the available capabilities and technologies. However, the unification of global practices allows to isolate the advantages and disadvantages of each approach, and on the basis of comparative analysis and laboratory tests to adapt certain ideas and solutions to rather complex and unique conditions in open pit mining in Russia.

If the issue of studying the characteristics and properties of dusty materials, their changes under the influence of external factors are to be considered (Jin et al., 2021), then first of all it is necessary to note the research of Xianbo Su and others (Su et al., 2020). The scientist and colleagues claim that a detailed study of the properties of coal dust can help increase the efficiency of dust suppression by understanding the dependence of wettability, hydrophilicity of dust on its chemical and dispersed composition, the shape of dust particles, porosity or the presence of sorbed gases and impurities.

So, scientists have taken a number of dust samples at various coal mines: in the faces and at different sites of mine workings. According to the obtained data, when analyzing the chemical and dispersed composition, it was found that the dust taken directly in the faces has the most complex chemical composition; the fractional composition also varies in different sampling sites, but the dust fraction up to 10 microns prevailed in the samples. In addition, it was found that dust particles, as a rule, exist in the state of agglomerates, when dust particles of smaller diameter are adhesively bonded to a larger dust particle. It was also determined that the wettability of dust particles from coal dust samples taken in mines in China depends on a number of its characteristics: the carbon and oxygen content on the surface of dust particles, the oxygen-carbon ratio, ash content, the content of bound carbon and, in particular, the size of dust particles.

At the same time, the following dependences were obtained: the wettability of coal dust increases with a decrease in the carbon content on the surface of the dust particles, an increase in the oxygen content and an increase in the oxygen-carbon ratio on the surface of the dust particle, which indicates a direct relationship between the oxygen content and the hydrophilicity of coal dust particles. As for the functional groups containing oxygen and carbon, an increase in their content improves the wettability of dust particles, since in the presence of water and under the action of dipole forces, functional groups combine with hydrogen in water molecules due to hydrogen bonds, thereby improving the wetting ability of water on dust particles. In addition, it is noted that with an increase in ash content and, accordingly, a decrease in the content of bound carbon on the dust surface, the wettability of coal dust also increases, since ash, which is a non-combustible residue during coal combustion, mainly consists of mudstone (clay shale), which, in turn, has greater hydrophilicity than coal, which explains the improvement in the wettability of such coal dust particles.

The results obtained in this study suggest that the effectiveness of dust suppression is directly related to the physicochemical properties of the dust itself. In this case, even the most expensive and effective surfactants can have an effect lower than expected. For example, when using binding dust suppressing solutions that provide good adhesion ability for sticking dust particles, but do not have sufficient wetting ability, when fighting coal dust with low ash content and low oxygen content on the surface (for example, with low porosity and, consequently, poor sorption ability), this composition will not be able to moisten and "grab" a dust particle for further binding.

Another study by Xiaonan Wang and colleagues is also devoted to the study of the influence of various physicochemical properties of dust particles on their wettability (Wang et al., 2019). In this case, scientists propose a solution to the problem of choosing the most effective wetting agent based on the study of the physicochemical properties of the dusting material: the degree of metamorphism (coal samples with varying degrees of metamorphism, such as anthracite, lignite, coking coal and others were selected for the study), surface morphology, chemical structure, porosity.

As a result of the work, the scientists concluded that the wettability of coal dust particles mainly depends on the chemical composition and content of individual components, the micromorphology of dust particles, their porosity. It is noted that porosity plays a major role in determining the wettability of the particle: it was determined that the contact angle decreases with increasing porosity. If we study the dependence of the wettability of coal dust on the degree of metamorphism of the mineral, then, according to research, there is a drop in the degree of wettability from high for lignite (brown coal) to low for bituminous (fatty) coal, very low for coking coal and again high for anthracite.

Another study by Xiaoxue Liao is also devoted to the investigation of the dependence of the wettability of coal depending on the degree of metamorphism of the source of coal dust (Liao et al., 2021).

A slightly different vector for studying the dependence of the properties of dust particles on their wettability during dust suppression was chosen by Qun Zhou and colleagues (Zhou et al., 2018b). Scientists note that many modern studies are aimed at determining the correlation between the wettability of coal dust particles and their chemical composition, size, degree of metamorphism, justifying the high hydrophobicity of dust particles. In their work, the scientists drew attention to the features of the shape and surface roughness of dust particles, their porosity and sorption capacity. For this purpose, it was decided to use fractal dimensions when describing the dispersed composition of dust particles. Fractal dimensions can take on a non-integer value, reflecting the features of the shape of an object in space. For example, if the fractal dimension of a dust particle has a value close to 2 (the topological dimension of the plane), then in space the speck of dust has a flatter shape, and it is not correct to apply the average diameter to such a particle. Thus, scientists do not take into account the average diameter of dust particles, but they take into account the roughness of dust particles, which, in turn, allows for a more accurate assessment of the specific surface area.

According to the results obtained, the scientists found a strong positive correlation between the fractal dimensions of the particles and the surface features of an individual particle. Thus, with an increase in the fractal dimension, that is, with the approximation of the shape of a speck of dust from flat to volumetric, the specific area of dust particles and their sorption capacity significantly increased. This, in turn, contributes to the formation of a gas film on the surface of dust particles and the deterioration of their wettability. Moreover, with an increase in the fractal dimension of the dust particles, the total volume of porosities also increased, which prevents the uniform distribution of the wetting agent around the dust mote. Thus, with an increase in the fractal dimension of dust particles, their wettability sharply deteriorates.

The results of this study provide a very significant assessment that allows to look at the process of wetting dust particles from a completely different angle: to consider not so much the chemical composition and the presence, for example, of functional groups on the surface of a speck of dust, as the shape features reflecting the porosity and specific surface area of the particle.

Over the past decades, many scientists around the world have been developing and synthesizing the most effective and economically feasible dust suppressing solutions with high wetting ability (Jiang et al., 2020). At the same time, the proposed solutions differ both in chemical composition and cost, and in the principle of action when reacting with a dust mass. However, in the last few years, the issue of environmental friendliness and safety of the proposed solutions for dust suppression has become particularly relevant and acute (Kornev et al., 2021). Therefore, when developing dust suppressing compounds, scientists face many tasks to fulfill all the requirements for the dust suppressing agents.

Currently, one of the most common ways to reduce increased dustiness in the world and the most common way in Russia as well is hydro-dusting (dust suppression with the use of water) (Kovshov et al., 2019; Letuev et al., 2020). However, the efficiency of dust suppression with water is quite low, in particular, due to the high surface tension of ordinary water (Chang et al., 2021). This method requires significant economic costs due to the need for frequent treatment of dusty surfaces and, most importantly, requires a stable source of industrial purity water. Moreover, the unfair use of such a source can have a strong negative impact on ecosystems. At the same time, aqueous solutions of binding agents are often made on the basis of water, which makes it possible to increase the efficiency of dust suppression but harms the environment and the water system in particular.

The scientific work by Qun Zhou and Botao Qin presents a broad overview of dust suppression methods using compositions made on the basis of aqueous media (Zhou, Qin, 2021). The authors propose to divide the existing approaches to dust suppression using aqueous solutions into 3 categories: methods based on spraying water (solutions) to precipitate a floating dust mass; methods of hydrosaturation of the coal seam before development, reducing the release of dust during subsequent development of the seam; the use of wet scrubbers to capture the resulting dust mass.

The authors note that when applying hydrosaturation of a coal seam, scientists mainly rely on the permeability of the formation, not taking into account the low wettability of the coal body, which is why even with sufficient water supply pressure, the coal body was practically not saturated with water. As for the spraying of water and aqueous solutions during hydro-spraying, scientists believe that the main factors determining the effectiveness of this method are the wettability of the dust mass and the parameters of atomization (spraying) of water, for example, the average size of liquid droplets. At the same time, it is also noted that today it is very important to study the interaction of droplets in the spray torch with dust particles, since due to insufficient droplet density or very low wettability of dust particles, it is possible that when small particles collide, there will be no reaction between a speck of dust and a drop, or a collision will not occur at all. Therefore, it is necessary to control the ratio of the density of droplets in the flare and the probability of coagulation interaction between the smallest particles.

In modern practices, chloride compounds used as binding agents for dust suppression are common, for example, $CaCl_2$, $MgCl_2$ and others. However, when used, chlorides lead to severe corrosion of metal structures, equipment and machinery, which calls into question the use of such compositions in open and underground mining operations, since equipment in the process of excavating and transporting rocks is in the direct contact with dusty material. Therefore, pure chlorides are often replaced by their modifications. For example, in the work by Guoqing Shi and colleagues, the possibility of using a semi-organic dust suppressing composition made of $CaCl_2$, carbamide (urea) and the bacterium bacillus pasteurii, capable of solidifying sand in the presence of a source of calcium and urea, is considered (Shi et al., 2022).

According to the results of this study, it is noted that the high efficiency of the developed biological dust-suppressing composition is achieved by suppressing secondary sources of coal dust, the particle size of which exceeds 200 microns, and with the dust suppression of brown coal dust, high efficiency is observed with the size of dust particles exceeding 100 microns. However, as indicated, the respirable fraction, which has the main negative impact on the body of workers, includes dust from 1 to 10 microns. Dust with a particle size exceeding 100 microns easily leaves the lungs together with sputum, is able to settle independently in the absence of external whipping forces, and most often does not require additional measures for deposition and consolidation.

Organic dust suppressing compounds deserve special attention, since they do not pose a threat to ecosystems, but on the contrary can contribute to increasing the fertility of the treated soil surfaces and the appearance of green vegetation on them. So, an example is the work of Haihan Zhang and others (Zhang et al., 2018). The authors of this study suggest using guar gum, which is a natural polymer, as a binding agent and the main component of their dust suppressing composition, prepared by chemical transformation of its functional hydroxyl groups -OH. Scientists note that when using guar gum in a composition with sodium dodecylbenzenesulfonate (a synthetic substance that reduces surface tension and increases wetting ability), they form a strong film on the coal dusting surface, preventing the removal of dust mass. It is also indicated that the resulting film is able to withstand a pressure of 29 kPa, while losing about 60% of its mass in a month after use. Moreover, the organic composition of the dust-suppressing agent and its decomposability without causing secondary harm to the environment are separately noted.

In recent years, a new trend in dust suppression has been gaining popularity in parallel with the chemical synthesis of new dust suppressing compounds. It consists in the development of additional means to increase the efficiency of dust suppression and the use of dust-suppressing agents due to external influences and changes in their, first of all, physical properties. In particular, one of the methods is based on the research and development of methods for the use of magnetic fields for the treatment of dust-suppressing compounds.

The scientific work of Hetang Wang and others is devoted to the study of changes in the properties of dust-suppressing agents after exposure to a magnetic field (Wang et al., 2019b). The authors of the study note that after exposure to a magnetic field on anionic and nonionic dust-suppressing compositions, changes in two characteristics of solutions were studied: wetting ability and permeability (infiltration ability), while the time of exposure to the magnetic field, the surface tension of the agents, the wetting angle and the rate of infiltration of substances were recorded.

As a result, scientists observed changes and improvements in these properties and characteristics of non-ionic dust suppressing agents. The authors explain the change in the physical properties of the studied compounds by the dynamic process of formation and destruction of hydrogen bonds due to the rotation of the magnetic field in which the substances under study were located. The authors of the work claim that the use of magnetic fields in order to increase the efficiency of dust suppression can significantly improve the indicators of reducing the concentration of floating dust. For example, the surface tension of the studied composition of Tween-80 at a concentration of active components of 0.5% decreased by 11.8 mN/m after a 7-minute exposure to a magnetic field. In addition, there was a decrease in the wetting angle to 16.3° and a decrease in the infiltration time of the wetting agent in comparison with the same substance without exposure to magnetic field. At the same time, to carry out the magnetization of the studied compositions, the authors developed a device with a permanent magnet and a rotating magnetic field, and to improve the degree of magnetization, a turbulent flow was twisted to ensure a uniform effect on the entire volume of the liquid.

Also, the works of Junqing Meng and colleagues are devoted to the study of the influence of anionic and nonionic wetting agents, for example (Meng et al., 2021).

Another work of scientists Qun Zhou and others is devoted to the development of a device for the magnetization of dust suppressing compounds, the study of properties that change under the influence of a magnetic field, as well as the determination of the optimal parameters of the magnetic field to ensure effective and sufficient magnetization (Zhou et al., 2019).

As part of the work, scientists assembled 2 installations to create different conditions for magnetization of the studied water-based dust-suppressing solutions and further compare the effectiveness of each sample. At the same time, a static magnetic field, magnetic field from a point source, pulsating magnetic field and paired magnetic field were studied. As a result of the conducted research, the authors conclude that a paired magnetic field consisting of a pulsating and funnel-shaped (swirled) improves the wetting ability of liquids to a greater extent. Thus, in the investigated water-based binding compound, after exposure to a magnetic field, the surface tension decreased to 26.37 mN/m, and the wetting angle decreased by almost 30% to 23.97˚. Moreover, the memory effect of the dust suppressing agent was noted after exposure to magnetic field: for 540 seconds after the termination of the magnetic field effect, the increased wetting ability of the composition under study remained.

## 3.4 Analysis of unsolved scientific problems

Despite the active development and development of more and more advanced means and methods of dust suppression, a number of problems related to the peculiarities of reducing air dustiness remain unresolved. Moreover, with the development of technologies and the intensification of all processes, there are more and more new tasks that scientists are facing in the fight against dust.

For example, at present, a single method for selecting an effective dust-suppressing agent suitable for all known dusting conditions has not yet been developed, at least within the enterprises of the mineral resource sector (Xu et al., 2018). At this stage of human development, technologies and available knowledge do not allow us to sufficiently understand the processes of dust formation from the point of view of unification of the proposed solutions to reduce the dustiness of the air of working areas. But today there are also scientific problems and tasks that at the moment can be solved by a comprehensive analysis and study, the selection of the correct solution through desk research and field testing.

Thus, the question of the comprehensive study of the dusting process from the point of view of the influence of various factors on the intensity of dust formation in various technological processes remains open. Currently, too few studies have been conducted to establish a correlation between, for example, the porosity of the material that is the source of the emitted dust and the amount (intensity) of this dust to rely on them, that is, many of the deduced statements and theses require a critical approach and comprehensive verification of the reliability of the results obtained.

Moreover, the solution to the problem of increased dustiness in the workplace is largely complicated by a wide range of different conditions at different workplaces and at different industrial facilities. For example, the chemical composition and properties of dust in a coal mine may differ significantly from the same properties of coal dust in open-pit mining or in warehouses. This problem is well covered, for example, in the works by Younes Shekarian and colleagues (Shekarian et al., 2021) and Pedro Trechera and others (Trechera et al., 2022). This explains why it is an almost impossible task to solve the problems of increased air dustiness in different workplaces by the same methods.

Another scientific problem of the modern sphere of dust control is outdated views on the problem itself. Most of all existing studies are based on the statement that the most harmful dust fraction for an employee is respirable dust with a particle size from 1 to 10 microns. This statement is indisputable, however, according to new research, nano-sized dust particles can have the same and even more disastrous effect on the body of a worker due to other physical and chemical parameters of particles that contribute to the aggravation of harmful effects, primarily on the human respiratory system. Rui Zhang et al. wrote in detail about the problem of nanoparticles and their properties in their works (Zhang et al., 2021), Long Fan and Shimin Liu (Fan, Liu, 2021). From this it can be concluded that it is necessary to expand the view on the problem of increased dustiness of air in the workplace, to rely not only on the classical and conservative point of view, but also to look for additional factors that can also have one or another effect on the health of workers.

Dust suppression, various methods and means of reducing the concentration of dust in the air are a broader area within the framework of the problem of increased dustiness of the working areas. A large community of scientists around the world is developing both dust suppressing compounds and devices for spraying them.

The main problem for scientists working on the chemical aspect of dust suppressing agents is the development of a composition that meets all of the following requirements: high efficiency in application, which allows to reduce the concentration of dust in the air to MPC, the cheapness of the final product, the availability of raw materials for production, environmental friendliness and safety of the product, minimal labor costs for production / delivery and minimal costs for technical re-equipment and modification. Some requirements, as a rule, can be neglected, for example, the costs of re-equipment of irrigation equipment used for dedusting in open-pit mining are not required, since mainly the compositions being developed have a viscosity comparable to water, which allows them to be used without significant changes. But efficiency, environmental friendliness, safety and economic feasibility are the basis for such a solution to the problem. It is not always possible to meet all the requirements, so scientists are still developing the best possible dust-suppressing agent.

For example, the substances universin-A and universin-B were developed, based on resins, oils and asphaltenes. These components are able to interact very actively with ground surfaces, especially effectively binding dust particles and soil particles under the influence of solar radiation in open-pit mining. However, in addition to high efficiency, these compounds are difficult to produce, they have a high cost, relatively high toxicity, and can negatively affect atmospheric air (especially when heated) and groundwater (Kovshov, Pasynkov, 2020).

Another option for dust suppression is the use of hygroscopic salts as a dust suppressing agent. The essence of using these salts is the absorption of moisture from the atmospheric air and its return to the ground, which allows you to moisten the surface layer and reduce the intensity of dust removal. However, it is obvious that the main disadvantage of this method is very low efficiency in regions and areas with low relative humidity (Kovshov, Pasynkov, 2020).

It was also mentioned above that chloride compounds such as $CaCl_2$, $MgCl_2$ and others are quite common dust suppressing agents. They are able to form a solid surface, as if fixing it and reducing dust formation. However, unlike other substances, these compounds greatly accelerate the corrosion destruction of metals, which greatly reduces the attractiveness of these substances for use in mining.

Another most common of the known methods is the use of lignosulfonate – this substance is a product of pulp and paper production, is often a waste and is therefore easily accessible and cheap. When applied, lignosulfonate is mixed with the top layer of the soil, thus creating a new fixed coating that replaces the dust layer and prevents dust removal. However, a very significant disadvantage of this substance is its water solubility, that is, when used in conditions of a large amount of precipitation, its use becomes impractical.

Thus, among the main problems in the development of dust-suppressing compounds, one can distinguish toxicity and non-environmental friendliness, a high degree of dependence on precipitation and external conditions, the cost of components and the complexity of production, high corrosion ability, harmfulness.

When investigating the possibility of magnetization of water and surfactants to increase the efficiency of the dust suppression means used, problems and tasks also arise that require solutions for the full application of the proposed solutions.

First of all, there is little information about the influence of magnetic fields on water and surfactants today, so these theses and especially statements about increasing the wettability and effectiveness of the use of magnetized binding agents should be taken critically and checked properly. In a general sense, the effect of the magnetization of surfactants and water can be considered not fully studied (Wang et al., 2019b).

Based on the first problem, it can be concluded that the development of an effective method of magnetization of dust-suppressing agents is also questionable due to the lack of knowledge of the issue in general and, in particular, the small amount of data for comparative analysis. Moreover, there was no confirmation of field tests of magnetizing devices, except for the work of Quan Zhou and colleagues, which could justify the possibility and effectiveness of using the technology in real conditions (Zhou et al., 2017; Zhou et al., 2019).

Also, by analogy with the freezing and defrosting of dust agglomerates, after which larger particles are able to break down into smaller dust particles, thereby causing greater harm to the human body and making a much greater contribution to the overall dust situation, the behavior of dust agglomerates has not been studied after the spillage of magnetized surfactants and drying.

The solution of the existing scientific problems related to dust suppression in the workplace at the enterprises of the mineral resource complex will allow at least step-by-step progress towards improving workplaces and improving working conditions for the dust factor.

One of the most pressing problems nowadays is the lack of knowledge of the basic processes underlying the formation of dust masses. The work of Pedro Trachera and colleagues is also devoted to the designation of the main unknown aspects of dust formation related to its properties and characteristics (Trechera et al., 2021). To solve the problem, it is proposed to apply an integrated approach to the study of dust samples formed under different conditions, dust of different chemical composition and origin, differing in properties, using a wide range of generally accepted methods for studying the characteristics of the dust mass, as well as further combining the data obtained into a common database for systematization of the results obtained and their possible processing.

The main problem in the development of dust suppressing compositions is the ratio of their characteristics to meet the requirements. Similarly to the works of Haihan Zhang (Zhang et al., 2018) and Qingguo Yao (Yao et al., 2017) it is proposed to develop an organic dust suppressing composition based on waste from plant production. This will ensure the environmental friendliness of the solution, taking into account its independent and rapid decomposition, contribute to increasing the potential fertility of the treated surfaces, as well as the absence of secondary harmful effects on the environment. In the future, it is proposed to conduct a comprehensive study on the possible change in the chemical structure of the solution due to the destruction of internal bonds in the dust-suppressing agent, as well as the selection and development of environmentally friendly additives that can potentially increase the effectiveness of the solution, as well as increase its possible shelf life after preparation. This will make it possible to ensure the availability of the components of the manufactured composition, make it environmentally friendly and safe for the employees of the enterprise and provide competitive efficiency in dust suppression.

In addition to the development of dust-suppressing agents, there is also the problem of the lack of a unified methodology for selecting a dust-suppressing agent suitable for certain conditions. This problem is really relevant, because with the wrong selection of dust suppressants, enterprises incur very high costs without obtaining the proper positive effect. The correct selection of dust suppression means adapted to specific conditions makes it possible to quickly and effectively solve the problem of increased dustiness of the air without additional costs for workers' compensation and equipment repairs. However, it is not always possible to resort, for example, to physical modeling of the dust suppression process, as proposed in the work by Lei Zhou (Zhou et al., 2018a).

Therefore, it is necessary to develop and test a new methodology for evaluating the effectiveness of dust-suppressing compounds, while the methodology should be based on the fundamental principle of operation of a particular tool. For example, if a dust-suppressing agent is designed to bind dust particles and form a crust on a dusting surface, then it is necessary to investigate the strength of adhesion reflecting the adhesion of dust particles between each other (Kondrasheva et al., 2021).

When magnetizing dust-suppressing compounds and surfactants, the main problem is the lack of sufficient knowledge about the processes and changes taking place, thanks to which it is possible to judge the effectiveness of the magnetization devices. Consequently, it is proposed to develop a number of magnetizing devices that create magnetic fields of various strengths and shapes, and further study the dust-suppressing properties of the treated compounds. Also, an important component will be the memory effect of the treated substances, since this characteristic will reflect the main effect of dust suppression with these compounds.

## 3.5 Conclusion on Chapter 3

A comprehensive study and understanding of the processes of dust formation depending on the physicochemical parameters of the source material, for example, a mineral, the development of innovative means of dust suppression and safe binding compounds, as well as devices using basic physical principles to improve the efficiency of dust suppression processes provide for increasingly safe working conditions at enterprises of the mineral resource complex.

Modern knowledge of the principles of dust formation and their dependence on the characteristics of solid materials allows us to judge the close relationship of the intensity of dusting with the properties of the dust source. Moreover, the chemical and dispersed composition, morphological structure and sorption capacity of dust particles determine their ability to wettability, which, in turn, reflects the possibility of using certain means of dust suppression to reduce dust.

Currently available dust suppressants allow relatively effective reduction of dustiness of the air in the places of application, however, the methods and solutions used can sometimes cause more harm than good or can have too high cost disproportionate to their effectiveness. This may be due to both the intrinsic characteristics of the solution, such as toxicity or complexity of the agent production, and external factors, such as weather conditions (Omane et al., 2018) or the constantly changing dynamic load on the binding layer.

The means for the magnetization of surfactants in order to increase their wetting ability and, accordingly, the effectiveness of dust suppression are questionable due to the lack of sufficient data and research that can objectively prove the effectiveness of the proposed solutions, therefore, the technology of magnetization requires additional study and confirmation of its effectiveness in laboratory and field conditions.

# 4 Substantiation of proposed measures to solve the problem under study

## 4.1 Idea of solving the problem of increased dustiness of the air

Nowadays, there are a wide variety of ways to reduce dustiness in the workplace, in particular, enterprises of the mineral resource complex.

As mentioned in chapters 2 and 3 of the Master thesis, the effectiveness of modern applied and proposed methods of dust suppression is questionable, since it is limited due to a wide list of requirements for them: environmental friendliness and safety of measures, economic feasibility and accessibility, noticeable effectiveness of application and resistance to various kinds of impacts (especially when it comes to fixing a dusty surface compositions and solutions). Moreover, when developing certain measures, the fact is often overlooked that dust formation, like mining operations, are dynamic processes that are influenced by many factors (Mo, Ma, 2022; Qin et al., 2021). In particular, a number of such factors determine the effectiveness of the proposed solutions to the problem of increased dust load. For example, the use of hygroscopic salts and their solutions in areas with low relative humidity will have a negative effect due to the destruction of salt crystals and their additional contribution to the overall dust load. As a result, the development of solutions to improve the efficiency of existing dust suppression methods is of particular importance for modern science.

One of the most common methods of dust suppression at mineral resource enterprises remains hydro-spraying with water. This is due to several factors: the availability of fresh water sources of industrial purity in most mining regions of our country, the ease of preparation of dedusting measures and their organization at a mining facility, low costs in comparison with other solutions, the lack of regulatory methods of dust suppression or evaluation of their effectiveness. Therefore, the authors of the study decided to propose measures to improve the efficiency of hydraulic spraying at enterprises of the mineral resource sector.

A systematic analysis of modern scientific literature sources aimed at solving the problem of low efficiency of the applied methods of dust suppression has shown that the most promising method today is the magnetization of aqueous media.

The effect of magnetic fields on the physicochemical characteristics of aqueous media is still not fully understood, so today it is difficult to talk about the full implementation of the method of magnetization in industrial conditions. Moreover, there is still no sufficient scientific base devoted to the study of the effectiveness of the method of magnetization of aqueous solutions from the point of view of dust suppression. The research works covering this topic are quite localized: most of the research was carried out by Chinese scientists, and the works of American, Polish and Portuguese colleagues were also found. In addition, when conducting a scientific review, there are often works by the same scientists on the influence of magnetic fields on water-based dust suppressants, which indicates a fairly small scientific community engaged in the study of this issue. Hence, it can be argued both about the relevance of the study, since the possibility of using magnetic fields in the field of dust suppression has almost not been studied and has possible prospects for wide application, and about the lack of demand for this direction due to the low interest and involvement of the scientific community. Nevertheless, in order to form a more complete picture and obtain their own developments and data, as well as to make their own contribution to the development and deeper study of this issue, it was decided to conduct a study of the magnetization of aqueous media in relation to the effectiveness of dust suppression and, in particular, to reduce the concentration of the respirable fraction.

The analyzed scientific works indicate an improvement in the wetting ability of aqueous media and solutions after prolonged exposure to magnetic fields of various nature (Ding et al., 2011). In particular, a number of researchers have found that the surface tension decreases and the wetting angle decreases in magnetized water, as well as in magnetized surfactants on a water basis. Surface tension can be characterized as the force of attraction of the surface layer of liquid molecules to the molecules inside this liquid. Thus, the lower the surface tension of the liquid, the less the force of attraction of the outer layer of the liquid molecules to the inner molecules and the easier it is for a drop of such liquid to moisten or capture a dust particle. As a result, moistened dust particles stick together better into larger agglomerates with a larger mass, which leads to their settling. The wetting angle Θ, in turn, is related to the surface tension and also characterizes the wetting ability of the liquid. It reflects the angle between the horizontal surface and the tangent drawn in the vertical plane to the surface of the liquid drop (Fig. 8).

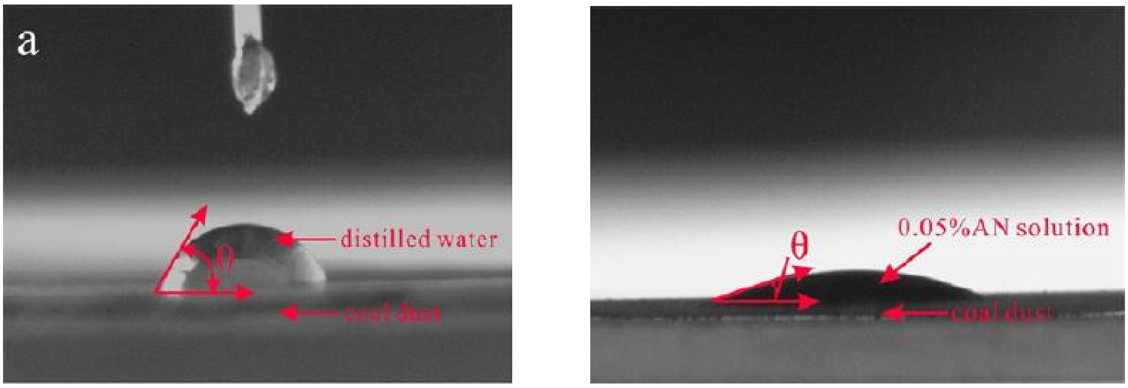



**Figure 8: Parameters of the wetting capacity of a liquid drop**

Source: (Su et al., 2020)

Here: on the left – a drop of distilled water; on the right – carbamide-ammonia surfactant.

In other words, the smaller the wetting angle, the more the drop spreads over the horizontal surface and the better the liquid wets this surface. Therefore, reducing the wetting angle also improves the wetting ability of the liquid and increases the dust suppression efficiency. Moreover, due to the improvement of the wetting ability and the reduction of the surface tension of the liquid, the researchers also observed an improvement in the infiltration ability of the liquid. That is, when the liquid was magnetized, along with a decrease in surface tension, it was found that the time of infiltration (or penetration) of the liquid into porous structures and materials was noticeably reduced. This means that it is easier for the magnetized liquid to penetrate into pores and loose structural materials, including bulk roads, platforms, etc. This, in turn, makes it possible to further study the increase in the effectiveness of binding fixing compounds, since for such substances the depth of penetration of the dust-suppressing agent into the dusting layer of soil or soil is important. However, from the point of view of the basic principles of magnetization, there is still no proven justification for the reasons for the change in the physicochemical characteristics of aqueous media after exposure to a magnetic field, as well as the reasons for improving the efficiency of dust suppression by magnetized liquids.

According to some studies, for example, to the work of Hetang Wang (Wang et al., 2019) it is assumed that an improvement in the wetting ability of the liquid and, consequently, an increase in the efficiency of dust suppression occurs due to the dynamic process of destruction and formation of hydrogen bonds in the structure of water molecules under the influence of a magnetic field. This, in turn, reduces the attractive forces between the molecules and thereby leads to a decrease in the surface tension of the liquid.

Other studies suggest that an increase in the efficiency of dust suppression with magnetized water or surfactants is associated with the electric charge of dust particles. For example, in the study of Zholdybayeva Z.I. and Zuslina E.H., it is said that after magnetization, a dipole water molecule also acquires a weak charge and, depending on the sign of the charge of a dust particle, the interaction of a speck of dust with a drop of water differs: either the particles are attracted by a drop of water and thereby precipitated, or vice versa the particles are repelled and deposited due to a larger potential for deposition on the surface (Zholdybaeva, Zuslina, 2016).

Nevertheless, despite the current unexplored fundamentals of the effect of magnetization on the specific characteristics of aqueous media and on the interaction of dust particles with dispersed liquid droplets, it can be argued about the potentially possible effectiveness of suppression of respirable fraction dust by magnetized aqueous compositions and the need to test this hypothesis in the office and field conditions.

## 4.2 Substantiation of significance of the problem solution

Nowadays, hydro-spraying remains one of the most at first glance cheap and economically affordable means of dust suppression at enterprises of the mineral resource complex (Letuev et al., 2020). In particular, if we talk about open pit mining, then the advantages of using hydro-spraying can also include the simplicity of filling tanks of irrigation machines, provided there is an open reservoir with permitted water intake and organization of irrigation measures, as well as the imaginary benefit of these measures due to the large length of linear sources of dust formation - technological access roads that make the main contribution to the overall dust load at open pit mining facilities (Korshunov et al., 2021).

Such an imaginary benefit is because the efficiency of hydro-spraying is considered sufficient if the schedule of irrigation works is observed, namely, the passage of the machine should be carried out every 3-4 hours and every 1.5-2 hours in a hot climate. However, this approach leads to high costs due to significant consumption of water, diesel fuel, increased wear and loss of the initial cost of the equipment used, as well as large salary payments to drivers of irrigation machines due to frequent watering. Therefore, in real circumstances, such a method of irrigation works is not observed, which leads to a significant decrease in the effectiveness of these measures, intensive dusting and a strong increase in the concentration of dust in the surface layer of atmospheric air of working areas, an increase in the risk of occupational diseases and injuries at work, and so on.

The transition of enterprises to complex synthetic polymer surfactants, organic dust-suppressing compounds or other substances is complicated primarily by the fact that the organization is not interested in excessive costs for solving labor protection and industrial safety problems, in particular the problem of increased dustiness of the air. This is due to the high risks and low payback of these measures in a short period of time, the disproportionately high cost of investment in the introduction of new dust suppression tools in some cases, as well as the lack of motivation of the employer in additional costs for solving problems that, although inefficiently, are solved by existing means.

Moreover, many of the dust-suppressing and binding compounds and surfactants offered on the market carry potential harm to the environment or employees of the enterprise who may come into contact with the substance and its vapors. For example, some oil-containing surfactants or inorganic synthetic binding agents can be toxic to both living organisms and ecosystems by entering groundwater or atmospheric air. And some of the dust-suppressing substances cannot be used at all in certain cases. For example, $CaCl_2$ salts are often used as a binding and hardening agent, however, as is known, chloride compounds are very corrosive substances, and their use on road sections or sites where mining equipment is actively used will lead to corrosion and damage to equipment up to the impossibility of its further use.

Thus, the following situation is observed in the market of dust–suppressing agents and methods to combat increased air dustiness: insufficient motivation and interest of the organization (employer) in the introduction of new effective measures to reduce the dustiness of the air of working areas on the one hand, and a small number or complete absence of competitive and effective means - potential substitutes for the most common today hydro-dusting. There are two ways to solve this problem:

- Development of an effective, cheap, affordable, environmentally friendly and safe dust suppressing composition, or
- Development of means and methods to increase the efficiency of the applied means of dust suppression, including hydro-spraying.

In our opinion, the second approach is the most affordable and promising for today. It avoids a number of problems associated with the development of new solutions and requirements for them, since the means and substances used in modern times already satisfy at least some of the requirements. Moreover, this approach makes it possible, due to relatively small labor costs and financial investments, to get closer to solving the problem of increased air dustiness without major changes in production, the need to organize a production line for dust-suppressing composition directly on the territory of a mining facility or the need to debug logistics chains for the supply of components and substances.

In particular, if we consider the issue of magnetization, then this solution requires only one-time and minimal costs for the installation of magnetizing devices that practically do not require maintenance and do not require constant and operational control by personnel at all. Also, some studies show that the effect of applying magnetic fields to dust-suppressing agents is manifested not only in increasing the efficiency of dust deposition and improving working conditions, but also in reducing the amount of necessary surfactants, which leads to savings in the company's funds for dust suppression measures. (Wang et al., 2018). Therefore, in case of a positive effect from the influence of magnetic fields on the effectiveness of dust suppression measures, this solution will have great prospects for implementation in production facilities around the world.

This solution to the problem of increased dust load on the workplaces of personnel of enterprises of the mineral resource complex, as mentioned earlier, is of particular importance due to the widespread use of the method of hydro-dusting at mining enterprises in Russia. This means that enterprises will not need to change anything in the production line and in the organization of the dust suppression process in principle.

## 4.3 Methods and proposals for solving the problem

Since it was decided to study the effect of the magnetic field on the aqueous media and to change the efficiency of dust suppression by aqueous compounds after treatment with a magnetic field, the activities for the preparation and performing of the research were divided into the following stages in accordance with the given tasks:

1. Systematic analysis of scientific literature sources on the topic of dust formation, dust suppression and magnetization of water and surfactants.
2. Formulation of scientific hypotheses on the topic of the master's thesis in accordance with the studied and elaborated sources.
3. Selection of the most suitable method of magnetization of a dust suppressor for laboratory conditions and economical for industrial tasks.
4. Development of a laboratory stand simulating a linear dust source – a quarry technological road, to assess the dustiness of the air, analyze the dispersed composition of dust and study the effectiveness of dust suppression.
5. Conducting experimental studies on a manufactured stand to assess the dustiness of the air, analyze the fractional composition of dust and study the effectiveness of dust suppression.
6. Analysis of the dispersed composition and shape of dust particles using high-precision laboratory equipment.

7. Processing of the obtained results and formulation of conclusions based on the results of the study.

As a part of the analysis of literary sources on the subject of the study, classical and modern works were considered, dealing with the features of dust formation, correlation of dust properties and dust suppression efficiency, reviews of modern methods of dust suppression and dedusting, as well as ways to improve the effectiveness of these measures, in particular, the magnetization of dust suppressing compounds and surfactants. During the scientific review, both domestic and foreign developments were touched upon, which made it possible to form a more complete picture reflecting the variety of approaches to studying and solving the problem of increased air dustiness.

The Scopus scientific database was used as a search engine, which allows not only to access a large number of scientific articles, but also to set various filters when searching, which made it possible to use articles from highly rated journals with Q1 and Q2 quartiles when reviewing. The scientific electronic library eLibrary was also used, which provides access to many materials and articles indexed in the RSCI, Scopus and WoS databases, as well as the Internet search were implemented as well. A more detailed analysis of literary sources is presented in chapters 2 and 3 of the Master's thesis.

When formulating scientific hypotheses that provided a theoretical basis for further research, the main emphasis was placed on the conducted scientific review, which made it possible to analyze current trends in solving the problem of increased dustiness in the workplace, modern approaches to solving the problem, and also allowed to evaluate and identify current and unresolved scientific problems that nevertheless require solutions for the possible implementation of the development in industry and the achievement of the research goal – improving the working conditions of personnel by the dust factor.

To select a means of magnetization, suitable for all or most parameters for both in-house research and field testing, a number of sources devoted to the study of the influence of magnetic fields of various nature on the physicochemical properties of aqueous media were analyzed. Thus, in the Qun Zhou study, it was found that the most effective method of magnetization is a combined electromagnetic field composed of a pulsating EMF and a funnel-shaped swirling EMF (Zhou et al., 2019). Nevertheless, magnetization with the help of an electromagnetic field requires large enough investments to comply with all the requirements of the process, to supply electrical communications and to organize the process in principle.

Therefore, in order to determine the effect of the magnetic field on the properties of liquids and their effectiveness in relation to dust suppression, it was decided to investigate the effect of a permanent magnetic field. This approach makes it possible to easily determine both the fact of the existence of the effect of magnetic field on the properties of a liquid and to evaluate the increase in the efficiency of dust suppression after prolonged magnetization.

For the correct selection of a permanent magnetic field (PMF) source, it was necessary to study the theoretical basis of the physics of PMF sources, the features of their manufacture and examples of industrial applications.

For uniform magnetization of the liquid, a permanent magnetic field source is placed in the center of a container filled with ordinary water. Such placement will allow the liquid to be magnetized in the tank as efficiently as possible by placing the source of the PMF in the center, as well as due to natural convection flows inside the tank. Therefore, it is important to take into account the duration of these processes – for this, the PMF source is placed for a day in a container with water: this will ensure a good and uniform magnetization of the aqueous medium, although further studies are supposed to take into account various parameters of magnetization: the magnetic potential of the field source, the shape of the magnetic field created, the nature of the field (constant / non-constant), the duration of magnetization, and so on. This, in turn, will make it possible to establish the dependence of the efficiency of magnetization and dedusting of the treated liquid on changes in certain process parameters, but this is the subject of another study.

The development of the laboratory stand was carried out on the basis of the Center for Geomechanics and Problems of Mining Production of St. Petersburg Mining University according to the methodology also developed by the Center. The laboratory stand was designed to assess the dustiness of air in a semi-closed system inside the stand by blowing the dust up and carrying out further measurements of the dispersed composition and mass concentration of dust.

Moreover, the laboratory stand was designed to study the effectiveness of dust suppression using irrigation systems when dispersing ordinary and magnetized water. Laboratory stands made in accordance with the principles of physical modeling allow us to take into account many factors that are close to real conditions in mining operations (Ivanov et al., 2021).

The method of creating the stand consists in mixing and manufacturing the basis of the model, which after solidification becomes a full-fledged imitation of a particular rock, depending on the selected composition, which in turn may differ in the ratio of components. At the same time, the geomechanical properties of the simulated rock are taken into account and transferred to the manufactured simulation model. In the manufacture of the stand, equivalent materials (EM) were used, which are a filler and a binding agent. As a filler, bulk materials are usually used, for example, fine $SiO_2$ sand. Epoxy resins or other bonding bases can be used to bind the particles.

First of all, the composition of the future mixture is selected – the basis for the manufactured model, which indicates the mass ratio of all components included in the mixture. In this case, it was decided to manufacture a model of fine $SiO_2$ sand, and to take ED-20 epoxy resin with a PEPA hardener as a binding agent. The correct calculation of the composition in accordance with the specified characteristics of the expected web allows you to obtain a very high-quality sample of rock or porous material while preserving the geomechanical properties of the simulated object and observing scale correspondences.

After calculating the ratio of the components of the required mixture, the weighted filler is poured into a mixer with two mixing augers.

Such mixers ensure sufficient mixing of the components, which is very important for maximum similarity of the characteristics of the final model with the original object of modeling, especially because the ratio of the components of the mixture by weight is very small, namely 100:1 (up to 0.01 kg of binder may be per 1 kg of filler).

Depending on the selected components, the mixing method may also vary. For example, when using ED-20 resin and PEPA hardener as a binding agent:

1. The $SiO_2$ filler with the calculated mass is poured into the mixer.

2. The rotation of the screws is turned on in the direction to the center, inside the mixer.
3. The required amount of ED-20 epoxy resin preheated to approximately 100℃ is weighed.
4. The ED-20 resin is poured evenly into a working mixer in a thin stream and 10 minutes are timed.
5. The required amount of PEPA hardener is weighed.
6. At the end of 10 minutes of mixing the filler and ED-20, the PEP hardener is also poured into the mixture in a thin stream, and another 5 minutes are timed.
7. At the end of 5 minutes of mixing, the mixture is poured into a container to move to the manufactured model.

Next, the mixture is delivered to a pre-prepared formwork, which is the shape that the final model should take, and a uniform layer of no more than 4-5 cm thick is poured inside the formwork. To remove air, reduce the pores between the filler particles and ensure the specified strength and other geomechanical properties, 2 methods are used: the rolling method and the ramming method. The method of laying consists in using a special roller of the set mass (2-2.5 kg), which evenly and smoothly rolls on the surface of the future model, leveling and ramming the mixture in the formwork. The method of ramming consists in the gradual uniform pressing of the mixture into the formwork using a special pressing plate.

After ramming or rolling, the model is left alone for at least a day so that the mixture (in particular, resin droplets) cools down and seizes, binding the filler particles together. And as a result, a ready-made model with specified strength and geomechanical properties is obtained, simulating the properties of an initially specified rock or porous material.

Since the stand is also designed to measure and evaluate the effectiveness of hydraulic spraying, holes are provided in the short ends of the formwork for measuring and supplying water and air (to simulate wind flow), and irrigation lines are fixed on the long ends-the walls of the formwork, which are rubber tubes with an inner diameter of 0.5 cm with nozzles embedded in them for water dispersion.

In total, the model has 6 nozzles, 3 for each irrigation line. The nozzles are embedded at a distance of 65 cm from each other, which, taking into account their spray cone with an angle of up to 70 °, should provide for the most efficient and closest to real conditions hydro-spraying of the space inside the stand.

In addition, the stand should be covered with a protective transparent film: on the one hand, to prevent dusting of the laboratory premises and the possibility of monitoring the processes inside the stand, and on the other hand, to exclude the influence of external factors on the distribution of dust and dispersed water inside the stand. Thus, a conditionally isolated environment is created inside the stand, which allows the experiment to be carried out as close as possible to real conditions in open-pit mining: the impact of the laboratory atmosphere (air flows, humidity, local dust, etc.) is practically excluded, the amount of dust that has left the boundaries of the stand is also negligible, which makes it possible to simulate the scale similarity of the model and the amount of dust.

Experimental studies and measurements were carried out directly on the basis of the Center for Geomechanics and Mining Problems using a manufactured laboratory stand and provided and own laboratory equipment.

First of all, the measured dust sample was placed inside the stand, and the dust was weighed in accordance with the geometric scale of the model and the real object. This compliance was established based on the sampling methodology: dust samples taken at the enterprise were collected from a certain and measured surface area approximately equal to 15 $cm^2$. From here, through the mass of each of the sampled samples, the mass of dust placed inside the stand was calculated, equal to about 3-5 g.

Then, with the help of an air blower with a nozzle, an air flow was fed into the stand to blow up the dust mass previously placed on the surface of the model, and for complete blowing up and imitation of the wind flow in a real quarry, the work of the supercharger lasted about 10-15 seconds along the length of the model.

After the dust mass was blown up, the CEM DT-9880M dust particle counter was used to measure the dispersed composition and mass concentration of dust at various measuring points on the stand. The main measuring point is located on the short end of the model on the opposite side from the place of air and water supply to the model. The remaining points are placed along the length of the model at a distance of 65 cm from the main measuring point and from each other, on both sides of the model (on both walls). This arrangement of points allows to estimate the spatial distribution of the dust mass inside the stand, as well as to determine the change in the concentration or fractional composition of dust as it moves away from the place of blowing.

The CEM DT-9880M device allows to determine the distribution of the number of dust particles in the air by the size of dust particles with an accuracy of up to 50% for a fraction of 0.3 microns and up to 100% with a particle size of more than 0.45 microns. According to the manufacturer, there is a 5% chance of a random measurement error per 2 million analyzed particles. At the same time, the device is able to determine the dispersed composition of dust in the air with a size of 0.3, 0.5, 1, 2.5, 5 and 10 microns. In addition, the CEM DT-9880M dust particle counter is also capable of detecting the mass concentration of dust, but only for fractions of 2.5 microns and 10 microns.

After recording the measurements, the air blower was switched on again to sweep up the dust that had settled during the measurements. Also, with a visible small amount of settled and blown dust, 0.5 g of new dust was also added to the stand. After the dust was blown up again, irrigation lines were switched on to suppress the floating aerosol. At the same time, in order to simulate the real working conditions of irrigation equipment, irrigation worked for 2-3 seconds. This approach simulates, for example, the passage of a watering machine on a technological road. After the irrigation was stopped, the dispersed composition and mass concentration of dust were measured at the same measuring points as during the usual dust mass blowing.

Further, the model was left to completely dry out and settle the dust that did not settle during suppression. After the simulation model was completely dried, the experiment was repeated, but with magnetized water and measurements at the same points. Also, each of these experiments was carried out 3 times each to average the results obtained and eliminate experimental errors.

As a result, an array of data is collected, which, after mathematical processing, makes it possible to conduct a comparative analysis of two methods of hydro-spraying and evaluate the relative effectiveness of each of them.

In addition to determining the dispersed composition using the CEM DT-9880M dust particle counter, the Center for Geomechanics and Mining Problems also provided an opportunity to measure the fractional composition and shape of dust particles using a high-precision optical analyzer for the size and shape of dust particles CAMSIZER XT. This equipment uses an optical method to analyze the size and shape of particles using 2 cameras that analyze larger particles (the base camera) and small dust particles (the camera with an increase in multiplicity), while performing dynamic analysis of images taken at a speed of 300 frames per second. This equipment is able to distinguish and determine dust particles ranging in size from 0.8 microns to 5 mm when using a module for dispersing the solid phase with compressed air. CAMSIZER XT also allows you to adjust each measurement to the parameters of a separate sample, its properties and the expected measurement result.

As a result of the measurement, CAMSIZER XT provides reports on the content of dust particles by size and shape in the form of a report in a table, distribution graphs and photo images of the particles themselves.

## 4.4 Conclusion on Chapter 4

Chapter 4 of the Master's thesis is devoted to the substantiation of the proposed measures to solve the problem under study, namely, the chapter describes the prerequisites for the use of means to increase the effectiveness of modern methods of dust suppression, in particular, magnetic fields of various nature.

The idea of using magnetic fields, both permanent magnetic and non-permanent electromagnetic, is relatively new, and therefore there is currently no reliable scientific foundation for basic fundamental research on this topic. Nevertheless, scientists around the world are beginning to pay attention to the possibility of using magnetic fields to change the physicochemical properties of liquids and to improve the means of dust suppression used today in this way. According to a number of studies, the effect of magnetic fields of various nature on dust-suppressing compositions having an aqueous basis can improve the wetting ability of a liquid, leading to a decrease in its surface tension, a decrease in the wetting angle, improving the infiltration ability of a liquid into porous and friable structures, and more. At the same time, these measures do not require significant costs for the design and implementation of devices for the magnetization of aqueous media in laboratory and industrial conditions.

It is worth noting that in modern production conditions, the most common solution to the problem of increased dustiness of air in the workplace remains hydro–spraying - the implementation of irrigation works using ordinary industrial purity water. At the same time, the methodology and basic principles of hydro-dusting of dusty surfaces are often not observed, for example, the frequency of departure of irrigation equipment does not correspond to the necessary one, which in turn leads to the almost complete absence of a positive effect of the measures carried out. Also, an important problem remains the difficulty of selecting surfactants and other binding agents for specific mining-geological and geomechanical conditions of mining operations, especially taking into account the requirements for dust-suppressing substances and compositions being developed. All this leads to the fact that the issue of increasing the effectiveness of the dust suppression means used is becoming more and more relevant, and scientists around the world are beginning to pay attention to solutions of this kind.

Based on the conducted scientific review and analysis of domestic and foreign experience in solving the problem of increased dustiness of the air, a methodology for implementing the proposed solutions was formulated, consisting of 7 stages. Among the stages of implementation of solutions, one can separately highlight a literary scientific review on the research topic, an analysis of achievements in the field of magnetization of aquatic environments, as well as the theoretical basis of magnetic fields and the basic principles of their impact on aquatic environments; the development of a laboratory stand to assess the degree of dustiness of the air and the effectiveness of dust suppression measures; conducting desk research using a manufactured stand and high-precision measuring equipment.

As a result of the formulation of the idea of solving the problem and substantiating the possibility of its implementation, a hypothesis was formulated: The use of permanent and non-permanent magnetic fields can increase the effectiveness of dust suppression measures and improve the working conditions at the workplaces of enterprises of the mineral resource sector by the dust factor. A number of studies and tests were conducted to test the hypothesis.

# 5 Experimental verification of the hypothesis

## 5.1 Development of an experimental stand

For experimental verification of the hypothesis formulated at the end of Chapter 4 of the Master's thesis, as well as within the framework of the methodology for implementing the proposed solutions for the magnetization of dust suppression means, a laboratory stand was developed to assess the degree of dustiness of the air of a conditionally isolated system simulating the space above a linear dust source in open-pit mining, and to study the effectiveness of the proposed solutions to improve the effectiveness of measures to suppress dust.

As a result of joint work with the Center for Geomechanics and Mining Problems of St. Petersburg Mining University, a laboratory stand was made, which is a model of a linear source of dust formation in a mining quarry.

The development of the stand began with the determination of the geometric parameters of the model, which was necessary for further calculation of the composition of the basis of the laboratory stand – a model of a dusting surface made of equivalent materials. The calculated composition of the basis of the model is presented in Table 2.

| Material | Mass, kg | Concentration, % vol. |
|---|---|---|
| Mixture of components | 40,00 | - |
| Filler $SiO_2$ | 39,64 | - |
| Binding agent (ED-20 + PEPA) | 0,36 | 0,9 |
| Epoxy resin ED-20 | 0,30 | - |
| Hardener PEPA | 0,06 | - |

**Table 2: Composition of the mixture**

After calculating the composition, according to the methodology developed by the Center for Geomechanics and Mining Problems and described in detail in Chapter 4 of the Master thesis, the weighted amount of filler (Table 2) it was poured into a special screw mixer (Fig. 9). Fine quartz sand $SiO_2$ with a grain size of no more than 1 micron was taken as the basis of the model.

**Figure 9: Auger mixer in operation**

Further, according to the methodology, the components of the mixture were added step by step and in the process of manufacturing the mixture in accordance with the calculated data from Table 2. It is important to note that the components of the mixture, namely ED-20 epoxy resin and PEPA hardener, should be added to the mixer slowly, in a thin stream: this ensures uniform mixing of the components, and after manufacturing the model will have evenly distributed and approximately the same geomechanical properties throughout the volume (Fig. 10).

**Figure 10: Adding ED-20 epoxy resin to the mixture**

After the end of mixing the base of the model, it is transported in a container to a pre-prepared formwork and laid out in a uniform layer over the entire area of the model. At the same time, the bulk layer of the base should not exceed 5 cm in height, since if the specified value is exceeded at the next stage of ramming or rolling the base of the model, the effectiveness of these measures will be reduced, which will lead to insufficient shrinkage of the layer by reducing air pores and to an uneven distribution of geomechanical properties in the model. The thickness of the bulk layer of the model base during its manufacture in accordance with the volume of the resulting mixture was 3 cm.

After leveling the base material of the model, the mixture was rammed using a special pressing plate (Fig. 11).

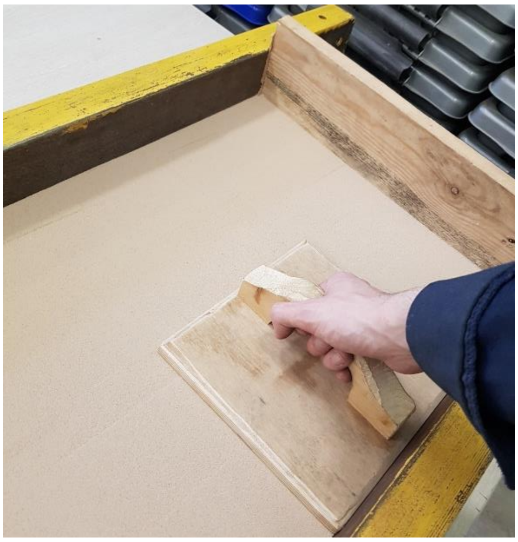


**Figure 11: Ramming of the mixture of the future basis of the model**

After these actions, the model was left for several days to cool down and solidify the mixture. The result of manufacturing a model of a linear source of dust formation in open pit mining is shown in Fig. 12.

**Figure 12: A ready-made model of a linear air dust source**

In order to be able to blow up dust from the surface of the model, measure the dust content in the air and check the effectiveness of dedusting measures using water spray nozzles, irrigation nozzle lines were installed along the stand, and the stand itself was covered with a transparent protective film. The result of the work on the manufacture of the laboratory stand is shown in Fig. 13.

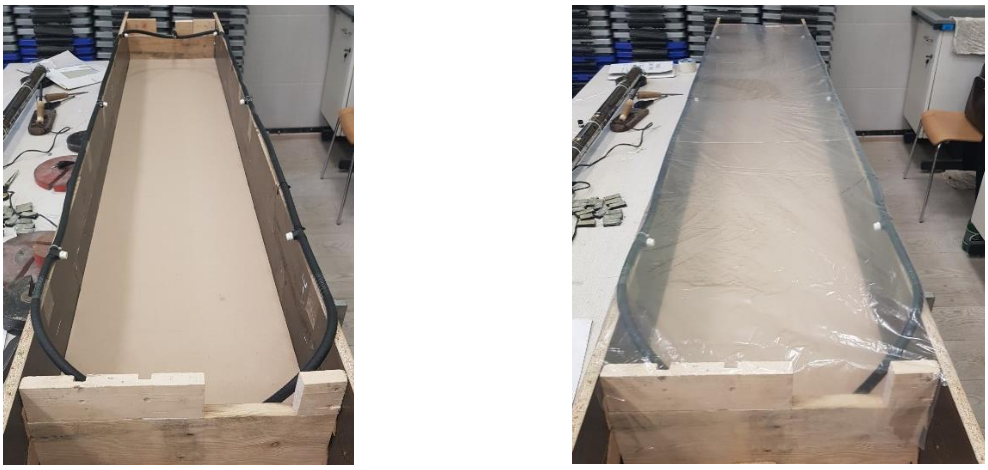


**Figure 13: Laboratory stand for air dust assessment**

For dust suppression measures, an irrigation system is provided, consisting of communication lines (rubber hoses), T-splitters, nozzle sprayers embedded in the hose, an electric pump and a water source. The low-pressure nozzles used for spraying are made of polyvinyl chloride (PVC), which ensures low cost and ease of installation of irrigation lines (Fig. 14 and 15).

**Figure 14: Spraying system**

**Figure 15: Low pressure nozzles**
(Source: evspray.ru)

## 5.2 Selection of a magnetizing method

To select a magnetizing method for the research of the effectiveness of dust suppression of a floating aerosol with the help of magnetized water, a review of modern solutions for the magnetization of aqueous media, as well as the theoretical basis for the effects of permanent magnetic and non-permanent electromagnetic fields on aqueous media was conducted.

As a result, a ring-shaped ferrite permanent magnet (Fig. 16), which was placed in a container with water for its magnetization, was chosen to carry out magnetization measures as a part of the implementation of the proposed solutions to reduce the increased dust load.

The choice in favor of ferrite magnetic materials was influenced by a number of factors and advantages of these magnetic means. First of all, ferrite magnets are practically not subject to corrosion, which is very important when magnetizing aqueous media, since in accordance with the task, it is necessary to place the magnet directly into the aqueous medium. Moreover, ferrite magnets are very resistant to demagnetization, which ensures the constancy of the magnetic field created by them. Hence, it is possible to neglect the change in the magnetic field and exclude a possible error during magnetization, assuming that the process occurs uniformly and with constant magnetic field parameters. Sources of a permanent magnetic field do not require human intervention during operation, thereby eliminating maintenance and maintenance of equipment. In addition, the direction and location of the magnetic lines at the annular magnet will allow it to cover a larger volume of liquid during magnetization in comparison with other permanent magnets having similar geometric parameters and magnetic potential, but a different shape (Fig. 17).

**Figure 16: Magnetization by a ferrite ring-shaped magnet**

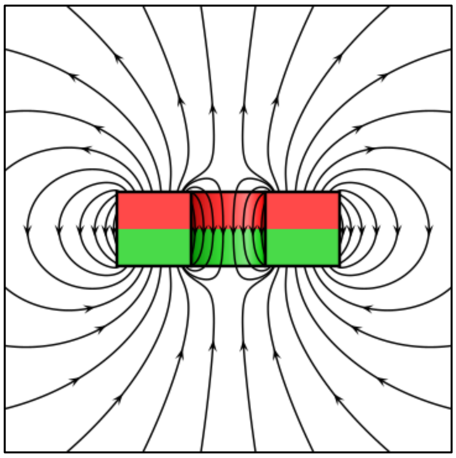


**Figure 17: Magnetic field around a ring-shaped magnet**
(Source: ru.wikipedia.org)

However, these magnets also have a number of disadvantages. First of all, it is fragility. The fact is that ferrite magnets by their nature are ceramics, which characterizes them as very strong, but fragile materials. And if in laboratory conditions, as part of an experiment, it is possible to exclude certain external influences, including physical ones, on a ferrite magnet and thereby avoid its destruction, then in industrial conditions it is impossible to deny the risks of destructive effects of various factors and absolutely guarantee the safety of such material.

In addition, as part of laboratory tests, small volumes of water or other liquid need to be magnetized, whereas in industrial conditions the volume of water used during dust suppression will be several orders of magnitude larger. In such circumstances, the effectiveness and potential of permanent ferrite magnets, even several, may be in question. Therefore, in order to ensure the effective magnetization of industrial volumes of water, it is necessary to manufacture special samples of ferrite magnets with industrial dimensions, purchase a large number of standard ferrite magnets or switch to a more convenient solution in industrial conditions – the use of non-permanent electromagnets.

The advantages of such a solution are obvious: in this case, the parameters of the electromagnetic field can be easily changed and adjusted by changing the characteristics of the electrical circuit, thereby creating the necessary EMF for the desired volume of liquid or its flow rate; the EMF potential can significantly exceed the same parameters of the permanent MF, which can lead to a reduction in the required time for sufficient magnetization of the liquid and to an increase in the effectiveness of these measures.

Nevertheless, the device generating the electromagnetic field requires prompt and periodic monitoring and maintenance, whereas the sources of PMF do not require any maintenance at all. Moreover, EMF generators also need a constant and stable source of electricity, and this means additional operating costs for electrical energy, the amount of which will depend on the duration of operation and the power of the devices. Another important point is the need for an EMF generator in a water–proof design to protect expensive electrical equipment from moisture, even if there is no need to immerse the device in an aqueous environment, which in turn increases the cost of the generator several times.

Hence, it can be concluded that for industrial conditions, the most suitable solution is using a source of a non-permanent electromagnetic field, but the positive effect of magnetic fields on dust suppression using aqueous solutions and media has not yet been fully proven and requires careful and comprehensive study. Therefore, a source of a permanent magnetic field was chosen as a means of magnetization, well suited for laboratory tests and not requiring expensive and lengthy preparation. The study is primarily aimed at substantiating the possibility of using magnetic fields in order to increase the effectiveness of dust suppression measures, and in further studies, if a positive result is obtained in this one, the impact and effectiveness of electromagnetic fields will be considered.

## 5.3 Dust sampling

When studying the effectiveness of dust suppression in laboratory conditions, an important point is to make the experimental conditions as close as possible to real ones. This becomes possible thanks to various methods of physical and computer modeling, however, when justifying methods and solutions to reduce the dust load, it is also important to be able to work with industrial dust samples collected directly on the territory of a mining enterprise.

Therefore, as part of the internship and departure to the Vostochny (Eastern) Mine of the Kirov branch of JSC Apatit, the collection of industrial dust samples for further testing and research was organized.

Samples of settled dust were collected on the territory of the Koashvinsky quarry, belonging to the Vostochy (Eastern) Mine of JSC Apatit, where open pit mining of high-quality apatite-nepheline ores is carried out. The sampling technique was as follows.

The territory of the Koashvinsky quarry was divided into conditional sections depending on the purpose or stage of mining operations. So, 5 sites were allocated:

1. A crusher located on the territory of a quarry and used for crushing oversized and large pieces of rocks in the open air.
2. Ore warehouse "Stack No. 1" with ore unloading by dump trucks and loading by excavator – face shovel, into railway dumpcars.
3. Rock face with loading of rocks by an excavator – face shovel.
4. Overburden face, the highest point of mining operations of the Koashvinsky quarry.
5. A rock face with loading of rocks by an excavator – a face shovel, and an ore face with loading of ore by a front loader.

In this case, the thesis was put forward about the different influence of air dust sources at open pit mining enterprises and the different contribution to the overall dust load at the mining facility. That is why the sites were selected in accordance with one or another stage of mining operations using various mining and transport equipment.

At each of the 5 sites, an area of 10 m by 10 m was allocated, lying on the path of the dust cloud after its formation (in accordance with the current direction of wind flow). On the allocated site, 5 points were identified, evenly distributed throughout the site. From each of these points, using a special polymer rubber spatula (Fig. 18), 3 small samples were taken into one container. Thus, the averaging of the selected sample was carried out and the exclusion of the error of the prevalence of dust from another dust source in each sample was ensured.

As a result of sampling on the territory of the Koashvinsky quarry, 5 averaged samples were made out of a total of 75 collected samples intended for further dispersed and optical analysis (Fig. 19).


Figure 18: Sampling of deposited dust

Figure 19: Samples of deposited dust

In addition, air samples were taken at each of the 5 sites for the dispersity analysis of the floating aerosol: 5 air samples were taken at each site along the trajectory of the dust cloud from the place of its formation (Fig. 20). The results of air sampling are presented in annex I (p.II).

**Figure 20: Air sampling for dust dispersity analysis**

According to the data obtained from the analysis of samples, in some sampling sites, an excess of dust concentrations over the MPC was recorded several times. For example, at the ore transshipment warehouse (sampling point #2), the actual concentration exceeded the maximum permissible concentration by 1.4 times (8.4

mg/m$^3$ with a maximum permissible concentration of nepheline dust of 6 mg/m$^3$), and at the site where excavation and loading operations are carried out in the ore and rock faces (sampling point #5), the actual dust concentration exceeded the MPC by 2.1 times (12,6 mg/m$^3$). At the same time, it was noticed that most of the specialists, site masters and geologists did not use personal protective equipment (PPE) when carrying out work on the sites under consideration.

It should also be noted that the cumulative determination of the dispersed composition of dust, both floating, examined in an air sample, and settled, is a very important feature of the work, since this approach allows us to assess what proportion of settled dust is capable of being blown up and directly have a negative impact on the health of mining personnel, as well as to determine the proportion of each fraction of dust contributing to contribution to the dust load represented by the floating aerosol.

## 5.4 Experimental research

In accordance with the set tasks, the following parameters were studied and analyzed: dustiness of the air in the conditionally isolated space of the laboratory stand; the dispersed composition of the collected samples of settled dust; the dispersed composition of the floating aerosol; the shape of dust particles from the selected samples; dustiness and dispersed composition after the dust suppression measures carried out on the stand, including dedusting with water and with magnetized water.

At the first stage of the experiment, 2-3 g of dust was blown up from samples taken at the Koashvinsky quarry inside the space of the laboratory stand using an air blower. After the dust mass was blown up, the dispersed composition and dust concentration inside the stand were measured using the CEM DT-9880M dust particle counter. At the same time, the display of the device shows the values of the number of dust particles by their average size (from 0.3 to 10 microns) in the mode of determining the fractional composition of the dust sample and the values of the mass concentration of dust in micrograms/m$^3$ for particles with an average diameter of less than 2.5 microns and less than 10 microns, respectively. An example of the results of measuring the dust content of air in a laboratory stand is shown in Fig. 21 and 22.

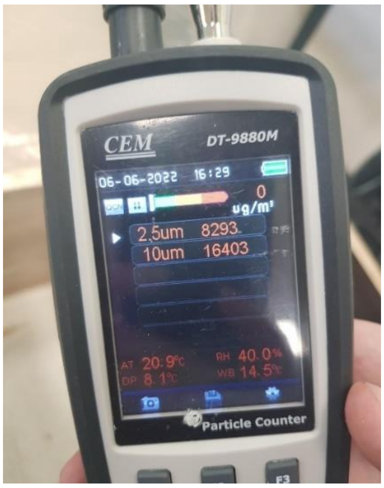



**Figure 21: Dust mass concentration measurement**


**Figure 22: Dust dispersity analysis**

Measurements of the parameters of the dustiness of the air after blowing up the sample were carried out at 7 points: 3 points on each side of the stand along its length and at 1 point at the short end of the model on the opposite side from the place of air and water supply.

As a result, an array of data was obtained consisting of the results of an assessment of the dispersed composition of dust floating in the air inside the laboratory stand and the mass concentration of dust (Table 3).

| No. | Dust mass concentration, $mg/m^3$ by particle size, µm | | Dispersity of dust sample by particle size, µm | | | | | |
|---|---|---|---|---|---|---|---|---|
| | < 2,5 | < 10,0 | 0,3 | 0,5 | 1,0 | 2,5 | 5,0 | 10,0 |
| 1 | 8,3 | 16,4 | 185 992 | 119 618 | 81 978 | 20 605 | 1654 | 628 |
| 2 | 7,9 | 17,1 | 173 421 | 107 673 | 74 620 | 19 592 | 1721 | 748 |
| 3 | 8,6 | 18,3 | 203 496 | 147 904 | 87 253 | 22 275 | 1921 | 883 |

**Table 3: Dustiness measurement results in measurement point #1**
(dry floating dust)

After the measurements were completed, during the dry blowing up of the dust mass, an additional 0.5-1.0 g of dust was placed in the stand to compensate for the part of the aerosol that was carried outside the boundaries of the laboratory stand through sampling holes and design leaks, and after repeated blowing, the atmosphere inside the model was first dedusted with ordinary room temperature water (Table 4).

| No. | Dust mass concentration, mg/m³ by particle size, µm | | Dispersity of dust sample by particle size, µm | | | | | |
|---|---|---|---|---|---|---|---|---|
| | < 2,5 | < 10,0 | 0,3 | 0,5 | 1,0 | 2,5 | 5,0 | 10,0 |
| 1 | 1,9 | 3,4 | 234 782 | 87 663 | 20 605 | 3326 | 965 | 326 |
| 2 | 2,1 | 3,7 | 247 532 | 94 371 | 23 504 | 3549 | 1153 | 378 |
| 3 | 1,8 | 3,5 | 230 741 | 85 733 | 19 581 | 3203 | 983 | 342 |

**Table 4: Dustiness measurement results in measurement point #1** (water)

After the measurements were completed, when evaluating the effectiveness of hydro-spraying, the model was left for a day until completely dry in order to exclude the influence of one experiment on another.

After the model was completely dried, the next part of the dust sample from the Koashvinsky quarry was placed and blown up in the stand, the dust was suppressed using an irrigation system, but with the use of a magnetized liquid, which was taken from the tank by a pump connected to it. The result of dedusting the air in the model using magnetized water is presented in Table 5.

| No. | Dust mass concentration, mg/m³ by particle size, µm | | Dispersity of dust sample by particle size, µm | | | | | |
|---|---|---|---|---|---|---|---|---|
| | < 2,5 | < 10,0 | 0,3 | 0,5 | 1,0 | 2,5 | 5,0 | 10,0 |
| 1 | 0,4 | 1,1 | 203 563 | 58 662 | 16 342 | 2463 | 568 | 227 |
| 2 | 0,6 | 1,2 | 215 372 | 63 631 | 17 855 | 2549 | 590 | 241 |
| 3 | 0,5 | 1,0 | 208 445 | 60 610 | 17 024 | 2503 | 549 | 217 |

**Table 5: Dustiness measurement results in measurement point #1** (magnetized water)

To ensure the reliability of the experimental data obtained, each of these tests was performed three times: dry floating dust measurements were carried out three times, hydro–spraying with water three times, and dedusting with magnetized water three times. Thus, the measurement results were averaged, the influence of measurement and experimental errors was reduced, or these errors were completely excluded.

After measurements and tests were carried out on a laboratory stand, work was carried out to determine the dispersed composition, as well as the shape of dust particles from samples of the settled dust mass taken at the Koashvinsky quarry of the Vostochny (Eastern) mine. The research was carried out on CAMSIZER XT laboratory equipment, which is a high-precision optical express analyzer of the size and shape of dust particles. This device uses the capabilities of two high–precision cameras: one basic, which takes pictures of dust particles without scaling, and the second - with magnification, which allows registering particles with a minimum linear size of 0.5 microns (Fig. 23).


**Figure 23: Express dust particle analyzer CAMSIZER XT**
(Source: https://www.dia-m.ru/)

At the same time, the software of this equipment allows very flexible configuration of the task file for adaptive or basic measurement, which in turn is of particular importance when evaluating dust samples from various sources and with different chemical compositions.

It is worth noting that the size of the particles analyzed by the CAMSIZER device depends not only on the resolution of both chambers, but also on the method of dispersing the dust sample during measurement. So, in this case, compressed air is used to separate the sample into individual dust particles, and therefore a compressor is also prepared in advance. This method of dispersion (there is also dispersion in liquid and dispersion due to gravity) limits the range of analyzed particles from 0.5 microns to 5 mm.

Before determining the parameters of the main sample, it is recommended to conduct a test sample, within the framework of which "Speed adaptation" is carried out – the device automatically adjusts its parameters based on the analyzed test sample, and also displays a curve of the dependence of the speed of flight of dust dispersed particles on their size.

After the end of the speed adaptation and the already corrected analysis of the main sample of the crushed solid phase, the device software issues a report including a graph of the distribution of dust particles by size, as well as tables including information about the size of the analyzed particles, their shape (fractal particle size), the percentage of particles of a certain size in the sample and, accordingly, the number of particles in size. An example of a report on the dispersion analysis of sample 1 is shown in Fig. 24 and 25. All the obtained results are give in annex II (p.III-VII).

CAMSIZER XT® Retsch® TECHNOLOGY

Ore dust after crusher

| | |
|---|---|
| Компания: | Апатит |
| Пользователь: | Лаборатория моделирования |
| Файл результатов: | C:\CamsizerXT\CAMDAT\Апатит\Апатит_проба1_xc_min_001.rdf |
| Файл задачи: | C:\CamsizerXT\CAMSYS\Апатит.afg |
| Время: | 06.06.2022 , 13:38 , Длительность 9 мин 9 s at 0.1 % площадь покрытия, Скорость изображения 1:1 , with X-Jet, gap width = 2.0 mm, dipersion pressure = 25.0 kPa |
| Модель частицы: | xc_min |
| Shape settings: | сферические Частицы |
| N. частиц: | CCD-B = 46168565 , CCD-Z = 2417048 |
| Velocity adaption: | Apatit1.ftv |
| приведение: | нет |
| Материал: | Apatite ore |

| Class dimension | [mm] | p3 [%] | Q3 [%] | SPHT3 | Symm3 | b/l3 | PDN |
|---|---|---|---|---|---|---|---|
| | < 0.1000 | 61.7 | 61.7 | 0.819 | 0.908 | 0.699 | 986968400 |
| 0.1000 - | 0.1250 | 9.6 | 71.3 | 0.819 | 0.898 | 0.682 | 168973 |
| 0.1250 - | 0.1600 | 8.9 | 80.2 | 0.826 | 0.896 | 0.698 | 85174 |
| 0.1600 - | 0.2000 | 6.8 | 87.0 | 0.827 | 0.891 | 0.727 | 32286 |
| 0.2000 - | 0.2500 | 4.8 | 91.8 | 0.824 | 0.889 | 0.715 | 11851 |
| 0.2500 - | 0.3150 | 3.4 | 95.2 | 0.814 | 0.884 | 0.702 | 4217 |
| 0.3150 - | 0.4000 | 1.8 | 97.0 | 0.799 | 0.879 | 0.680 | 1153 |
| 0.4000 - | 0.5000 | 1.1 | 98.1 | 0.781 | 0.875 | 0.660 | 327 |
| 0.5000 - | 0.6300 | 0.9 | 99.0 | 0.763 | 0.868 | 0.646 | 136 |
| 0.6300 - | 0.8000 | 0.5 | 99.5 | 0.760 | 0.865 | 0.656 | 41 |
| 0.8000 - | 1.0000 | 0.3 | 99.8 | 0.746 | 0.859 | 0.629 | 12 |
| 1.0000 - | 1.2500 | 0.0 | 99.8 | 0.655 | 0.744 | 0.706 | 1 |
| 1.2500 - | 1.6000 | 0.2 | 100.0 | 0.681 | 0.824 | 0.719 | 2 |
| 1.6000 - | 2.0000 | 0.0 | 100.0 | | | | 0 |
| 2.0000 - | 2.5000 | 0.0 | 100.0 | | | | 0 |
| 2.5000 - | 3.1500 | 0.0 | 100.0 | | | | 0 |
| 3.1500 - | 4.0000 | 0.0 | 100.0 | | | | 0 |
| 4.0000 - | 5.0000 | 0.0 | 100.0 | | | | 0 |
| 5.0000 - | 6.3000 | 0.0 | 100.0 | | | | 0 |
| 6.3000 - | 8.0000 | 0.0 | 100.0 | | | | 0 |
| 8.0000 - | 10.0000 | 0.0 | 100.0 | | | | 0 |
| 10.0000 - | 12.5000 | 0.0 | 100.0 | | | | 0 |
| 12.5000 - | 16.0000 | 0.0 | 100.0 | | | | 0 |
| > 16.0000 | | 0.0 | 100.0 | | | | 0 |

**Figure 24: The report of dispersity analysis of the sample 1 (table)**

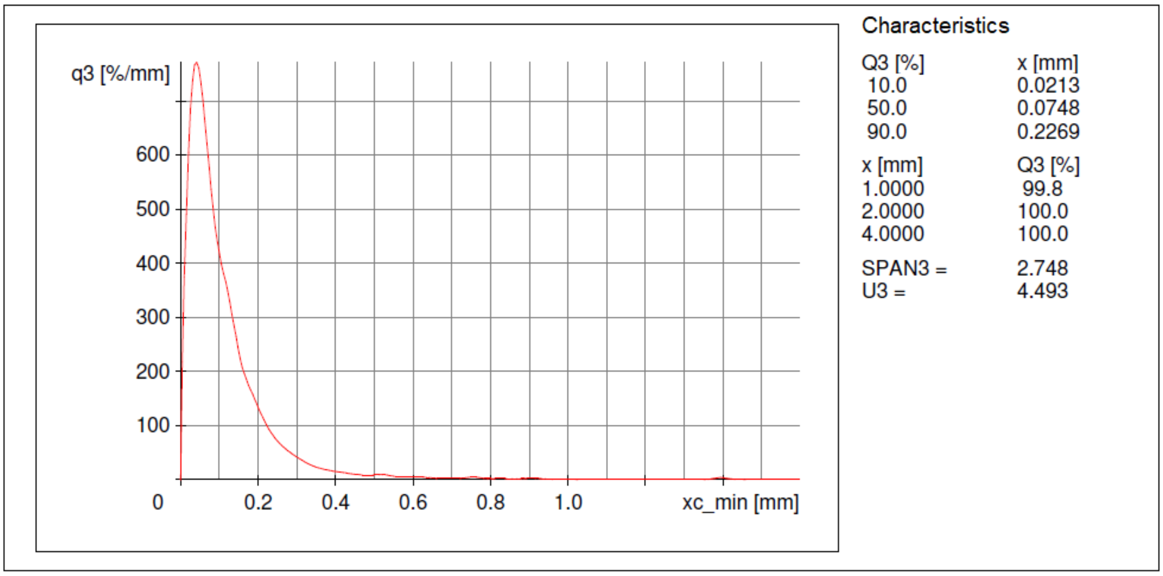



**Figure 25: The report of dispersity analysis of the sample 1 (curve)**

According to reports, the respirable dust fraction in all studied samples accounts for from 20% for the dust in the ore warehouse to 70% for dust in the crusher.

Separately, the software of the equipment saves photos taken during the registration and analysis of particles so that you can manually view them and evaluate the shape and relative size of the registered dust particles. In total, the device took more than 4,000 images with registered flying particles for 10 studies (5 adaptation and 5 main samples). An example of the photos from the base camera and the zoom camera taken by the CAMSIZER XT device during the analysis of sample 4 is shown in Fig. 26 and 27, respectively.

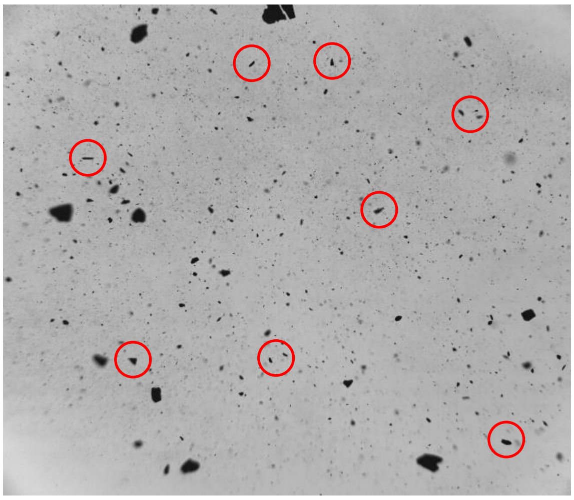


**Figure 26: Picture of dust particles (base camera)**

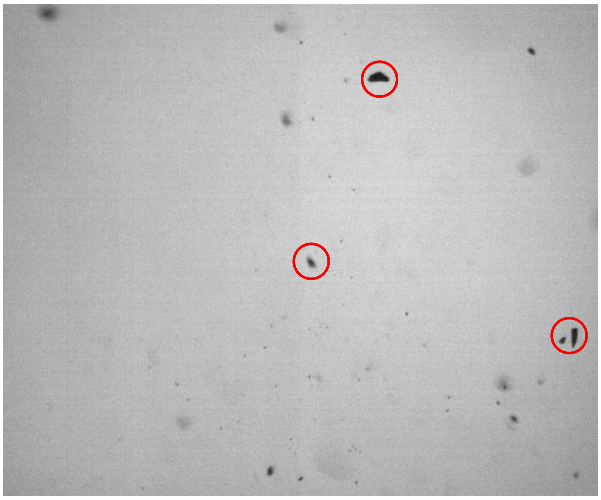


**Figure 27: Picture of dust particles (zoom camera)**

The red circles highlight the particles with the greatest potential for the development of pneumoconiosis and fibrosis in employees: these are elongated particles with a sharp shape (for example, needle-shaped). It can be seen that most of the particles are highlighted in the left photo from the base camera. This is due to the wider shooting angle of the base camera, that is, with a large number of captured particles. However, the particles highlighted in the left image from the base camera are small relative to the surrounding particles: they have a smaller size of about 1 micron, that is, they fall into the respirable fraction.

## 5.5 Discussion

The measurement of the dustiness of the air inside the laboratory stand after dry blowing showed that:

1. The dispersed composition of the blown dust is mainly represented by dust having a size smaller than the respirable fraction (up to 0.5 microns), however, the respirable part of the sampled sample is a very significant part, in particular particles of 1 and 2.5 microns in size. Such particles are most dangerous to the worker when inhaled, as they are capable of damaging the pulmonary alveoli.
2. The mass concentration of dust in the air after blowing up in some cases exceeds the maximum permissible concentration of apatite-nepheline dust by several times (for an apatite aerosol of hazard class 3, the MPC of 6 $mg/m^3$ is set, for a nepheline aerosol of hazard class 3 - 6 $mg/m^3$) and in some places is 10-16 $mg/m^3$.
3. Hydro-spraying with the use of ordinary water showed moderate efficiency, reducing the amount of floating particles in the air by about 1.5–2.0 times, and reducing the mass concentration of dust to 0.5-1.0 $mg/m^3$, which meets hygienic standards. At the same time, there was an increase in the number of dust particles with a size less than 1 micron, but a significant decrease in the number of particles with a fraction of 1 and 2.5 microns.
4. Hydro-spraying with the use of magnetized water showed increased efficiency in suppressing fine and medium-sized particles with a size of up to 2.5 microns: the number of particles was reduced by about 2.0-2.5 times,

and the dust concentration decreased to 0.1-0.3 mg/m$^3$, which indicates a higher efficiency of the magnetized water when suppressing the respirable dust fraction.

5. The dispersity analysis of samples of settled dust collected at the Koashvinsky quarry showed the prevalence of a respirable dust fraction of less than 10 microns, which indicates the importance of implementing dust suppression measures at the mining facility to reduce the harmful effects of aerosol on the health of workers.

The analysis of the shape of dust particles from samples taken at the Koashvinsky quarry showed the presence in the samples of small and larger particles having a sharp needle and plate elongated shape, which is particularly dangerous and has a high risk of leading to the development of pulmonary fibrosis.

## 5.6 Conclusion on Chapter 5

Chapter 5 of the Master's thesis is devoted to the description of the experimental part of the research and verification of the proposed theses and data obtained within the framework of the theoretical and review part of the work.

The laboratory stand which was made according to the methodology of the Center for Geomechanics and Problems of Mining Production of St. Petersburg Mining University made it possible to assess the dustiness inside the model after blowing up dust collected on the quarry territory, as well as to determine the effectiveness of the proposed measures for dedusting and improving the efficiency of dust suppression.

The established results and dependencies allow to judge that aerosols floating in the air at the workplaces of enterprises engaged in open pit mining and apatite-nepheline ores represent a moderate danger to the health of workers both from the point of view of the dispersed composition of dust, which is characterized by a significant content of respirable fraction, and from the point of view of the form of dust particles, some of which are represented by both large and small needle-like and sharp examples. Therefore, effective measures to suppress this dust are of great value for occupational health and safety at apatite-nepheline mines in general.

The conducted and described studies confirm that the use of magnetic and electromagnetic fields for the magnetization of water and surfactants can allow to a certain extent to increase the efficiency of dust suppression, especially in relation to the suppression of the respirable fraction. Nevertheless, further research is required on the use of electromagnetic fields in dust suppression, and also an important aspect is the approbation of laboratory research results in practice, in open-pit mining conditions.

# 6 Assessment of the risk of occupational disease development

## 6.1 Assessment methodology

One of the widely used and rational methods of risk assessment today is the Delphi method, which consists in an expert assessment of certain risks and further statistical processing of the data obtained.

As a part of the risk assessment, the Analytical Hierarchy Process method was also used to process the data obtained and determine the most important source of dust that contributes the most to the dust load and has a greater risk of leading to the development of pneumoconiosis in workers.

Moreover, the fuzzy set membership function used made it possible to determine the degree of belonging of certain risk parameters to the set of values under consideration. This, in turn, characterizes the reliability of data processing by minimizing the impact of introduced errors and inaccuracies.

As an object of statistical evaluation, 5 sampling sites were selected on the territory of open-pit mining operations, where air dustiness was measured. The purpose of this assessment is to determine the relative importance of each of the 5 sources of dust formation in terms of the total dust load and the impact on the health of personnel, as well as to identify the place of mining operations where the risk of pneumoconiosis among employees of the enterprise is highest. Thus, the authors determine the place of mining operations, which requires additional measures to reduce the dustiness of the air and improve the working conditions of open-pit mining personnel. Thus, the authors propose to implement a risk-based approach to reducing the occupational morbidity of workers by the dust factor.

First of all, 5 expert groups were interviewed to subjectively assess the impact of each of the assessed sources of dust on the risk of developing occupational respiratory diseases in open-pit mining personnel. The experts were provided with information on the nature and type of mining operations carried out at each sampling site, on the results of measurements of dust concentrations and its dispersed composition at each sampling point. The experts were also familiarized with the results of the analysis of the shape of dust particles from the samples taken at each of the 5 measurement sites. Thus, the awareness of experts about the dust load and the peculiarities of the influence of the dust factor on the personnel of the quarry was ensured.

The experts were asked to evaluate the impact of each of the dust sources considered in the study in pairs using the AHP method. At the same time, Saaty's rating scale from 1 to 9 was used to conduct this assessment, reflecting a comparative assessment of the relative significance of each of the studied elements:

- 1 - the criteria are equivalent,
- 3 - one criterion is somewhat more important than the other,
- 5 - one criterion is significantly more important than the other,
- - one criterion is undoubtedly more important than the other,
- - one criterion is absolutely more important than the other.

An example of an evaluation matrix of the relative importance of each of the sources is presented in table 6.

| | Source 1 | Source 2 | Source 3 | Source 4 | Source 5 |
|---|---|---|---|---|---|
| Source 1 | 1 | $X_{12}$ | $X_{13}$ | $X_{14}$ | $X_{15}$ |
| Source 2 | $1/X_{21}$ | 1 | $X_{23}$ | $X_{24}$ | $X_{25}$ |
| Source 3 | $1/X_{31}$ | $1/X_{32}$ | 1 | $X_{34}$ | $X_{35}$ |
| Source 4 | $1/X_{41}$ | $1/X_{42}$ | $1/X_{43}$ | 1 | $X_{45}$ |
| Source 5 | $1/X_{51}$ | $1/X_{52}$ | $1/X_{53}$ | $1/X_{54}$ | 1 |
| Column sums | $\sum_{i=1}^{5} X_{i1}$ | $\sum_{i=1}^{5} X_{i2}$ | $\sum_{i=1}^{5} X_{i3}$ | $\sum_{i=1}^{5} X_{i4}$ | $\sum_{i=1}^{5} X_{i5}$ |

**Table 6: Example of a matrix for AHP priority assessment method**

The AHP assessment of the significance of elements suggests that the data obtained in the matrix may not be complete due to possible discrepancies in the assessment of the relative importance of each of the elements. Such errors can be laid by the expert himself due to the large amount of data being processed. Therefore, an additional assessment of the integrity of the data presented in the matrix using the AHP method is necessary. This assessment is carried out in several stages.

First of all, the data presented in the pairwise evaluation matrix is normalized and presented as a new calculated matrix. Normalization is carried out by dividing each score from the original matrix by the sum of the same scores across the columns of the matrix. Additionally, the arithmetic mean of the normalized data obtained *Cij* is calculated, but already by lines (Table 7).

| | Source 1 | Source 2 | Source 3 | Source 4 | Source 5 | Mean value |
|---|---|---|---|---|---|---|
| Source 1 | $\frac{1}{\sum_{i=1}^{5} X_{i1}}$ | $\frac{X_{12}}{\sum_{i=1}^{5} X_{i2}}$ | $\frac{X_{13}}{\sum_{i=1}^{5} X_{i3}}$ | $\frac{X_{14}}{\sum_{i=1}^{5} X_{i4}}$ | $\frac{X_{15}}{\sum_{i=1}^{5} X_{i5}}$ | $\frac{\sum_{j=1}^{5} C_{1j}}{5}$ |
| Source 2 | $\frac{1/X_{12}}{\sum_{i=1}^{5} X_{i1}}$ | $\frac{1}{\sum_{i=1}^{5} X_{i2}}$ | $\frac{X_{23}}{\sum_{i=1}^{5} X_{i3}}$ | $\frac{X_{24}}{\sum_{i=1}^{5} X_{i4}}$ | $\frac{X_{25}}{\sum_{i=1}^{5} X_{i5}}$ | $\frac{\sum_{j=1}^{5} C_{2j}}{5}$ |
| Source 3 | $\frac{1/X_{13}}{\sum_{i=1}^{5} X_{i1}}$ | $\frac{1/X_{23}}{\sum_{i=1}^{5} X_{i2}}$ | $\frac{1}{\sum_{i=1}^{5} X_{i3}}$ | $\frac{X_{34}}{\sum_{i=1}^{5} X_{i4}}$ | $\frac{X_{35}}{\sum_{i=1}^{5} X_{i5}}$ | $\frac{\sum_{j=1}^{5} C_{3j}}{5}$ |
| Source 4 | $\frac{1/X_{14}}{\sum_{i=1}^{5} X_{i1}}$ | $\frac{1/X_{24}}{\sum_{i=1}^{5} X_{i2}}$ | $\frac{1/X_{34}}{\sum_{i=1}^{5} X_{i3}}$ | $\frac{1}{\sum_{i=1}^{5} X_{i4}}$ | $\frac{X_{45}}{\sum_{i=1}^{5} X_{i5}}$ | $\frac{\sum_{j=1}^{5} C_{4j}}{5}$ |
| Source 5 | $\frac{1/X_{11}}{\sum_{i=1}^{5} X_{i1}}$ | $\frac{1/X_{25}}{\sum_{i=1}^{5} X_{i2}}$ | $\frac{1/X_{35}}{\sum_{i=1}^{5} X_{i3}}$ | $\frac{1/X_{45}}{\sum_{i=1}^{5} X_{i4}}$ | $\frac{1}{\sum_{i=1}^{5} X_{i5}}$ | $\frac{\sum_{j=1}^{5} C_{5j}}{5}$ |

**Table 7: Example of a normalized AHP array**

Then, by the multiplication of the arithmetic mean values Mij and the column sums of the source data $\sum_{i,j=1}^{5} X_{ij}$, the value of the Eigenvalue or Eigenvector, or priority vector is calculated using the formula (1). This parameter reflects the relative weight between each of the criteria under consideration.

$$\lambda_i = M_{ij} \cdot \sum_{i,j=1}^{5} X_{ij}. \quad (1)$$

The result of the calculation is 5 values (depending on the number of evaluated criteria *n*) of Eigenvalue, which in total should be approximately equal to the number of criteria *n* considered:

$$\lambda_{max} = \sum_{i=1}^{5} \lambda_i \approx n. \tag{2}$$

The value of Maximum Eigenvalue $\lambda_{max}$ obtained by formula (2) is the main parameter for evaluating the consistency of the data in the evaluation matrix. Thus, to assess the consistency of the data array, it is necessary to determine the consistency ratio *CR* data by the formula (3):

$$CR = \frac{CI}{RI}, \tag{3}$$

where *CI* is the data consistency index determined by the formula (4);

*RI* is fixed by Saaty's scale, the value of the random consistency index depending on the number of evaluated criteria (Table 8).

$$CI = \frac{\lambda_{max} - n}{n - 1}. \tag{4}$$

| n | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RI | 0 | 0 | 0,58 | 0,9 | 1,12 | 1,24 | 1,32 | 1,41 | 1,45 | 1,49 | 1,52 | 1,54 | 1,56 | 1,58 | 1,59 |

**Table 8: Random consistency index scale**

At the same time, the calculated *CR* value should not exceed a certain benchmark, generally equal to the inconsistency degree of 10%.

Also, this analysis is divided into 2 stages: hierarchy single sorting and hierarchy total sorting, depending on whether one data set is evaluated or several in aggregate.

In addition, the authors propose the use of a subjective scale for assessing the harmfulness of workplaces, depending on the parameters and features of dust formation and the properties of the dust itself from this particular source. The scale is proposed to be divided into 5 categories depending on the subjective assessment of the harmfulness of the workplace by the dust factor: perilous, harmful, unsafe, generally safe and safe. The scale with the intervals of subjective assessment in scores is presented in Table 9.

| Level of safety | Perilous | Harmful | Unsafe | Generally safe | Safe |
|---|---|---|---|---|---|
| Score intervals | 100-80 | 80-60 | 60-40 | 40-20 | 20-0 |

**Table 9: Scale for assessing the harmfulness of workplaces by the dust factor**

Experts are invited to evaluate each of the criteria under study, namely, places-sources of intensive dust formation in open-pit mining, according to this scale of workplace harmfulness, taking into account the above-mentioned aspects of dust load in this zone: dispersed composition, dust concentration, form of dust particles.

After collecting data on the subjective assessment of the degree of harmfulness of the workplace, an array of data is compiled and the average values of points for each of the sources of dust formation from all expert groups are calculated (Table 10).

| | Source 1 | Source 2 | Source 3 | Source 4 | Source 5 |
|---|---|---|---|---|---|
| Expert gr. 1 | $b_{11}$ | $b_{21}$ | $b_{31}$ | $b_{41}$ | $b_{51}$ |
| Expert gr. 2 | $b_{12}$ | $b_{22}$ | $b_{32}$ | $b_{42}$ | $b_{52}$ |
| Expert gr. 3 | $b_{13}$ | $b_{23}$ | $b_{33}$ | $b_{43}$ | $b_{53}$ |
| Expert gr. 4 | $b_{14}$ | $b_{24}$ | $b_{34}$ | $b_{44}$ | $b_{54}$ |
| Expert gr. 5 | $b_{15}$ | $b_{25}$ | $b_{35}$ | $b_{45}$ | $b_{55}$ |
| Mean value | $B_{1j} = \frac{\sum_{j=1}^{5} b_{1j}}{5}$ | $\frac{\sum_{j=1}^{5} b_{2j}}{5}$ | $\frac{\sum_{j=1}^{5} b_{3j}}{5}$ | $\frac{\sum_{j=1}^{5} b_{4j}}{5}$ | $\frac{\sum_{j=1}^{5} b_{5j}}{5}$ |

**Table 10: Matrix of the harmfulness degree assessment**

Based on the mean expert scores reflecting the degree of harmfulness of workplaces, as well as taking into account the proposed scale of the degree of harmfulness of workplaces by the dust factor, the membership function of the investigated quantity to the fuzzy array *f* was used. This function allows to reflect the degree of membership of a number or a parameter to the selected imaginary array. In this case, with the help of the membership function, it is determined to what extent the scores set by experts relate to a particular category of harmfulness of workplaces according to the proposed scale (Table 9).

Thus, 5 systems of inequalities were compiled for each category of the degree of harmfulness of workplaces, reflected in formulas (5)-(9):

$$f_1(B_{1j}) = \begin{cases} 1, & B_{1j} \geq 80 \\ \dfrac{B_{1j} - 70}{10}, & 70 \leq B_{1j} < 80 \\ 0, & B_{1j} < 70 \end{cases} \tag{5}$$

$$f_2(B_{2j}) = \begin{cases} \dfrac{80 - B_{2j}}{10}, & 70 \leq B_{2j} < 80 \\ \dfrac{B_{2j} - 50}{20}, & 50 \leq B_{2j} < 70 \\ 0, & B_{2j} < 50 \\ 0, & B_{2j} \geq 80 \end{cases} \tag{6}$$

$$f_3(B_{3j}) = \begin{cases} \dfrac{70 - B_{3j}}{20}, & 50 \leq B_{3j} < 70 \\ \dfrac{B_{3j} - 30}{20}, & 30 \leq B_{3j} < 50 \\ 0, & B_{3j} < 30 \\ 0, & B_{3j} \geq 70 \end{cases} \tag{7}$$

$$f_4(B_{4j}) = \begin{cases} \dfrac{50 - B_{4j}}{20}, & 30 \leq B_{4j} < 50 \\ \dfrac{B_{4j} - 20}{10}, & 20 \leq B_{4j} < 30 \\ 0, & B_{4j} < 20 \\ 0, & B_{4j} \geq 50 \end{cases} \tag{8}$$

$$f_5(B_{5j}) = \begin{cases} 0, & B_{5j} \geq 30 \\ \dfrac{30 - B_{5j}}{10}, & 20 \leq B_{5j} < 30 \\ 1, & B_{5j} < 20 \end{cases} \tag{9}$$

The results of calculating the functions of the parameters belonging to fuzzy sets are presented in the form of a matrix [5 x 5] according to the number of evaluated criteria and participating expert groups. Also, in the form of an array [1 x 5], data on the specific weight of each of the evaluated sources in the Hierarchy total sorting total sample is presented.

After both of these matrices are multiplied to take into account the specific weight of the sources of dust formation in assessing the degree of harmfulness of each of them. Thus, a list of statistical parameters is taken into account at once, and as a result, an array of data is obtained in the form of a matrix [1 x 5] reflecting the relative magnitude of each of the sources of dust formation in the resulting probability of the development of occupational pathology of the respiratory tract in workers in this zone.

## 6.2 Calculation and risk assessment

As mentioned above, 5 expert groups were involved in the study, which, according to the Delphi method, were asked to assess the existing risks of developing pneumoconiosis and other occupational pathologies of workers employed in conditions of high dust load. Since the statistical calculation according to the described methodology has a significant volume, an example of calculation based on data from expert group 1 will be presented.

As a result of assessing the relative importance of each of the studied sources of dust formation, the following data set was obtained, presented in Table 11. The normalized matrix of the data from expert group 1 is presented in table 12.

| | Source 1 | Source 2 | Source 3 | Source 4 | Source 5 |
|---|---|---|---|---|---|
| Source 1 | 1 | 5 | 7 | 3 | 0,333 |
| Source 2 | 0,2 | 1 | 1 | 0,333 | 0,2 |
| Source 3 | 0,143 | 1 | 1 | 0,333 | 0,2 |
| Source 4 | 0,333 | 3 | 3 | 1 | 0,333 |
| Source 5 | 3,000 | 5 | 5 | 3 | 1 |
| Column sums | 4,676 | 15 | 17 | 7,666 | 2,066 |

**Table 11: Matrix for AHP priority assessment method (Exp.gr. 1)**

| | Source 1 | Source 2 | Source 3 | Source 4 | Source 5 | Mean value |
|---|---|---|---|---|---|---|
| Source 1 | 0,214 | 0,333 | 0,412 | 0,391 | 0,161 | 0,302 |
| Source 2 | 0,043 | 0,067 | 0,059 | 0,043 | 0,097 | 0,062 |
| Source 3 | 0,031 | 0,067 | 0,059 | 0,043 | 0,097 | 0,059 |
| Source 4 | 0,071 | 0,200 | 0,176 | 0,130 | 0,161 | 0,148 |
| Source 5 | 0,642 | 0,333 | 0,294 | 0,391 | 0,484 | 0,429 |

**Table 12: Normalized AHP array (Exp.gr. 1)**

According to the formula (1), the Eigenvector values are determined for each of the 5 sources of dust formation according to data from the expert group 1:

$$\lambda_1 = 0{,}302 \cdot 4{,}676 = 1{,}412;$$

$$\lambda_2 = 0{,}062 \cdot 15 = 0{,}930;$$

$$\lambda_3 = 0{,}059 \cdot 17 = 1{,}003;$$

$$\lambda_4 = 0{,}148 \cdot 7{,}666 = 1{,}135;$$

$$\lambda_5 = 0{,}429 \cdot 2{,}066 = 0{,}886.$$

In this case, the total values obtained are approximately equal to the number of criteria accepted in the calculation, which satisfies the condition (2):

$$\lambda_{max} = 1{,}412 + 0{,}93 + 1{,}003 + 1{,}135 + 0{,}886 = 5{,}3 \approx 5.$$

Therefore, by the ratio (4) consistency index CI will be equal to:

$$CI = \frac{5{,}3 - 5}{5 - 1} = 0{,}0915.$$

According to Saaty's scale, the value of the random consistency index RI when considering 5 criteria is RI = 1.12.

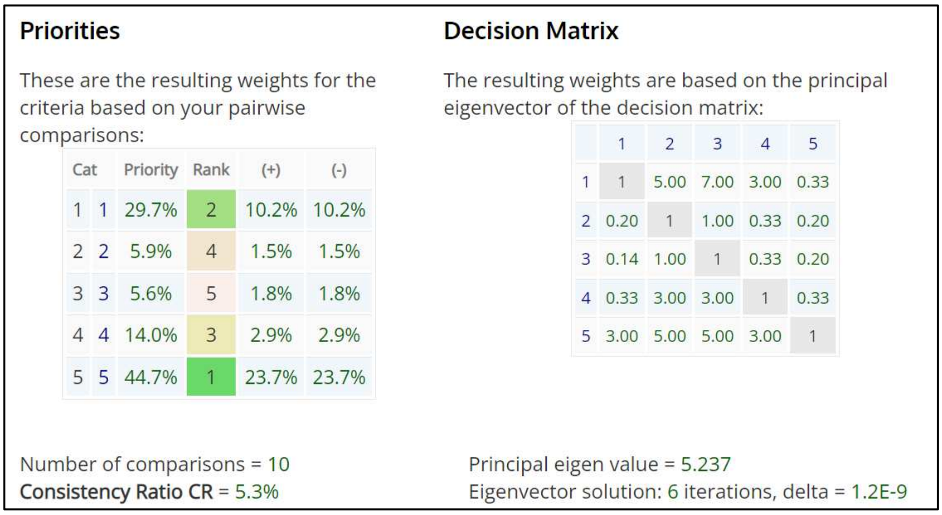
Then, according to the formula (3), the value of the degree of data integrity consistency rate CR for the array of data received from expert group 1 will be equal to:

$$CR = \frac{0{,}0915}{1{,}12} = 0{,}082 < 0{,}1 - Consistent\ data.$$

To confirm the reliability of the calculations made, an online calculator of the priority of criteria using the AHP method was used. The result of the verification of the correctness of the calculations is shown in Figure 28. According to the results of the verification, it is clear that the calculated data obtained converge with the results of the verification, and the verification and actual value of the consistency ratio CR was 5.3% for expert group 1, which indicates an even greater degree of data integrity.

Since the data are complete and consistent, it is possible to accept them for further statistical calculation. Similarly, the specific weight of all criteria, Maximum Eigenvalue and consistency rate are determined first for each expert group –

hierarchy single sorting, and then for the entire sample in aggregate – hierarchy total sorting. The results of this analysis are presented in table 13.


**Priorities**

These are the resulting weights for the criteria based on your pairwise comparisons:

| | Cat | Priority | Rank | (+) | (-) |
|---|---|---|---|---|---|
| 1 | 1 | 29.7% | 2 | 10.2% | 10.2% |
| 2 | 2 | 5.9% | 4 | 1.5% | 1.5% |
| 3 | 3 | 5.6% | 5 | 1.8% | 1.8% |
| 4 | 4 | 14.0% | 3 | 2.9% | 2.9% |
| 5 | 5 | 44.7% | 1 | 23.7% | 23.7% |

Number of comparisons = 10
Consistency Ratio CR = 5.3%

**Decision Matrix**

The resulting weights are based on the principal eigenvector of the decision matrix:

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1 | 1 | 5.00 | 7.00 | 3.00 | 0.33 |
| 2 | 0.20 | 1 | 1.00 | 0.33 | 0.20 |
| 3 | 0.14 | 1.00 | 1 | 0.33 | 0.20 |
| 4 | 0.33 | 3.00 | 3.00 | 1 | 0.33 |
| 5 | 3.00 | 5.00 | 5.00 | 3.00 | 1 |

Principal eigen value = 5.237
Eigenvector solution: 6 iterations, delta = 1.2E-9

**Figure 28: Validation of AHP analysis**
(Source: https://bpmsg.com/ahp/)

| Expert group | Hazard source | Hierarchy single sorting | | | Hierarchy total sorting | |
|---|---|---|---|---|---|---|
| | | $w_{ij}$ | $\lambda_{max}$ | CR | $W_{ij}$ | CR |
| Expert group #1 | Source 1 | 0,302 | 5,366 | 0,082 | 0,061 | 0,052 |
| | Source 2 | 0,062 | | | 0,012 | |
| | Source 3 | 0,059 | | | 0,011 | |
| | Source 4 | 0,148 | | | 0,029 | |
| | Source 5 | 0,429 | | | 0,087 | |
| Expert group #2 | Source 1 | 0,274 | 5,314 | 0,07 | 0,059 | |
| | Source 2 | 0,035 | | | 0,007 | |
| | Source 3 | 0,068 | | | 0,015 | |
| | Source 4 | 0,152 | | | 0,033 | |
| | Source 5 | 0,470 | | | 0,101 | |
| Expert group #3 | Source 1 | 0,403 | 5,118 | 0,026 | 0,080 | |
| | Source 2 | 0,050 | | | 0,010 | |
| | Source 3 | 0,073 | | | 0,015 | |
| | Source 4 | 0,117 | | | 0,023 | |
| | Source 5 | 0,357 | | | 0,070 | |
| Expert group #4 | Source 1 | 0,323 | 5,247 | 0,055 | 0,061 | |
| | Source 2 | 0,056 | | | 0,010 | |
| | Source 3 | 0,073 | | | 0,013 | |
| | Source 4 | 0,173 | | | 0,033 | |
| | Source 5 | 0,375 | | | 0,070 | |
| Expert group #5 | Source 1 | 0,309 | 5,400 | 0,089 | 0,063 | |
| | Source 2 | 0,044 | | | 0,009 | |
| | Source 3 | 0,117 | | | 0,023 | |
| | Source 4 | 0,112 | | | 0,022 | |
| | Source 5 | 0,419 | | | 0,085 | |

**Table 13: Consistency ratio analysis by the AHP method**

All the data obtained as a result of expert assessments are holistic and consistent, therefore, they can be accepted for further statistical analysis. It is worth noting that both according to Hierarchy single sorting and Hierarchy total sorting methods, it is clear that the crushing plant (Source #1) and the mixed rock and ore faces of the excavator (Source #5) have the greatest share of significance among all other sources of dust.

After assessing the relative importance of the assessed criteria, the expert groups also evaluated each source of dust formation in open-pit mining according to the proposed scale of the degree of harmfulness of workplaces based on data on the features of dust formation and the properties of the dust itself in these zones. The result of the expert evaluation is presented in table 14.

| | Source 1 | Source 2 | Source 3 | Source 4 | Source 5 |
|---|---|---|---|---|---|
| Expert gr. 1 | 66 | 57 | 69 | 72 | 78 |
| Expert gr. 2 | 71 | 53 | 63 | 69 | 81 |
| Expert gr. 3 | 69 | 61 | 72 | 81 | 84 |
| Expert gr. 4 | 73 | 55 | 62 | 67 | 76 |
| Expert gr. 5 | 73 | 54 | 66 | 63 | 74 |
| **Mean value** | **71** | **56** | **67** | **71** | **79** |

**Table 14: Matrix for assessing the degree of harmfulness of workplaces**

Then, each of the 5 averaged values of the expert groups' score was substituted in the membership function of the fuzzy set (5)-(9) to determine the degree of reliability of the data and the degree of belonging of each value to a particular category of harm according to the proposed scale.

The results of determining the values of the membership function are presented in the form of a corresponding matrix below. At the same time, the columns of the matrix reflect the sources of dust formation in order, and the rows represent expert groups:

$$S = \begin{vmatrix} 0,10 & 0,00 & 0,00 & 0,10 & 0,90 \\ 0,90 & 0,30 & 0,85 & 0,90 & 0,10 \\ 0,00 & 0,70 & 0,15 & 0,00 & 0,00 \\ 0,00 & 0,00 & 0,00 & 0,00 & 0,00 \\ 0,00 & 0,00 & 0,00 & 0,00 & 0,00 \end{vmatrix}$$

If we present the data on the specific gravity of each of the sources of dust formation determined from the Hierarchy total sorting aggregate sample in the form of a matrix, it will take the form (for example, Source #1):

$$A_1 = \begin{vmatrix} 0{,}061 & 0{,}012 & 0{,}011 & 0{,}029 & 0{,}087 \end{vmatrix}$$

Then it is possible to multiply the matrices of the specific gravity of dust sources Ai by the matrix of categorization by the harmfulness of workplaces S. As a result, Ri matrices will be calculated, reflecting the significance of each source of dustiness of the air of the working areas in the total dust load.

$$R_1 = \begin{vmatrix} 0{,}0169 & 0{,}0116 & 0{,}0119 & 0{,}0169 & 0{,}0557 \end{vmatrix}$$

$$R_2 = \begin{vmatrix} 0{,}0125 & 0{,}0127 & 0{,}0085 & 0{,}0125 & 0{,}0536 \end{vmatrix}$$

$$R_3 = \begin{vmatrix} 0{,}0171 & 0{,}0133 & 0{,}0108 & 0{,}0171 & 0{,}0731 \end{vmatrix}$$

$$R_4 = \begin{vmatrix} 0{,}0154 & 0{,}0125 & 0{,}0108 & 0{,}0154 & 0{,}0557 \end{vmatrix}$$

$$R_5 = \begin{vmatrix} 0{,}0139 & 0{,}0186 & 0{,}0107 & 0{,}0139 & 0{,}0573 \end{vmatrix}$$

According to the matrices $R_1$ – $R_5$, it can be seen that the source with the greatest potential for the development of pneumoconiosis and other respiratory pathologies in workers employed in this zone is Source #5, namely two operating faces with excavation of the hard-rock and ore-bearing rocks.

Thus, based on the risk assessment carried out, it can be argued that Source #5 is the most significant source of dust formation among those considered and requires the introduction of measures to reduce air dustiness to improve working conditions for the dust factor in this zone.

For the sake of clarity of the evaluation results, it is also possible to normalize the obtained matrices and reflect the share of the influence of each source of dust formation on the personnel of open-pit mining operations in the mining zones under consideration. The results of normalization of the obtained data are shown in Table 15.

| | Professional diseases development risk in personnel by sources of dust emission, % | | | | |
|---|---|---|---|---|---|
| | Source 1 | Source 2 | Source 3 | Source 4 | Source 5 |
| Expert gr. 1 | 14,96 | 10,27 | 10,53 | 14,96 | 49,29 |
| Expert gr. 2 | 12,53 | 12,73 | 8,52 | 12,53 | 53,71 |
| Expert gr. 3 | 13,01 | 10,12 | 8,22 | 13,01 | 55,63 |
| Expert gr. 4 | 14,03 | 11,38 | 9,84 | 14,03 | 50,73 |
| Expert gr. 5 | 12,15 | 16,26 | 9,35 | 12,15 | 50,09 |

**Table 15: Risk assessment matrix for risks of professional morbidity development**

It can be seen that as a result of the statistical processing of the expert estimates obtained, an occupational disease can occur with approximately 50% probability in workers employed at the sampling point of source #5, which is 2 simultaneously operating excavator faces for ore and rock. At the same time, the minimum risk value for source #5 is 49.29%, the maximum is 55.63%.

Therefore, according to the assessment, the safest place for mining operations at the Koashva quarry in terms of the risk of developing occupational respiratory diseases is Source #3 with a minimum risk value of 8.22%, the most dangerous is Source #5 with a maximum risk value of 55.63%.

## 6.3 Conclusion on Chapter 6

The risk of developing occupational diseases at enterprises of the mineral resource complex is growing every year due to an increase in the productivity of enterprises. At the same time, the detection of occupational diseases in employees leads not only to a deterioration in people's health and a decrease in their social status, but also to significant costs on the part of the employer company. Therefore, it is important to be able to correctly assess the risks of developing occupational diseases in employees, depending on the various parameters taken into account in order to avoid the loss of labor resources and preserve the life and health of personnel.

The authors carried out a comprehensive assessment of the risks of developing pneumoconiosis and other occupational pathologies associated with exposure to high-fibrogenic dust of high concentrations. For the analysis, the authors used Delphi methods, Analytical Hierarchy Process (AHP), pessimistic decision-making method, and also used the fuzzy set membership function to minimize errors and take into account the stochasticity of the estimated parameters.

At the same time, the parameters and features of dust formation in each zone under consideration were taken into account: the dispersed composition of dust and the shape of its particles, which largely characterizes the degree of fibrogenicity of dust, as well as the mass concentration of dust. The basis for the statistical analysis of the risk of respiratory diseases in workers was an expert assessment conducted within the framework of the Delphi method.

As a result of the analysis, it was revealed that the most dangerous from the point of view of the development of occupational diseases in the personnel at the apatite-nepheline quarry under study was mixed rock and ore-bearing rocks. The reason for this result may be the presence of a large number of sources of dust formation in this zone: an excavator and a front loader working simultaneously, the proximity of access technological roads, high intensity of work on extraction, loading and transportation of the extracted rock mass.

The results of the risk assessment within the framework of the risk-based approach in this case are used to identify the main and most significant sources of increased air dust and timely implementation of the necessary measures to reduce it. The proposed risk assessment model makes it possible to use a risk-based approach and most effectively improve working conditions for the dust factor.

# 7 Conclusion

Due to the high level of morbidity of personnel with respiratory pathology, increased wear of equipment and injuries, the problem of increased dustiness at enterprises of the mineral resource complex remains particularly relevant and requires an integrated approach when searching for various solutions to reduce the level of exposure to the dust factor on workers.

In the Master's thesis, a study is presented on the possibility of using magnetic fields for the magnetization of aqueous media in order to increase the efficiency of hydro-dusting of dusty surfaces on the territory of open-pit mining facilities. As a result of the work carried out, the following was carried out: research on the relevance of the topic research in aspects of statistics and features of the technological process at the Koashvinsky quarry of JSC "Apatit"; the analysis of the state of knowledge of the problem of increased dustiness of the air, taking into account both Russian and foreign experience in attempts to reduce the level of dustiness of the air of working areas, is carried out; the substantiation of the idea of solving the problem proposed in the framework of the master's thesis and consisting in the use of permanent magnetic fields to improve the dust-suppressing and dust-settling ability of the liquid is presented; the results of in-house studies on a self-made laboratory stand designed to assess the dustiness of air in a conditionally closed model system and analyze the effectiveness of the hydro-spraying method using various dust-suppressing agents are reflected.

As part of laboratory studies, work was carried out to determine the relative effectiveness of dust suppression using ordinary water and water magnetized in a constant magnetic field. At the same time, a manufactured laboratory stand was used, which is a physical model of a linear source of dust formation at a quarry.

As a result, it was found that both methods are quite effective immediately after carrying out irrigation measures, however, taking into account the speed of dust deposition and the orientation of irrigation to a certain fraction, the use of magnetized water has 10-15% greater efficiency compared to conventional water.

The authors of the study suggest that by using magnetized water as a cheap and affordable dust-suppressing agent, it is possible to reduce the dustiness of the air in open-pit mining operations, thereby improving the quality of working conditions for the dust factor and reducing the incidence of respiratory pathology among personnel.

Moreover, a comprehensive risk assessment was carried out to evaluate the possible risks of respiratory diseases development in personnel of an open pit mine. A model for risk assessment was suggested and used for the performed evaluation. As a result, it was found that the most dangerous workplaces are located in the area of dust source #5, which is the rock and ore faces, working simultaneously.

Thus, all the tasks set in the final qualifying work-master's thesis have been completed, thereby achieving the goal of the work.

Since the proposed measures for the use of magnetized water as a dust-settling agent have shown positive efficiency results in laboratory tests, including physical modeling of the irrigation process, it is possible to apply these measures in industrial conditions. In this connection, the authors plan to develop a draft device for water magnetization using permanent or non-permanent magnetic fields for practical determination of the effectiveness of measures in open-pit mining and possible further implementation of the solution if a positive effect is obtained.

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# 9 List of Figures

# 10 List of Tables

# 11 List of Abbreviations

| | |
|---|---|
| AHP | Analytic Hierarchy Process |
| APFA | Aerosols of predominantly fibrogenic action |
| EM | Equivalent materials |
| EMF | Electromagnetic field |
| MF | Magnetic field |
| MPC | Maximum permissible concentration |
| PD | Professional diseases |
| PM | Particulate matter |
| PMF | Permanent magnetic field |
| PPE | Personal protective equipment |
| PVC | Polyvinyl chloride |

# Annex Table of Contents

# Annex I

| Dust source | No. | Dust mass concentration, mg/m³ PM10 | Dispersity of dust sample by particle size, μm | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 0,3 | 0,5 | 1,0 | 2,5 | 5,0 | 10,0 |
| 1 – Crusher | 1 | 3,1 | 126 432 | 69 342 | 29085 | 4155 | 1473 | 553 |
| | 2 | 3,8 | 145 632 | 75 892 | 38380 | 6021 | 832 | 492 |
| | 3 | 3,6 | 138 354 | 73 104 | 37270 | 4932 | 1045 | 648 |
| | 4 | 3,5 | 135 949 | 71 945 | 43197 | 7405 | 1251 | 301 |
| | 5 | 2,9 | 129 590 | 70 243 | 19888 | 7118 | 1385 | 444 |
| 2 – Ore Warehouse | 1 | 5,3 | 171 493 | 99 391 | 29862 | 7271 | 1430 | 688 |
| | 2 | 4,5 | 165 390 | 87 047 | 35015 | 6204 | 1264 | 607 |
| | 3 | 5,6 | 184 533 | 112 081 | 28977 | 3938 | 1142 | 383 |
| | 4 | 5,1 | 170 243 | 97 503 | 33291 | 3304 | 1120 | 462 |
| | 5 | 4,8 | 168 420 | 94 200 | 35813 | 4167 | 1067 | 551 |
| 3 – Rock face | 1 | 2,3 | 99 421 | 64 078 | 26547 | 4541 | 1171 | 546 |
| | 2 | 2,6 | 114 389 | 68 955 | 32051 | 6886 | 806 | 337 |
| | 3 | 2,4 | 105 679 | 64 902 | 24795 | 4393 | 1455 | 583 |
| | 4 | 2,8 | 119 511 | 73 459 | 41230 | 7633 | 869 | 427 |
| | 5 | 3,1 | 124 893 | 75 881 | 32226 | 4208 | 1130 | 309 |
| 4 – Overburden face | 1 | 3,7 | 152 287 | 99 056 | 23383 | 5773 | 1458 | 340 |
| | 2 | 3,1 | 123 094 | 74 467 | 20624 | 4309 | 1191 | 511 |
| | 3 | 3,3 | 136 645 | 78 879 | 23487 | 7183 | 1114 | 345 |
| | 4 | 3,5 | 145 882 | 95 044 | 20756 | 6195 | 986 | 440 |
| | 5 | 3,3 | 138 203 | 79 936 | 44126 | 7743 | 1483 | 528 |
| 5 – Rock and ore faces | 1 | 7,2 | 170 001 | 110 207 | 20706 | 4802 | 886 | 428 |
| | 2 | 7,5 | 174 405 | 114 856 | 22276 | 5566 | 1227 | 534 |
| | 3 | 8,4 | 183 203 | 119 043 | 21049 | 4055 | 913 | 598 |
| | 4 | 8,1 | 180 426 | 117 763 | 21002 | 3479 | 1203 | 624 |
| | 5 | 7,9 | 178 968 | 115 994 | 29085 | 4155 | 1473 | 553 |

**Table 16: The results of measuring the dustiness of the air at the Koashvinsky quarry**

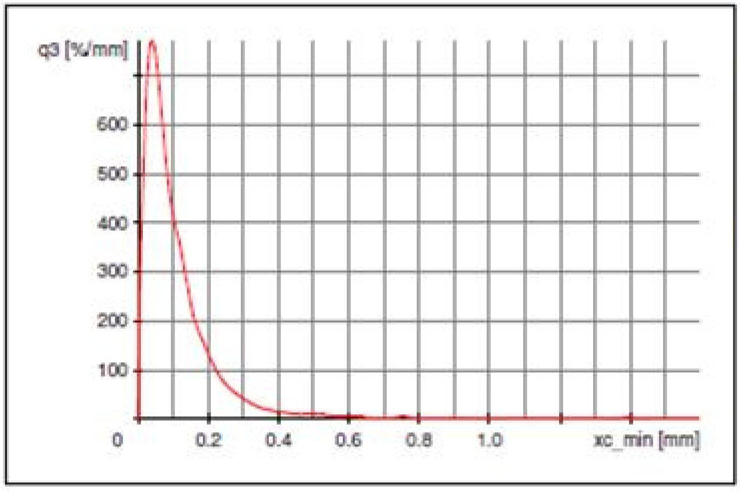
# Annex II

CAMSIZER XT® Retsch TECHNOLOGY

## Ore dust after crusher

| | |
|---|---|
| Компания: | Апатит |
| Пользователь: | Лаборатория моделирования |
| Файл результатов: | C:\CamsizerXT\CAMDAT\Апатит\Апатит_проба1_xc_min_001.rdf |
| Файл задачи: | C:\CamsizerXT\CAMSYS\Апатит.afg |
| Время: | 06.06.2022 , 13:38 , Длительность 9 мин 9 s at 0.1 % площадь покрытия, Скорость изображения 1:1 , with X-Jet, gap width = 2.0 mm, dipersion pressure = 25.0 kPa |
| Модель частицы: | xc min |
| Shape settings: | сферические Частицы |
| N. частиц: | CCD-B = 46168565 , CCD-Z = 2417048 |
| Velocity adaption: | Apatit1.ftv |
| приведение: | нет |
| Материал: | Руда апатитовая |

| Размер класса | [mm] | p3 [%] | Q3 [%] | SPHT3 | Symm3 | b/l3 | PDN |
|---|---|---|---|---|---|---|---|
| | < 0.1000 | 61.7 | 61.7 | 0.819 | 0.908 | 0.699 | 986968400 |
| 0.1000 - | 0.1250 | 9.6 | 71.3 | 0.819 | 0.898 | 0.682 | 168973 |
| 0.1250 - | 0.1600 | 8.9 | 80.2 | 0.826 | 0.896 | 0.698 | 85174 |
| 0.1600 - | 0.2000 | 6.8 | 87.0 | 0.827 | 0.891 | 0.727 | 32286 |
| 0.2000 - | 0.2500 | 4.8 | 91.8 | 0.824 | 0.889 | 0.715 | 11851 |
| 0.2500 - | 0.3150 | 3.4 | 95.2 | 0.814 | 0.884 | 0.702 | 4217 |
| 0.3150 - | 0.4000 | 1.8 | 97.0 | 0.799 | 0.879 | 0.680 | 1153 |
| 0.4000 - | 0.5000 | 1.1 | 98.1 | 0.781 | 0.875 | 0.660 | 327 |
| 0.5000 - | 0.6300 | 0.9 | 99.0 | 0.763 | 0.868 | 0.646 | 136 |
| 0.6300 - | 0.8000 | 0.5 | 99.5 | 0.760 | 0.865 | 0.656 | 41 |
| 0.8000 - | 1.0000 | 0.3 | 99.8 | 0.746 | 0.859 | 0.629 | 12 |
| 1.0000 - | 1.2500 | 0.0 | 99.8 | 0.655 | 0.744 | 0.706 | 1 |
| 1.2500 - | 1.6000 | 0.2 | 100.0 | 0.681 | 0.824 | 0.719 | 2 |
| 1.6000 - | 2.0000 | 0.0 | 100.0 | | | | 0 |
| 2.0000 - | 2.5000 | 0.0 | 100.0 | | | | 0 |
| 2.5000 - | 3.1500 | 0.0 | 100.0 | | | | 0 |
| 3.1500 - | 4.0000 | 0.0 | 100.0 | | | | 0 |
| 4.0000 - | 5.0000 | 0.0 | 100.0 | | | | 0 |
| 5.0000 - | 6.3000 | 0.0 | 100.0 | | | | 0 |
| 6.3000 - | 8.0000 | 0.0 | 100.0 | | | | 0 |
| 8.0000 - | 10.0000 | 0.0 | 100.0 | | | | 0 |
| 10.0000 - | 12.5000 | 0.0 | 100.0 | | | | 0 |
| 12.5000 - | 16.0000 | 0.0 | 100.0 | | | | 0 |
| > 16.0000 | | 0.0 | 100.0 | | | | 0 |




Характеристики

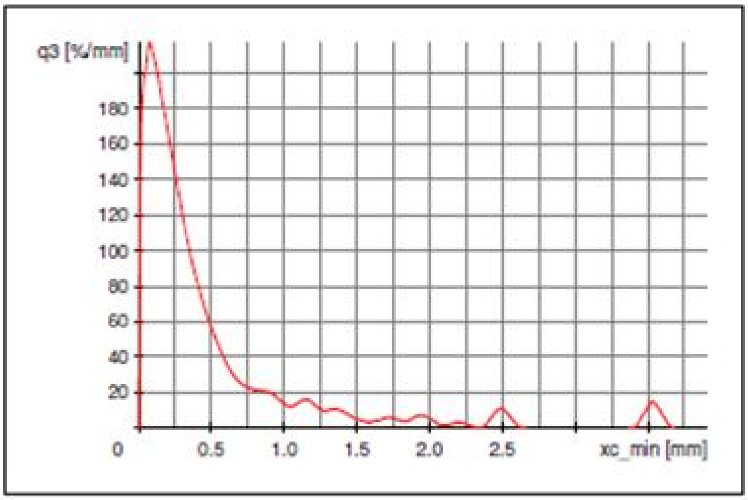
| Q3 [%] | x [mm] |
|---|---|
| 10.0 | 0.0213 |
| 50.0 | 0.0748 |
| 90.0 | 0.2269 |
| **x [mm]** | **Q3 [%]** |
| 1.0000 | 99.8 |
| 2.0000 | 100.0 |
| 4.0000 | 100.0 |
| SPAN3 = | 2.748 |
| U3 = | 4.493 |

CAMSIZER XT® Retsch TECHNOLOGY

# Ore dust from Stack No.1

| | |
|---|---|
| Компания: | Апатит |
| Пользователь: | Лаборатория моделирования |
| Файл результатов: | C:\CamsizerXT\CAMDAT\Апатит\Апатит_проба2_xc_min_002.rdf |
| Файл задачи: | C:\CamsizerXT\CAMSYS\Апатит.afg |
| Время: | 06.06.2022 , 14:11 , Длительность 5 мин 35 s at 0.1 % площадь покрытия, Скорость изображения 1:1 , with X-Jet, gap width = 2.0 mm, dipersion pressure = 25.0 kPa |
| Модель частицы: | xc min |
| Shape settings: | сферические Частицы |
| N. частиц: | CCD-B = 21919444 , CCD-Z = 1337019 |
| Velocity adaption: | Apatit2.ftv |
| приведение: | нет |
| Материал: | Руда апатитовая |

| Размер класса | [mm] | p3 [%] | Q3 [%] | SPHT3 | Symm3 | b/l3 | PDN |
|---|---|---|---|---|---|---|---|
| | < 0.1000 | 23.6 | 23.6 | 0.819 | 0.905 | 0.702 | 401238529 |
| 0.1000 - | 0.1250 | 5.1 | 28.7 | 0.817 | 0.896 | 0.677 | 71120 |
| 0.1250 - | 0.1600 | 6.9 | 35.6 | 0.825 | 0.897 | 0.690 | 53742 |
| 0.1600 - | 0.2000 | 7.2 | 42.8 | 0.828 | 0.890 | 0.724 | 27216 |
| 0.2000 - | 0.2500 | 7.7 | 50.5 | 0.829 | 0.891 | 0.717 | 15132 |
| 0.2500 - | 0.3150 | 8.1 | 58.6 | 0.825 | 0.889 | 0.709 | 8169 |
| 0.3150 - | 0.4000 | 8.3 | 66.9 | 0.818 | 0.886 | 0.696 | 4044 |
| 0.4000 - | 0.5000 | 6.8 | 73.7 | 0.808 | 0.882 | 0.690 | 1722 |
| 0.5000 - | 0.6300 | 5.6 | 79.3 | 0.795 | 0.879 | 0.675 | 722 |
| 0.6300 - | 0.8000 | 4.1 | 83.4 | 0.784 | 0.882 | 0.664 | 248 |
| 0.8000 - | 1.0000 | 4.0 | 87.4 | 0.786 | 0.882 | 0.663 | 121 |
| 1.0000 - | 1.2500 | 3.4 | 90.8 | 0.768 | 0.897 | 0.624 | 48 |
| 1.2500 - | 1.6000 | 2.5 | 93.3 | 0.738 | 0.874 | 0.580 | 18 |
| 1.6000 - | 2.0000 | 2.3 | 95.6 | 0.697 | 0.872 | 0.571 | 7 |
| 2.0000 - | 2.5000 | 1.8 | 97.4 | 0.773 | 0.877 | 0.771 | 4 |
| 2.5000 - | 3.1500 | 0.6 | 98.0 | 0.807 | 0.889 | 0.696 | 1 |
| 3.1500 - | 4.0000 | 2.0 | 100.0 | 0.673 | 0.841 | 0.700 | 1 |
| 4.0000 - | 5.0000 | 0.0 | 100.0 | | | | 0 |
| 5.0000 - | 6.3000 | 0.0 | 100.0 | | | | 0 |
| 6.3000 - | 8.0000 | 0.0 | 100.0 | | | | 0 |
| 8.0000 - | 10.0000 | 0.0 | 100.0 | | | | 0 |
| 10.0000 - | 12.5000 | 0.0 | 100.0 | | | | 0 |
| 12.5000 - | 16.0000 | 0.0 | 100.0 | | | | 0 |
| > 16.0000 | | 0.0 | 100.0 | | | | 0 |




**Характеристики**

| Q3 [%] | x [mm] |
|---|---|
| 10.0 | 0.0397 |
| 50.0 | 0.2467 |
| 90.0 | 1.1784 |

| x [mm] | Q3 [%] |
|---|---|
| 1.0000 | 87.4 |
| 2.0000 | 95.6 |
| 4.0000 | 100.0 |

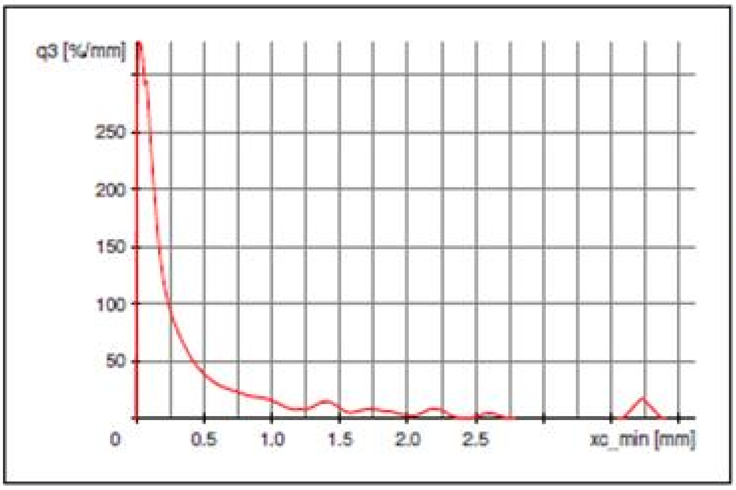
SPAN3 = 4.615
U3 = 8.238

CAMSIZER XT®   Retsch® TECHNOLOGY

## Dust from rock excavator face

| | |
|---|---|
| Компания: | Апатит |
| Пользователь: | Лаборатория моделирования |
| Файл результатов: | C:\CamsizerXT\CAMDAT\Апатит\Апатит_проба3_xc_min_003.rdf |
| Файл задачи: | C:\CamsizerXT\CAMSYS\Апатит.afg |
| Время: | 06.06.2022 , 14:50 , Длительность 7 мин 20 s at 0.1 % площадь покрытия, Скорость изображения 1:1 , with X-Jet, gap width = 2.0 mm, dipersion pressure = 25.0 kPa |
| Модель частицы: | xc_min |
| Shape settings: | сферические Частицы |
| N. частиц: | CCD-B = 39750095 , CCD-Z = 2317170 |
| Velocity adaption: | Apatit3.ftv |
| приведение: | нет |
| Материал: | Руда апатитовая |

| Размер класса | [mm] | p3 [%] | Q3 [%] | SPHT3 | Symm3 | b/l3 | PDN |
|---|---|---|---|---|---|---|---|
| | < 0.1000 | 38.6 | 38.6 | 0.813 | 0.904 | 0.706 | 816176888 |
| 0.1000 - | 0.1250 | 4.9 | 43.5 | 0.827 | 0.899 | 0.689 | 85935 |
| 0.1250 - | 0.1600 | 5.0 | 48.5 | 0.842 | 0.899 | 0.713 | 49528 |
| 0.1600 - | 0.2000 | 5.1 | 53.6 | 0.827 | 0.891 | 0.725 | 23033 |
| 0.2000 - | 0.2500 | 5.1 | 58.7 | 0.825 | 0.890 | 0.714 | 12080 |
| 0.2500 - | 0.3150 | 5.2 | 63.9 | 0.822 | 0.887 | 0.705 | 6171 |
| 0.3150 - | 0.4000 | 5.3 | 69.2 | 0.814 | 0.886 | 0.688 | 3151 |
| 0.4000 - | 0.5000 | 4.4 | 73.6 | 0.802 | 0.882 | 0.680 | 1313 |
| 0.5000 - | 0.6300 | 4.3 | 77.9 | 0.792 | 0.881 | 0.661 | 622 |
| 0.6300 - | 0.8000 | 4.1 | 82.0 | 0.788 | 0.882 | 0.662 | 303 |
| 0.8000 - | 1.0000 | 3.8 | 85.8 | 0.765 | 0.881 | 0.620 | 131 |
| 1.0000 - | 1.2500 | 2.5 | 88.3 | 0.779 | 0.874 | 0.642 | 46 |
| 1.2500 - | 1.6000 | 3.6 | 91.9 | 0.774 | 0.888 | 0.668 | 35 |
| 1.6000 - | 2.0000 | 2.8 | 94.7 | 0.776 | 0.891 | 0.642 | 13 |
| 2.0000 - | 2.5000 | 1.8 | 96.5 | 0.751 | 0.863 | 0.607 | 4 |
| 2.5000 - | 3.1500 | 0.8 | 97.3 | 0.735 | 0.838 | 0.646 | 1 |
| 3.1500 - | 4.0000 | 2.7 | 100.0 | 0.719 | 0.849 | 0.701 | 1 |
| 4.0000 - | 5.0000 | 0.0 | 100.0 | | | | 0 |
| 5.0000 - | 6.3000 | 0.0 | 100.0 | | | | 0 |
| 6.3000 - | 8.0000 | 0.0 | 100.0 | | | | 0 |
| 8.0000 - | 10.0000 | 0.0 | 100.0 | | | | 0 |
| 10.0000 - | 12.5000 | 0.0 | 100.0 | | | | 0 |
| 12.5000 - | 16.0000 | 0.0 | 100.0 | | | | 0 |
| > 16.0000 | | 0.0 | 100.0 | | | | 0 |




Характеристики

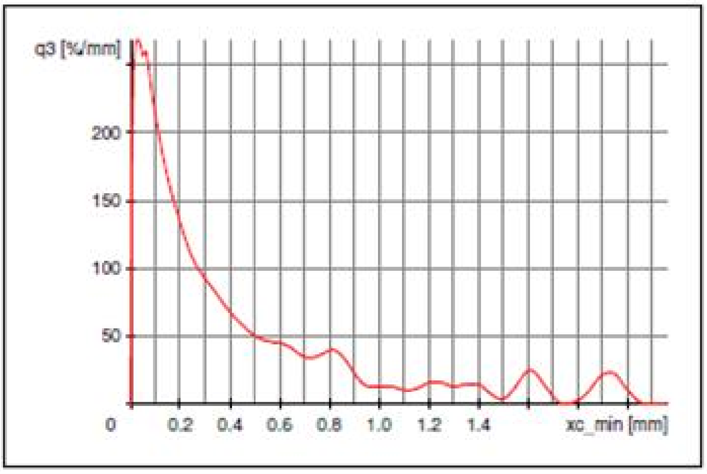
| Q3 [%] | x [mm] |
|---|---|
| 10.0 | 0.0226 |
| 50.0 | 0.1709 |
| 90.0 | 1.3955 |
| **x [mm]** | **Q3 [%]** |
| 1.0000 | 85.8 |
| 2.0000 | 94.7 |
| 4.0000 | 100.0 |
| SPAN3 = | 8.030 |
| U3 = | 11.599 |

CAMSIZER XT® Retsch TECHNOLOGY

# Dust from overburden excavator face

| | |
|---|---|
| Компания: | Апатит |
| Пользователь: | Лаборатория моделирования |
| Файл результатов: | C:\CamsizerXT\CAMDAT\Апатит\Апатит_проба4_xc_min_005.rdf |
| Файл задачи: | C:\CamsizerXT\CAMSYS\Апатит.afg |
| Время: | 06.06.2022 , 15:18 , Длительность 1 мин 53 s at 0.1 % площадь покрытия, Скорость изображения 1:1 , with X-Jet, gap width = 2.0 mm, dipersion pressure = 25.0 kPa |
| Модель частицы: | xc min |
| Shape settings: | сферические Частицы |
| N. частиц: | CCD-B = 9358401 , CCD-Z = 487656 |
| Velocity adaption: | Apatit4.ftv |
| приведение: | нет |
| Материал: | Руда апатитовая |

| Размер класса | [mm] | p3 [%] | Q3 [%] | SPHT3 | Symm3 | b/l3 | PDN |
|---|---|---|---|---|---|---|---|
| | < 0.1000 | 28.6 | 28.6 | 0.810 | 0.904 | 0.694 | 133310523 |
| 0.1000 - | 0.1250 | 3.8 | 32.4 | 0.818 | 0.896 | 0.707 | 16637 |
| 0.1250 - | 0.1600 | 7.2 | 39.6 | 0.824 | 0.899 | 0.676 | 15721 |
| 0.1600 - | 0.2000 | 5.6 | 45.2 | 0.821 | 0.891 | 0.713 | 6246 |
| 0.2000 - | 0.2500 | 5.6 | 50.8 | 0.818 | 0.887 | 0.703 | 3345 |
| 0.2500 - | 0.3150 | 6.2 | 57.0 | 0.809 | 0.885 | 0.686 | 1794 |
| 0.3150 - | 0.4000 | 6.7 | 63.7 | 0.798 | 0.883 | 0.673 | 1008 |
| 0.4000 - | 0.5000 | 5.8 | 69.5 | 0.797 | 0.880 | 0.673 | 440 |
| 0.5000 - | 0.6300 | 6.0 | 75.5 | 0.780 | 0.873 | 0.668 | 228 |
| 0.6300 - | 0.8000 | 6.1 | 81.6 | 0.774 | 0.877 | 0.637 | 110 |
| 0.8000 - | 1.0000 | 5.2 | 86.8 | 0.751 | 0.876 | 0.632 | 52 |
| 1.0000 - | 1.2500 | 3.5 | 90.3 | 0.769 | 0.859 | 0.688 | 16 |
| 1.2500 - | 1.6000 | 3.9 | 94.2 | 0.663 | 0.871 | 0.511 | 7 |
| 1.6000 - | 2.0000 | 5.8 | 100.0 | 0.729 | 0.862 | 0.631 | 7 |
| 2.0000 - | 2.5000 | 0.0 | 100.0 | | | | 0 |
| 2.5000 - | 3.1500 | 0.0 | 100.0 | | | | 0 |
| 3.1500 - | 4.0000 | 0.0 | 100.0 | | | | 0 |
| 4.0000 - | 5.0000 | 0.0 | 100.0 | | | | 0 |
| 5.0000 - | 6.3000 | 0.0 | 100.0 | | | | 0 |
| 6.3000 - | 8.0000 | 0.0 | 100.0 | | | | 0 |
| 8.0000 - | 10.0000 | 0.0 | 100.0 | | | | 0 |
| 10.0000 - | 12.5000 | 0.0 | 100.0 | | | | 0 |
| 12.5000 - | 16.0000 | 0.0 | 100.0 | | | | 0 |
| > 16.0000 | | 0.0 | 100.0 | | | | 0 |




Характеристики

| Q3 [%] | x [mm] |
|---|---|
| 10.0 | 0.0289 |
| 50.0 | 0.2418 |
| 90.0 | 1.2358 |

| x [mm] | Q3 [%] |
|---|---|
| 1.0000 | 86.8 |
| 2.0000 | 100.0 |
| 4.0000 | 100.0 |

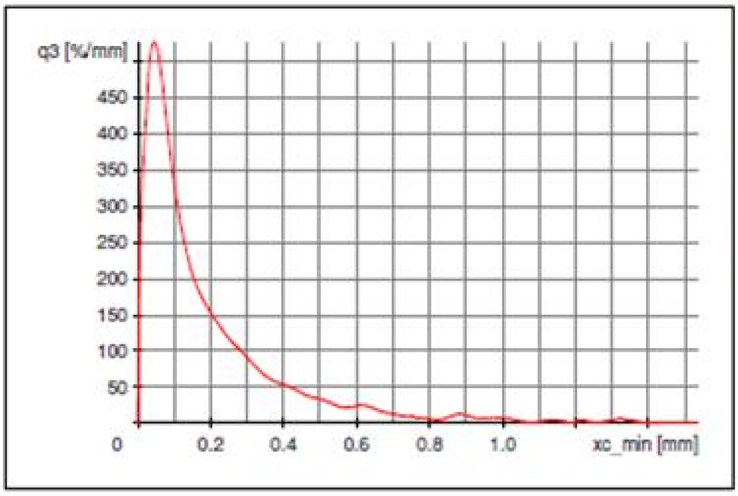
SPAN3 = 4.992
U3 = 12.065

CAMSIZER XT®

# Dust from rock & ore faces

| | |
|---|---|
| Компания: | Апатит |
| Пользователь: | Лаборатория моделирования |
| Файл результатов: | C:\CamsizerXT\CAMDAT\Апатит\Апатит_проба5_xc_min_005.rdf |
| Файл задачи: | C:\CamsizerXT\CAMSYS\Апатит.afg |
| Время: | 06.06.2022 , 16:14 , Длительность 4 мин 9 s at 0.1 % площадь покрытия, Скорость изображения 1:1 , with X-Jet, gap width = 3.0 mm, dipersion pressure = 30.0 kPa |
| Модель частицы: | xc min |
| Shape settings: | сферические Частицы |
| N. частиц: | CCD-B = 20338190 , CCD-Z = 1001612 |
| Velocity adaption: | Apatit5.ftv |
| приведение: | нет |
| Материал: | Руда апатитовая |

| Размер класса | [mm] | p3 [%] | Q3 [%] | SPHT3 | Symm3 | b/l3 | PDN |
|---|---|---|---|---|---|---|---|
| | < 0.1000 | 47.1 | 47.1 | 0.832 | 0.909 | 0.714 | 258262611 |
| 0.1000 - | 0.1250 | 7.2 | 54.3 | 0.831 | 0.897 | 0.715 | 47752 |
| 0.1250 - | 0.1600 | 7.4 | 61.7 | 0.843 | 0.896 | 0.716 | 25549 |
| 0.1600 - | 0.2000 | 6.8 | 68.5 | 0.836 | 0.891 | 0.744 | 11638 |
| 0.2000 - | 0.2500 | 6.7 | 75.2 | 0.837 | 0.892 | 0.733 | 5811 |
| 0.2500 - | 0.3150 | 6.5 | 81.7 | 0.833 | 0.890 | 0.725 | 2981 |
| 0.3150 - | 0.4000 | 5.4 | 87.1 | 0.828 | 0.890 | 0.718 | 1191 |
| 0.4000 - | 0.5000 | 4.3 | 91.4 | 0.804 | 0.882 | 0.689 | 475 |
| 0.5000 - | 0.6300 | 3.4 | 94.8 | 0.795 | 0.883 | 0.679 | 187 |
| 0.6300 - | 0.8000 | 2.2 | 97.0 | 0.780 | 0.883 | 0.689 | 62 |
| 0.8000 - | 1.0000 | 1.6 | 98.6 | 0.763 | 0.875 | 0.722 | 23 |
| 1.0000 - | 1.2500 | 0.9 | 99.5 | 0.794 | 0.909 | 0.691 | 6 |
| 1.2500 - | 1.6000 | 0.5 | 100.0 | 0.826 | 0.860 | 0.745 | 2 |
| 1.6000 - | 2.0000 | 0.0 | 100.0 | | | | 0 |
| 2.0000 - | 2.5000 | 0.0 | 100.0 | | | | 0 |
| 2.5000 - | 3.1500 | 0.0 | 100.0 | | | | 0 |
| 3.1500 - | 4.0000 | 0.0 | 100.0 | | | | 0 |
| 4.0000 - | 5.0000 | 0.0 | 100.0 | | | | 0 |
| 5.0000 - | 6.3000 | 0.0 | 100.0 | | | | 0 |
| 6.3000 - | 8.0000 | 0.0 | 100.0 | | | | 0 |
| 8.0000 - | 10.0000 | 0.0 | 100.0 | | | | 0 |
| 10.0000 - | 12.5000 | 0.0 | 100.0 | | | | 0 |
| 12.5000 - | 16.0000 | 0.0 | 100.0 | | | | 0 |
| > 16.0000 | | 0.0 | 100.0 | | | | 0 |




Характеристики

| Q3 [%] | x [mm] |
|---|---|
| 10.0 | 0.0249 |
| 50.0 | 0.1097 |
| 90.0 | 0.4607 |

| x [mm] | Q3 [%] |
|---|---|
| 1.0000 | 98.6 |
| 2.0000 | 100.0 |
| 4.0000 | 100.0 |

SPAN3 = 3.973
U3 = 6.080