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# Research Progress of Coal Stacks Reducing Dust Emissions: Ecological Technology in the Example of the Karaganda Region

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**Abstract**

Air pollution issues are relevant all over the world, especially in industrial areas. The main pollution of the atmosphere is caused by dust emissions from industry. This article discusses the issue of dust emission from the coal industry. The purpose of this research is a comprehensive analysis and environmental assessment of the impact of coal storage processes on the environment. The study was conducted on the example of a coal deposit in the Karaganda region of the Republic of Kazakhstan. The Karaganda region is the industrial base of Kazakhstan, and is characterized more by coal industry facilities. In addition to the impact during the mining period, coal storage is also a serious problem. The problem of storing energy coals on a large scale of their extraction and consumption has a huge impact on the environment, but it is of great economic importance for the region. In this paper, practical methods of combating weathering are considered using the example of coal: small fraction—0–50 mm; large fraction—50–300 mm; oversized—more than 300 mm. Calculations of the formation of emissions, the maximum surface concentrations of pollutants from coal depots were carried out, and plots of their dispersion were constructed. When plotting the dispersion of pollutants, it was revealed that the largest concentration of substances falls on the territory of the coal deposit. According to the data obtained, a directly proportional dependence of the amount of emissions on the volume of incoming coal and the area of the base of the coal stacks is obvious; the temperature fluctuation in the stacks during the research is in the range from 21.9 to 26.1 °C. Scientifically researched anti-emission cover (AEC) on coal stacks. AEC has advantages for a specific climate (frequent winds, dryness): preservation of properties up to 90% over their service life; resistant to environmental aggressiveness and mechanical influences. This method solves two tasks: the first task is to prevent spontaneous combustion of coal stacks, and the second task is to reduce dust emissions from coal stacks. Measures have been developed to minimize the negative impact of coal stacks on the environment.

**Keywords:** coal; waste; environment; mines; landfills; dust

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## 1. Introduction

Currently, there is a problem of spontaneous combustion of coal stacks. Coal stacks are a dangerous source not only from the point of view of fire danger, but also from the environmental one, because dusting occurs from their surface. And when coal stacks

ignite, the environment is also polluted by combustion products. Dusting from coal dumps increases significantly with increased winds. Stormwater during the erosion of stacks pollutes the nearest reservoirs.

In the Karaganda region, coal mining operations are underway at such large deposits as Shubarkolskoye, Kuznetsk, Zhalyn, Borly, and Kushokinskoye [1–4]. Coal mining in the Karaganda region of the Republic of Kazakhstan is carried out by open-pit and underground mining methods. The article examines the impact of open-pit coal mining (Figure 1).



**Figure 1.** Coal mining at the coal mine.

Stacks of coal were accepted as the studied object. The subject of the study is their impact on the environment and public health. Coal stored in the environment is a dangerous source of flammability and dust. The processes of ignition and dusting of coal stacks are closely interrelated from an environmental point of view. It addresses issues of safety, risks, and environmental impacts. Thus, the intake of coal dust into the environment occurs as a result of transportation, loading, and unloading operations, while the natural conditions of the enterprise's location play an important role [5]. Coal dust settles on the surface of soils, water sources, vegetation, and the ecosystem as a whole, contributing to its accumulation and formation of a combustible mixture, which increases the risk of ignition. Fires in coal stacks lead to the release of toxic components into the atmospheric air, which leads to a deterioration in air quality, negatively affecting the health of the population and ecosystems [6]. Fires are also an uncontrolled process, in some cases even prolonged, which leads not only to significant economic losses, but also to environmental consequences [7,8]. Thus, it is necessary to control the dusting process and prevent the ignition of coal stacks, as this is an important aspect of environmental and fire safety [9,10].

The purpose of this work is a comprehensive analysis and environmental assessment of the impact of coal storage processes on the environment, identifying the main environmental hazards.

The objectives of the scientific work are:

- research of the impact of coal storage processes on the ecosystems of the area where the analyzed pollution source is located;
- research of the composition and volume of emissions during coal storage in piles;
- development of measures to minimize the negative impact of coal piles.

Depending on climatic conditions, such as the movement of air masses, precipitation, and the radioactivity of solar energy, the rate of decrease in the valuable properties of technological raw materials varies, while coal weathering occurs: it loosens, grinds, loses luster and sintering ability, and such an indicator as coking properties changes [11–14]. This process is called coal oxidation or weathering.

Depending on how the processes of destruction and alteration of rocks occur in different climatic conditions, they are classified into physical and chemical weathering [15,16].

Physical weathering is characterized by loosening and fragmentation of the coal mass, while there is no change in its chemical composition. As a result of the influence of the temperature factor (for example, in the form of sharp fluctuations) on the coal mass, its volume changes rapidly, which leads to and is the cause of its cracking and crushing. An analysis of the physical weathering of coal massifs in different climatic zones has shown that the water factor plays an important role in sharply continental and cold conditions. Water gets into microcracks, freezes, and expands, which leads to the fragmentation of large conglomerates into smaller ones. Thus, the grinding process occurs, which leads to a change in the color of the coal masses [17].

Chemical weathering is characterized by reactions that occur under the influence of atmospheric air, in particular, the presence of oxygen in its composition, during the interaction of mineralized water saturated with oxygen and carbon dioxide. Thus, chemical weathering is the process of decomposition of the mineral components of coal with the formation of new compounds that have more stable properties, i.e., the decomposition reaction of the organic component of coal occurs. Chemical weathering is accompanied by oxidation and moisture absorption, due to which complex chemical reactions occur that lead to a change in the original properties of coal [18]. The result of such reactions and changes in the coal mass is the formation of fine coal dust, leading to coal losses during loading and unloading operations, especially under adverse meteorological conditions. Voroshilov S.P., Voroshilov Ya.S., and others [18] established a direct relationship between the rate of oxidation and the distribution of moisture.

Studies have shown that aqueous solutions of anti-pyrogens can reduce the risk of spontaneous combustion of coal stored in storages by reducing the rate of oxygen sorption by coal and increasing its humidity [19].

Flame retardants not only suppress the reaction at the ignition stage, but also act as a reinforcing coating to suppress dusting on the surface of coal depots [20–22].

The scientific novelty lies in the selection and expansion of the field of application of anti-emission coatings, which are used to suppress dust and prevent spontaneous combustion of coal piles, taking into account the physical and geographical conditions of the area. This makes it possible to comprehensively address the issues of environmental safety and the preservation of mineral resources.

There are several methods of coal storage aimed at preserving its operational characteristics: protective, semi-protective, and open-stack storage. The methods of protective storage of coal include storage in the form of briquettes and in underwater tanks. Semi-protective methods are open-stack storage of enriched coal, as well as its storage in dry pits and silos. Open stacked coal storage is the most common and economical practice for storing raw coal, which is stacked in stacks of various lengths and trapezoidal cross-section. This method requires compliance with strict regulations, since coal, being outdoors, is exposed to atmospheric factors, which lead to weathering, oxidation, and grinding of the material [23].

The choice of the method and conditions of storage of fossil coals depends on their physicochemical properties. The main such property is the exothermic chemical reaction (process) of oxidation and decomposition of coal. The temperature of coal increases with insufficient heat transfer and the presence of moisture. Stored coal undergoes weathering processes, which lead to a significant deterioration in its quality: humidity increases by 1% per month, ash content increases, calorific value decreases significantly, and coal destruction and crushing are observed [17]. The oxidation process reduces the calorific value of weathered coal and imposes restrictions on the use of weathered coal as fuel [24].

Thus, there are the following types of coal weathering processes, structured in the form of a table (Table 1).

**Table 1.** Coal weathering processes.

| Types of Process | Description | Reason | Result |
|---|---|---|---|
| Physical weathering | Grinding of coals without changing their chemical structure and composition. It begins on the surface of coal, in places of contact with the external environment, and its effect manifests itself in physical destruction under the influence of solar energy, atmosphere, and water. | It is caused by various factors (sun, wind, precipitation, and ambient temperature). Depending on the nature of the influencing factor, the nature of the destruction of coal during physical weathering varies. In some cases, the destruction process occurs inside the coal without the participation of an external acting agent. | With prolonged exposure to temperature fluctuations and different expansion coefficients, the mutual adhesion of individual mineral grains in coal is disrupted, and it cracks and breaks up into separate fragments. |
| Mechanical weathering | Occurs under the mechanical influence of extraneous agents | Freezing of water has a particularly destructive effect. When water gets into the cracks and pores of coal and then freezes, it increases in volume by 9–10%, while producing enormous pressure. | The coal splits into separate fragments |
| Chemical weathering | A set of different chemical processes that result in further destruction of coal | The destruction of coal under the influence of physical weathering is always accompanied to one degree or another by chemical weathering. The main factors of chemical weathering are water, oxygen, carbon dioxide, and organic acids. | The structure and composition of minerals change significantly, and new minerals are formed that correspond to certain physicochemical conditions. |

The authors analyzed the sources of dust formation, the effect of dust on the environment, dust suppression methods used in coal mines in general, and also considered the problem of dust suppression in coal mines in the Far North [25]. This problem is relevant today, as many Russian coal mining enterprises operate in low-temperature conditions.

The sources of dust formation in the quarry during the extraction and processing of mineral raw materials are shown in Figure 2 [26,27].

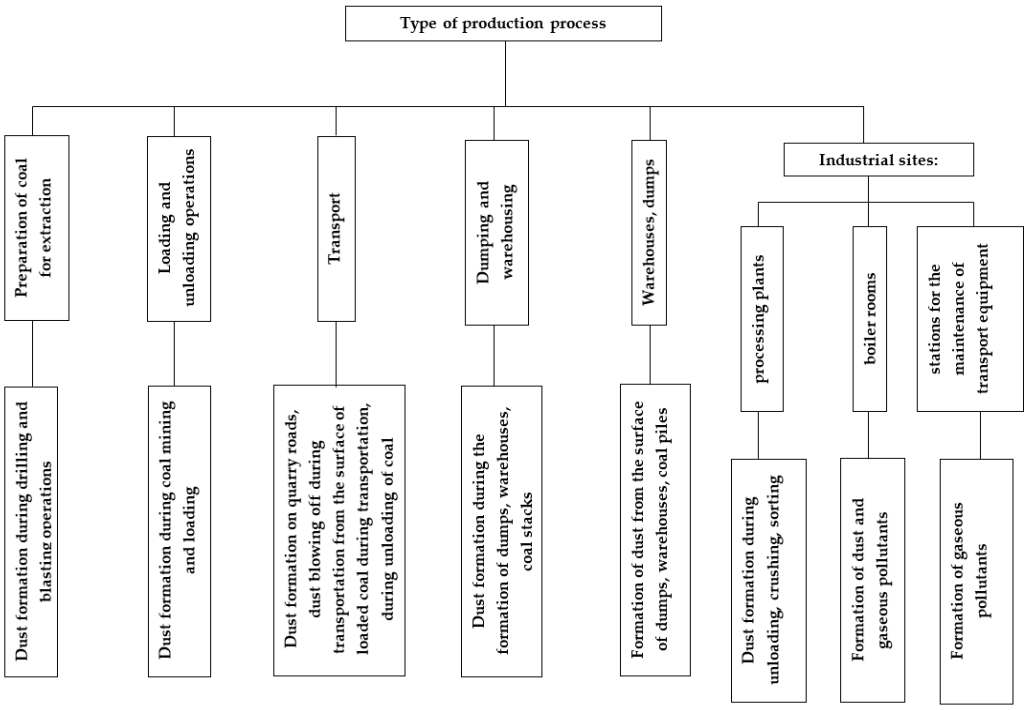



**Figure 2.** The main sources of dust formation in mining enterprises.

An analysis of scientific articles [25,28] showed that the dust concentration exceeds the maximum permissible concentrations at all stages of coal mining, processing, storage, and transportation at coal mines.

The obtained research results [29] allow us to draw the following conclusions: coal dust is fire and explosive; ignoring dust suppression means increasing the fire and explosion hazard of coal dust; continuous monitoring and monitoring of coal dust in the atmosphere can reduce the accident rate.

During loading and unloading, the coal mass is destroyed and worn out [28]; therefore, a large amount of dust enters the atmosphere. Therefore, the problems associated with coal storage in open storage include coal dust contamination of the area near the formed coal stack, as well as its spread beyond the working area [30–34].

In open coal storage, dusting occurs not only during loading and unloading operations and the formation of coal stacks, but also during coal storage in them [33,35]. One of the effective ways to control dusting is to coat the surface of stacks with solutions of chemical reagents [33].

The problem of dusting and spontaneous combustion of coal mass in stacks is not unique to Kazakhstan. This problem occurs in Russia, China, Germany, America, India, and other countries [32,36–42]. Thus, scientists have considered the issues of dusting in the northern coal mines of China in winter [43], in the province of Xinjiang in northwestern China [44]. Coal storage causes air pollution not only in the work area, but also in the surrounding areas (provinces of India) [41,42]. Due to the danger of environmental pollution in Germany, coal mining was abandoned in 2018 [45]; open-pit mining of brown coal leads to environmental changes [46]. The article [47] provides studies on the accumulation of coal dust as a result of dusting from an open coal storage located on the border with the settlement of Curtis Bay, Baltimore, Maryland, and the USA. The team of authors K. Y. Kirichenko, A. S. Kholodov, and others conducted research in Primorsky Krai (Russia) and concluded that coal dust is one of the strongest pollutants in the atmosphere [48]. The paper [49] describes the characteristics of the Russian coal mining industry as the most polluting environment, describes the negative impact on environmental components, and pays special attention to sources of dust formation, including open coal depots. The authors of [50] revealed a linear relationship between coal dust and wind speed, i.e., the amount of dust from a coal storage is directly proportional to wind speed.

## 2. Materials and Methods

Methodological approach to the development of measures for optimal safe storage of coal in storages

Stages of experimental research:

Stage 1. Preparatory and organizational

Study of the conditions necessary for the implementation of experimental work (collection of information, analysis of conditions):

1. Analysis of initial data and materials from previous studies of coal storage time, depending on the technology used.
2. Analysis of methods and technological solutions to prevent weathering of ordinary coal and to increase its shelf life.

Stage 2. Experimental research

1. Assessment of the volume and shelf life of coal mass in stacks, the dynamics of its receipt and shipment to consumers. Estimation of the size of the extracted coal.
2. Conducting experimental measurements of the temperature of stacks with thermal sensors (or a portable temperature probe with a scale up to 150 °C or lowering a thermometer in a stack into vertical control metal pipes with a diameter of 0.025

to 0.050 m) in operational coal stacks in a coal mine, depending on the shelf life, conditions, and size of the coal mass. Metal tubes for thermal probes are placed inside during the formation of coal stacks.

3. Investigation of the weathering process over time and depending on the chemical composition of the stored coals; creation of a regular grid of diagnostic sensors across the space of technological stacks, and monitoring of the temperature of coals.
4. Conducting experimental tests and applied research in the following areas, considering the influence of ash content in the range of 5–13%, humidity—14.5%, volatile matter yield—43.5%, non-volatile (bound carbon)—76%, sulfur content—0.5%.

Stage 3. Practical-applied

1. Conducting experimental studies to determine the impact of coal on the environment.
2. Development of proposals to reduce environmental impact.

Instruments, equipment, and materials: Conducting experimental measurements with a thermal imager with thermal sensors; a portable thermal probe with a scale up to 150 °C; it can also be used to lower the thermometer in a stack into vertical control metal pipes with a diameter of 0.025–0.050 m.

The oxidation processes of coal in stacks are especially active in the warm season (summer), so there is a need for constant temperature monitoring of coal. A portable thermal probe with a measuring scale up to +150 °C is used to monitor the temperature parameters of coal.

Vertically mounted metal control tubes with a diameter of 0.025–0.05 m are used to determine the temperature distribution in coal stacks. The basal ends of the tubes are hermetically sealed and sharpened to facilitate their immersion in the coal mass. The apical ends of the tubes are closed with wooden stoppers fixed to the top of the tube. Thermometers are attached to the plugs, which are lowered inside the tubes on a flexible cable. The following procedures are followed to ensure high accuracy of thermometers:

- exposure for 20 min after immersion in the medium to achieve thermal equilibrium;
- the use of a metal protective case when removing the thermometer from the tubes to prevent mechanical damage;
- placement of the mercury tank in a copper capsule filled with technical oil or iron filings to maintain constant thermal contact;
- using a rubber stopper to fix a constant distance (3–4 mm) between the mercury tank and the capsule wall.

To ensure proper temperature control inside the coal stack, the pipes should be installed as follows:

- the pipes should be placed on the top of the stack, following a checkerboard pattern, with a maximum distance between the pipes of 25 m;
- the lower ends of the pipes must be at least one-quarter of the height of the stack from its base;
- each control pipe must have a clearly visible serial number placed on the protruding end of the pipe at a height of at least 0.2 m above the stack surface;
- the area around the installed pipes must be carefully sealed to ensure the accuracy of temperature measurements.

Temperature monitoring with a portable probe without mounting metal pipes is carried out as follows:

- measurements are made on the upper base of the stack in three sections: in the central part and at a distance of 0.25 of the stack length from its ends;

- in stacks with a width of more than 50 m, three measurements are performed: in the center of the upper base and on the ridge of the stack, at a distance of 10 m from the ends;
- in stacks with a width of less than 50 m, the temperature is measured in the center of the upper base;
- on the slopes of the stack, measurements are carried out at a distance of 2 m from the bottom edge;
- the distance between the temperature measuring points on the slopes corresponds to the same distance as on the upper base of the stack (in the central part and at a distance of 0.25 of the stack length from the ends, measured at the lower base);
- when measuring the temperature on the playground or ridge, the thermal probes are installed vertically, while on the slopes, they are perpendicular to the surface;
- after taking measurements, the holes formed by the thermal probe, as well as footprints, are filled in with coal;
- if a solid frozen layer of coal is found at the control points, the temperature in these places is not measured;
- the depth of immersion of the thermal probe in the stack when measuring the temperature of coal is 1.25–1.5 m.

It was revealed that the temperature fluctuation in the stacks lies in the range from 21.9 to 26.1 °C during the research (using AEC) (Figure 3, Table 2).




**Figure 3.** Temperature sensor in the stack.

**Table 2.** Temperature sensor in the stack.

| Coal Stack | Average Monthly Temperature, °C; | | | | |
|---|---|---|---|---|---|
| | April | May | June | July | August |
| Without AEC | 27 | 32.5 | 36.4 | 40.2 | 40.2 |
| With AEC | - | 25.8 | 25 | 24.3 | 22.1 |
| With AEC | - | 26.1 | 25.1 | 24.8 | 22.5 |
| With AEC | - | 25.1 | 23.4 | 22.5 | 21.9 |

Measurements in Table 2 show that the temperature of a coal stack coated with AEC is lower than in a stack without AEC and does not increase.

Environmental monitoring of emissions was carried out using devices such as the GANK-4 gas analyzer, Atmas dust analyzer, AVA 1 aspirator, meteoscope, and Aeroqual Series 500 portable air quality monitor. The devices and equipment used in the research belong to the scientific laboratory of Abylkas Saginov Karaganda Technical University. All the equipment is included in the register of SI of the Republic of Kazakhstan and has passed the scheduled metrological certification (verification). The GANK-4 gas analyzer determined the concentration of suspended solids, sulfur dioxide, hydrogen sulfide, and inorganic dust in the

air. An Atmas dust analyzer and an Aeroqual 500 series portable air quality monitor were used to quickly measure the PM2.5 and PM10 dust particle concentrations.

In this paper, practical methods of combating weathering are considered using the example of coal: small fraction—0–50 mm; large fraction—50–300 mm; oversized—more than 300 mm. The characteristics of coal are shown in Table 3. As a rule, coal is stored in open coal storages that occupy large areas (Figure 4).

**Table 3.** Characteristics of the investigated grade D coal.

| Indicator | Ash Content, % | Total Moisture, % | Release of Volatile Substances, % | Non-Volatile (Bound) Carbon, % | Specific Heat of Combustion, MJ/kg |
|---|---|---|---|---|---|
| Parameter | 5. . .13 | 14.5 | 43.5 | 76.0 | 30.14 |



**Figure 4.** Coal storage and transshipment (photos of the authors).

The coal of the section under consideration belongs to group IV due to its tendency to oxidize. The maximum height of the stacks for these coals is 5.0 m. The height of the stacks in the storage is 5.0 m. The capacity of one coal stack is 100,000 t. The design capacity of the portside open-pit coal storage of the stacked type by grades and fractions is 1,000,000 t. The design area of the coal storage is 212,500 $m^2$. The length of the stack ensures the independent and safe operation of the processing equipment at the coal intake to the storage (dump trucks) and at the coal shipment from the storage (front wheel loader).

Description of the existing coal storage method:

An on-board open coal storage of the stack type is used for the temporary storage of extracted coal, averaging the quality indicators of the extracted coal. Coal storage is provided in stacks. Coal stacks are formed for the entire period of operation of the mine by dumping coal from dump trucks in touching cones without dump trucks entering the stack.

A rail-mounted open-air coal storage of the stack type is used for loading into railway wagons, accumulating coal in order to ensure the rhythmic and independent operation of the mine for extraction and shipment to the consumer. The design capacity of the storage is determined from the accumulation conditions according to the standards of coal quality indicators, the efficient operation of the front loader on shipment from the storage, and the design parameters of the stack during its formation.

A front-mounted wheeled loader with a universal bucket with a capacity of V = 10.2 $m^3$ was adopted for the shipment of coal from the stack. The design parameters of the forklift truck make it possible to load coal into railway wagons. The track development at the instrument coal depot consists of four tracks. The length of the railway access track in the storage is full—1100 m; useful—880 m; switches—2 pcs.

The storage is illuminated and fenced with metal panels. Control of the amount of incoming coal to the rail-mounted open coal storage of the stack type is carried out on automotive electronic scales. The delivery of coal from the mining faces to the instrument open coal storage of the stack type is provided by trucks with a lifting capacity of 60 t.

In the practice of combating weathering and oxidation of extracted coal, mechanical mixtures are used when it is stored in open and closed storages, the action of which is aimed at reducing the activity of reactions on the sorbing surface of minerals or reducing the surface area. They exert mechanical, chemical, and chemical-mechanical effects by means of grouting microcracks on the surface of minerals by means of protective coverage.

Thus, these coatings (anti-emission cover, hereinafter referred to as AEC) have not only the properties of preventing oxidation, which causes spontaneous combustion, but also help to reduce emissions of pollutants into the atmosphere.

As an AEC, it is possible to use aqueous solutions of calcium chloride, phosphate, carbonate, nitrate, ammonium sulfate, potassium permanganate, phenol-formaldehyde resin, polyacrylamide, lime slurry suspensions, inert dust, talc shale, open-hearth slag grinding, blast furnace slag grinding, landfill sands of aluminum plants, and soda plant waste [51–57].

Coal pits, stacks, and rock dumps also use phthalic and naphthenic acids, furfural, and waste from chemical industries (methanol water, waste from caprolactam workshops). Mixtures of various AECs are used to increase efficiency and reduce consumption. Also, all kinds of film coatings of pieces of coal, solutions of lime, clay, and other substances, tamper cracks.

General AEC requirements:

- maximum wetting and penetrating power;
- technologically advanced in preparation and use;
- have a low cost;
- non-toxic;
- must have a long shelf life.

According to the mechanism of action, AECs are divided into several groups (Table 4).

**Table 4.** AEC classification by mechanism of action.

| Group | Description | Result |
|---|---|---|
| The first group | Chemical inhibitors of the oxidation reaction, i.e., reducing the rate of these reactions | Molecules of reacting substances are rendered inactive |
| The second group | Various substances by applying them to the surface | Blocking of combustible materials |
| The third group | Pore blockers in charcoal by filling them with the appropriate liquid | It makes it difficult for oxygen to diffuse into a piece of coal, while also dissipating heat by evaporating water |
| The fourth group | - Insulating coatings;<br>- Modern technological coverage, with different layers | - They prevent air filtration through the coal stack, and also do not have a synthetic effect on the consumer properties of coal<br>- Provide an osmotic effect of interaction with the surrounding atmosphere, protecting coal products from precipitation and other natural phenomena |

Examples of the use of certain types of AEC (justification and analysis):

Calcium hydroxide (slaked lime) is a fairly effective AEC, which has been confirmed by many years of use. Its main disadvantage is its high alkalinity and, like any suspension, the ability to precipitate to the bottom of the container during storage [51,52].

Inert dust made from limestone reduces the likelihood of coal oxidation due to the mechanical insulation of its surface [51,58]. Therefore, their effectiveness depends on the heat capacity and density. Therefore, when choosing an AEC, it is necessary to pay attention to its density. The same mass of powder at a low density will be able to insulate a large surface. In addition, the light powder is transported with the associated air flow over long distances, which provides a significant area of protection. At the same time, the powder must not be distributed outside the coal depots.

However, it should be noted that significant amounts of solid AEC are required to reliably isolate the coal surface from the air. The use of dissolved substances may be more economically justified.

A mixture of limestone milk and calcium chloride: The mixture is a dense, insulating, and at the same time chemically inhibiting compound. However, care must be taken when preparing such mixtures, as they may lose their properties [51,53–55]. Also, the disadvantage is that they are practically not found near coal deposits, so their use as AEC is limited by the high cost of transportation.

A mixture of liquid glass and ammonium chloride leads to the formation of a viscous colloidal solution of silicic acid with uncertain properties depending on the preparation conditions [51,56]. When processing coal stacks, AEC suspensions are used to fill cracks. Liquid glass with surfactants and calcium chloride, slaked lime with surfactants, and liquid glass with fillers in the form of dolomite dust or chamotte powder are used as suspensions.

AEC cover-forming agents are substances that form a continuous film on the surface of coal, which has sufficient hardness, strength, elasticity, good adhesion, and is resistant to moisture. Film-forming AECs are sprayed and used to create insulating coatings on the surface of stacks and accumulations of loose coal [57,59]. Various compositions are used as cover-forming agents, for example, liquid glass (27–29%), sulfonol NP-3 (5–6%), dolomite dust (20%), water (up to 100%), or an aqueous 50% polyvinyl acetate emulsion (24%), sulfonol NP-3 (9%), and others. The consumption of film-type AEC is 0.3–0.6 kg per 1 $m^2$ of coal surface.

The coating protects the surface of the stack from contact with oxygen in the air and also prevents spontaneous combustion and dust formation. This method of insulating the surface of coal from the air was chosen as the most environmentally friendly.

A literature review of existing known alternative types of AEC, including those based on liquid glass, has been conducted. However, polyacrylamide-based AECs were practically investigated and selected. In this study, emphasis was placed on optimizing the application and evaluating the effectiveness of polyacrylamide-based AEC, as the most promising in terms of price-quality ratio, and the possibility of implementation at existing mining enterprises, taking into account the physical and geographical conditions of the area. Alternative types of AEC, including those based on liquid glass, require a detailed study, which is beyond the scope of the objectives of this study and may become the subject of further work.

## 3. Results

An analysis of pollutant emissions in the Republic of Kazakhstan for the period 2015–2023 showed that the Karaganda region is in 2nd place (after the Pavlodar region) (Table 5). In 2023, the amount of emissions from the Karaganda region was 20.15%, which is equivalent to 455 thousand tons [60].

**Table 5.** Emissions of pollutants into the atmosphere in 2015–2023, thousand tons (compiled on the basis of statistical data [60]).

| Region | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|
| Atyrau | 110.7 | 167.1 | 177.0 | 172.3 | 164.5 | 154 | 160.3 | 132.1 | 140.1 |
| East Kazakhstan | 127.1 | 128.7 | 129.3 | 130.7 | 128.8 | 127.2 | 128.1 | 83.3 | 80.9 |
| Karagandinskaya | 596.4 | 593.0 | 598.7 | 587.5 | 641.3 | 627.7 | 569.7 | 469.0 | 455.0 |
| Kostanay | 91.6 | 98.7 | 114.8 | 124 | 130.5 | 123.4 | 137.9 | 121.4 | 118.3 |
| Pavlodarskaya | 552.9 | 542.7 | 609.8 | 709.3 | 721.5 | 723 | 736.2 | 724.2 | 694.2 |
| Republic of Kazakhstan | 2180.0 | 2271.6 | 2357.8 | 2446.7 | 2483.1 | 2441.0 | 2407.5 | 2314.8 | 2257.5 |

The main emissions occur in the Karaganda and Pavlodar regions, which are industrial and coal regions.

When forming coal storages, it is necessary to consider emissions from coal unloading and storage [34,60–63]. Emissions of coal into the environment occur during loading and unloading and storage in stacks (Tables 6 and 7, Figure 5).

**Table 6.** Emissions into the atmospheric air from coal dumping.

| Indicators for Calculation | Units of Measurement | Parameter | | |
|---|---|---|---|---|
| A coefficient that considers the moisture content of the material | | 1.2 | | |
| Wind speed (average) | m/s | 5 | | |
| The amount of coal entering the storage | t/year | 413,160 | 1,000,000 | 2,000,000 |
| Gross dust emission | t/year | 0.72 | 1.764 | 3.528 |

**Table 7.** Emissions into the atmospheric air when coal is blown off the surface of the storage.

| Indicators for Calculation | Units of Measurement | Parameter | | |
|---|---|---|---|---|
| A coefficient that considers the moisture content of the material | | 1.2 | | |
| Wind speed (average) | m/s | 5 | | |
| The base area of the stacks | $m^2$ | 450 | 212,500 | 425,000 |
| Gross dust emission | t/year | 1.54791 | 730.9575 | 1461.8 |

Tables 5 and 6 show the initial data and calculation results for the volume of emissions entering the atmospheric air:

- when loading coal, depending on its volume (Table 5);
- when blowing coal dust particles from the surface of the stack, depending on its area.

According to the obtained data (Tables 5 and 6), a directly proportional dependence of the amount of emissions on the volume of incoming coal and the base area of coal stacks is obvious.

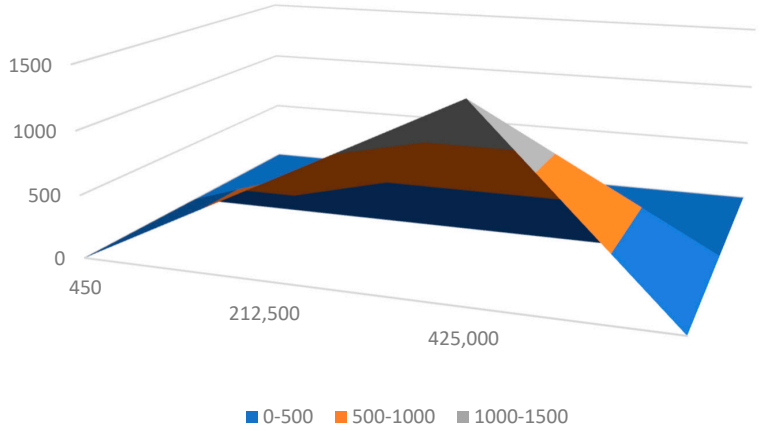



**Figure 5.** Emissions from the surface of the coal storage.

Figure 5 was constructed based on forecast data on the increase in the coal storage area (Table 6).

The dispersion of the maximum concentrations of pollutants in the surface layer of the atmosphere is calculated (Figure 6). Mathematical modeling methods are used to assess the impact of emissions of harmful substances on the quality of atmospheric air, in accordance with current design standards. According to mathematical statistics on the accuracy of measurements, the reliability coefficient of the results obtained was 0.95 with a measurement error of 5% [64].

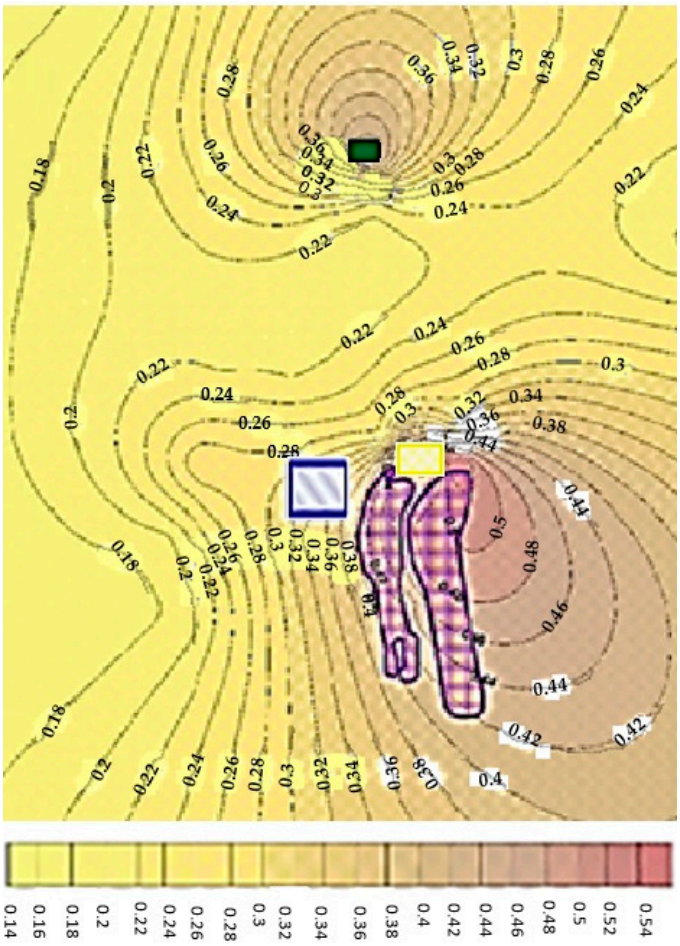



**Figure 6.** The scheme of dust dispersion in the atmosphere at the coal site: —quarry; —mine water reservoir; —work area; —shift houses.

The calculation of the dispersion of maximum surface concentrations was carried out on a software package developed in accordance with [34,61,62,65]. The software package allows calculations of single concentrations of pollutants emitted by point, linear, and planar sources, and calculates surface concentrations of both individual substances and groups of substances, with the effect of summation of harmful effects.

A special computer program, "ERA" version 3.0, developed by "Scientific and Production Association Logos" LLC, was used for computer modeling. The size of the main calculation rectangle for determining the maximum surface concentrations is determined considering the influence of pollution with sides X = 1342 and Y = 1220 m and a grid pitch of 122 m. In Figure 6, the areoles of coal dust are marked with a darker color, which can be observed at the source of dust emission. The further away from the source of coal dust, the less pollution and the lighter the color. It depends on the wind and the flat terrain. According to [63], the maximum permissible concentration for inorganic (coal) dust is as follows: maximum single 0.5 mg/m$^3$; average daily 0.15 mg/m$^3$.

Conclusions from Figure 6: A diagram with the main sources of emissions is shown, featuring a quarry and a work area where a coal storage is located. The greatest concentration of substances falls on the territory of the coal storage. However, the dust cloud spreads throughout the industrial site and reaches the evaporator pond. The further away from the source of emission, the lower the concentration.

According to the Environmental Code of the Republic of Kazakhstan [9], it is necessary that the concentrations of pollutants comply with the environmental requirements and standards of the Republic of Kazakhstan [66].

Previous studies have shown that polyacrylamide-based covering reagents are the most effective AECs for the natural and climatic conditions of the Karaganda region. The Karaganda region is characterized by an extremely continental climate, with a large constant wind load (Figure 7).

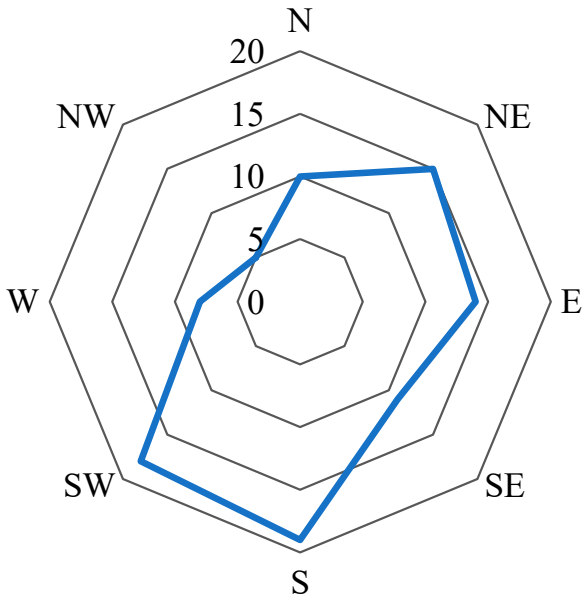



**Figure 7.** Average annual wind direction for 2020–2024 (%).

In June 2022, experiments were conducted to coat coal stacks by AEC. Three reagents were used in the experiment. The reagent characteristics are given in Table 8.

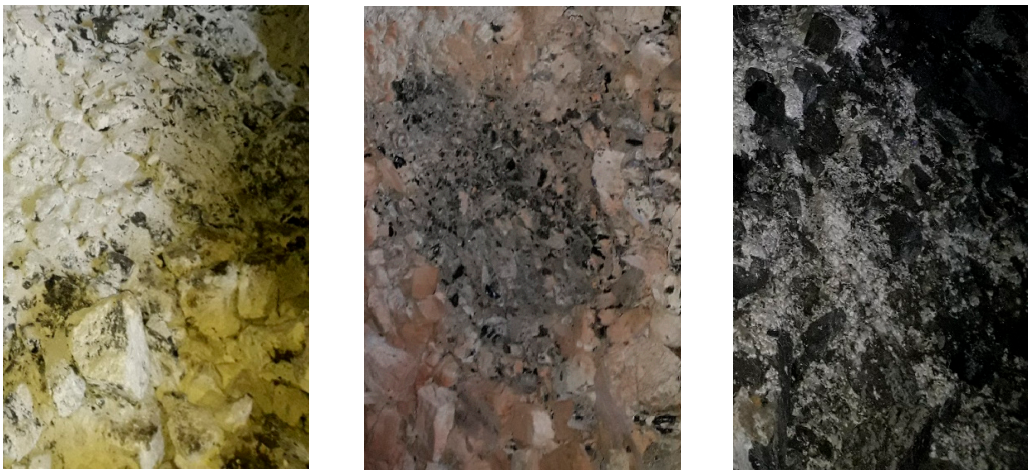
**Table 8.** Characteristics of the tested reagents.

| Indicators | Description of the Reagent | | |
|---|---|---|---|
| | **№ 1** | **№ 2** | **№ 3** |
| Chemical type | Anionic polyacrylamide | Anionic polyacrylamide | Anionic polyacrylamide |
| Appearance | Opaque liquid with a light-yellow tint | White milky liquid | White liquid |
| Degree of charge | High | High | High |
| Molecular weight | High | High | High |
| Specific gravity at 25 °C | 1.0–1.1 | 1.05–1.2 | 1.04–1.1 |
| Freezing point, °C | −18 | 0 | 0 |
| The content of the active component, % | 65 | 60–70 | At least 55 |
| Specific consumption, g/m$^2$ | 50 | 50 | 50 |

The following conditions were observed during the research:

- areas of the equal size (150 m$^2$, on one side of the stack) were treated;
- application of AEC is a single application;
- simultaneous method of application of AEC subjects (date, time, climatic conditions during the application period).

During the experiment, three sections of the same size were processed on one side of the stack (to ensure the correctness of the experiment: wind direction, solar heat distribution, and precipitation). The size of the cultivated area was 10 m by 15 m (150 m$^2$) (Figure 8).



Reagent No. 1 Reagent No. 2 Reagent No. 3

**Figure 8.** Covered sections of the coal stack.

The application was carried out in the morning. The air temperature was +32 °C. The air humidity is 16%. The wind direction is southerly, with an average wind speed of 1.9 m/s.

The application of AEC coatings was carried out by a spray device. The concentration of each finished solution is 5%. The solution consumption was 1 L/m$^2$. The specific reagent consumption is 50 g/m$^2$. The film forms almost immediately after applying the solution (within 10 to 15 min).

Monitoring of the sites was carried out:

- the condition of the experimental sites was assessed after 24 h. Treatment of the site with chemical reagent No. 1 resulted in the formation of an elastic, flexible covering with a thickness from 1.1 mm to 1.9 mm. The covering formed at site No. 2 had

the following properties: elasticity, bending flexibility, rubber-like stretchability, and thickness in the range of 1–1.9 mm. A covering similar to a crust formed on the area treated with chemical reagent No. 3. The thickness of the crust was 1.6–2.8 mm.

- the inspection was carried out 45 days after the sites were processed. There was no precipitation during this period. The safety of the film coating in the areas treated with reagents No. 1 and No. 2 was preserved by 90–95%. The properties of these films remained at the level of the first inspection. Uniform surface cracking was observed in the area treated with reagent No. 3. The site was no longer examined.
- the next inspection was carried out in autumn, 90 days after the processing of the plots. During this period, there were both precipitation and the first frosts. The preservation of the covering in the areas treated with reagents No. 1 and No. 2 was preserved by 90%. The coating is visually different in the area treated with reagent No. 1. In some places, the covering is layered. In places where the covering is delaminated, the thickness reaches 12 mm, the coating is hard, not elastic, and brittle. In the places of the single-layer coating, the covering remained elastic, flexible, and 1.1–1.9 mm thick. In the area covered with reagent No. 2, the visual coating is almost the same and uniform. The coating is single-layer, elastic, flexible, stretchable, and 1–1.9 mm thick.
- the final inspection was carried out in April 2023. The film-forming coatings have been lying all winter, covered with snow. The air temperature for the entire period of the experiment ranged from +36 °C to −37 °C. A visual inspection of the sites showed that the film was preserved on 40 % of the area of the studied sites. In the area coated with reagent No. 1, the cover is thick, reaching a thickness of 9 mm. In the area treated with reagent No. 2, the cover is plastic, thin, and 3 mm thick. The key characteristic of the tested AEC coatings is their strength and resistance to mechanical stress and loads caused by human walking on their surface.

## 4. Discussion

As a result of the research, it was revealed that the transshipment of coal from dump trucks to the storage is a source of dust emission. However, the main emission values occur at the stage of coal storage. As the stack area increases, the amount of emissions during storage can increase hundreds of times. Thus, it is necessary to develop measures to reduce dust, but at the same time, it is necessary to monitor the quality of coal.

Environmental protection measures are a set of technological, technical, organizational, social, and economic measures aimed at protecting the environment and improving its quality. The general classification of environmental protection measures is shown in Figure 9.

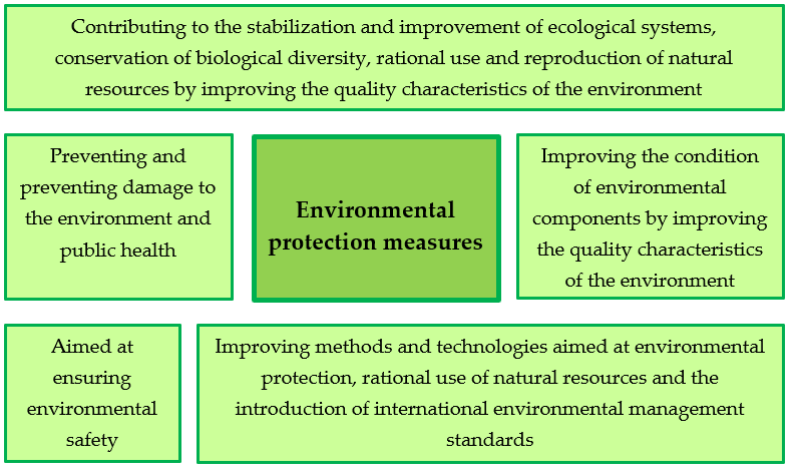



**Figure 9.** General classification of environmental protection measures.

Based on the above general classification of environmental protection measures, measures have been developed to reduce the risks of environmental impact during coal storage.

The algorithm of measures to reduce the environmental impact of coal storage facilities:

(1) Organization of a meltwater and groundwater drainage system to prevent flooding of coal stacks:

- Assessment of the territory (landscape, groundwater level, soil type, possible flooding areas, as well as climatic conditions) and design of the drainage system (grooves and drainage wells);
- Development and laying of grooves (dimensions should consider the volume of water flow for the period of heavy rains and snowmelt, as well as the slope of the direction of water from the stacks towards drainage wells and drainage systems);
- Installation of drainage wells with filters (to prevent clogging) in places with large concentrations of wastewater.

The event is aimed at creating a reliable system that will protect coal stacks from flooding, minimize the risks to coal storage, and prevent its damage.

(2) Design of coal stacking sites:

- Install a heat-conducting coating in the form of compacted crushed stone, clay, cobblestone, and paving stones under the stack;
- Construction of sites with a mandatory slope from the center to the edges for the forced outflow of meltwater and rainwater;
- Provide for the availability of spare sites (at least 5% of the total area) that will effectively cope with force majeure situations (cooling of superheated coal and expansion of storage area in case of increased storage volumes).

The measures will create optimal conditions for long-term and safe storage of coal, reducing the risks associated with the effects of weather factors and providing an opportunity to respond promptly to changing operating conditions.

(3) Organization of the division of coal stacks into zones for the safe operation of equipment during the reception and shipment of coal. The division of each stack into two zones:

- one is formed;
- the second, fully formed, is shipped.

This measure significantly increases the safety and efficiency of work in the storage: it optimizes the production process, prevents possible emergencies, increases the capacity of the storage (formation and shipment are carried out in parallel without mutual impact), improves logistics and organization of work processes, increasing productivity and reducing equipment downtime.

(4) Gradual loading of coal in closed storages to prevent oxidation. Coal loading should be carried out gradually along the entire length of the stack. This measure helps to improve air circulation and reduce the risk of oxidation in conditions of high humidity.

(5) Organization of environmental protection measures. The use of protective coatings and temperature control to prevent oxidation of coal during long-term storage:

- AEC solution treatment of the surface of the stacks in the summer;
- Temperature monitoring in stacks using mercury thermometers;
- Coal is shipped from the stack when the temperature reaches 30–35 °C;
- When the temperature reaches 60 °C in any of the sensors, treat the spontaneous combustion site locally with AEC solutions or ship heated coal from this site.

The event includes the use of special compounds to cover coal stacks, as well as temperature control and environmental protection measures to ensure the safety and security of coal.

The proposed algorithm is acceptable for the existing climatic conditions in the area of the analyzed enterprise.

## 5. Conclusions

As a result of the research, it was revealed that one of the main sources of atmospheric pollution is coal storage. This is a source of dust and fire hazard. The calculation of emissions showed that their volumes depend on the amount of coal and the stack area. This relationship is linear. The dispersion of coal dust directly depends on wind activity and terrain. Rules for the open storage of coal have been developed:

Conditions for coal storage in stacks:

- when forming stacks, it is necessary to consider the brand of coal (it is not permissible to form a stack of coal of various grades);
- minimization of coal unloading and stacking time (no more than 2 days);
- consideration of parameters: area no more than 350 $m^2$; length no more than 30 m; capacity no more than 1000 t;
- placing an information plate near each stack with data on the brand of coal and the date of its arrival at the storage;
- systematic visual monitoring and monitoring of the temperature regime of stacks (different stack depths). The temperature regime of the stacks is monitored through special tubes arranged in a checkerboard pattern inside the stack. At the upper end of the pipe, which has a pointed lower end to facilitate hammering, a plug is installed that locks the cord to which a metal case with a technical thermometer is attached. In this case, the pipe rises 0.3 m above the stack surface. This type of regular monitoring will help prevent coal weathering (oxidation);
- to monitor atmospheric air pollution and measure the levels of physical impact on atmospheric air at the border of the sanitary protection zone (SPZ) and the residential area;
- to plant green spaces around the perimeter of the SPZ.

AECs based on polyacrylamide have not only the effect of protecting coal stacks from spontaneous combustion but also perform an environmental function (dust suppression), and have been subjected to research. The experiment was conducted throughout the year in the Karaganda region. The research results show that coal storage in open coal dumps is possible for a long period of time when surfaces are covered by AEC. The tested AEC showed good results:

- ease of preparation and use of AEC;
- low cost on the market;
- coatings retain their properties for a 90% long period of time;
- rapid hardening of the coating;
- withstand the aggressiveness of the environment (temperature fluctuations, constant and strong wind load, various types of precipitation (rain, snow, hail));
- they have shown strength and resistance to mechanical influences and loads, such as human walking on them.

In this case, the economic efficiency is as follows:

- if there are no dusting or fire hazards, enterprises will not be subject to penalties under the Environmental Code of the Republic of Kazakhstan [9];
- elimination of payments for excessive and unauthorized emissions;
- starting from 2025, enterprises that implement the best available technologies (BAT) will be exempt from emission fees for 10 years; otherwise, the emission fee rates will be increased by 2–8 times;

- the enterprise will be issued a comprehensive environmental permit to operate in accordance with environmental requirements (Article 112 [9]).

There will also be a social (environmental) effect that eliminates the risks of air emissions and the possibility of coal self-ignition, which will have a positive impact on the welfare of the population.

Recommendations for the use of anti-emission coatings:

1. Application time: The optimal time for applying reagents to dust-prone surfaces is the beginning of the second quarter of this year. A necessary condition is a favorable meteorological situation: no precipitation (rain, snow), low wind speed, lack of snow cover, and surface moisture in the cultivated areas.
2. Frequency of treatment: The recommended frequency of coating is once a year during the warmer months.
3. Parameters of the working solution: The working solution for the application must have a concentration of 5 %. The specific consumption of the reagent should be at least 50 $g/m^2$.
4. Application technology: The coating should be applied evenly using air spray equipment (nozzle type).
5. Post-application conditions: After coating, it is necessary to ensure that there is no mechanical impact on the treated area for 2–3 h, necessary for the coating to harden.
6. Application quality requirements: The coating must be applied evenly, without gaps. If necessary, it is allowed to increase the specific consumption of the reagent and apply a multilayer coating, which does not reduce the anti-emission properties of the material.

The research was conducted using the example of the Karaganda region. The region is characterized by steppe landscapes and the absence of mountains, strong winds, and little precipitation in summer. Such conditions are unfavorable. These conditions contribute to the blowing off of coal dust and spontaneous combustion processes. Therefore, this algorithm is applicable in various climate conditions.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| AEC | Anti-emission cover |
| SPZ | Sanitary protection zone |

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