Analysis and Forecasting of PM2.5, PM4, and PM10 Dust Concentrations, Based on In Situ Tests in Hard Coal Mines

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Abstract: The method of analyzing the results of dust concentration measurements in mine workings that was conducted within the ROCD (Reducing risks from Occupational exposure to Coal Dust) European project using the developed dust prediction algorithm is presented. The analysis was based on the measurements of average dust concentration with the use of the CIP-10R gravimetric dust meters, for the respirable PM4 dust concentration, and IPSQ analyzer for instantaneous concentration measurements (including PM2.5 dust) and with the use of Pł-2 optical dust meters for instantaneous concentration measurements of PM10 dust. Based on the analyses of the measurement results, the characteristics of the distribution of PM10, PM4, and PM2.5 dust particles were developed for the tested dust sources. Then, functional models based on power functions were developed. The determined models (functions) allow predicting the dust distribution in such conditions (and places) for which we do not have empirical data. The developed models were implemented in a specially developed online tool, which enables predicting the concentration of PM10, PM4, and PM2.5 dust (on the basis of dust concentration of one source) at any distance from the dust source.

Keywords: dust; in situ tests; prediction

1. Introduction

The concentration of coal mining production worldwide and the winning of thinner and thinner coal seams means that the mining personnel are exposed to a number of hazards. Coal dust is one of such hazards. It is first and foremost a danger of explosion, endangering human life, and damaging equipment; however, coal dust is also a lung hazard arising from its prolonged exposure to the human respiratory system. Despite international efforts to predict and protect miners' health, a constant high incidence of lung diseases among miners, often with severe consequences, has been recorded for several years [1–3]. Pneumoconiosis resulting from long-term inhalation of free silica, manifested by chronic bronchitis and emphysema, and sometimes by heart failure and cardiac hypertrophy, is the most common occupational disease caused by mine dust [4,5]. Symptoms of pneumoconiosis usually appear after several years; therefore, these diseases are most often diagnosed only among retired miners [6]. The share of new cases of pneumoconiosis diagnosed in Poland, and caused by coal mining processes, is shown in Figure 1 [7,8].
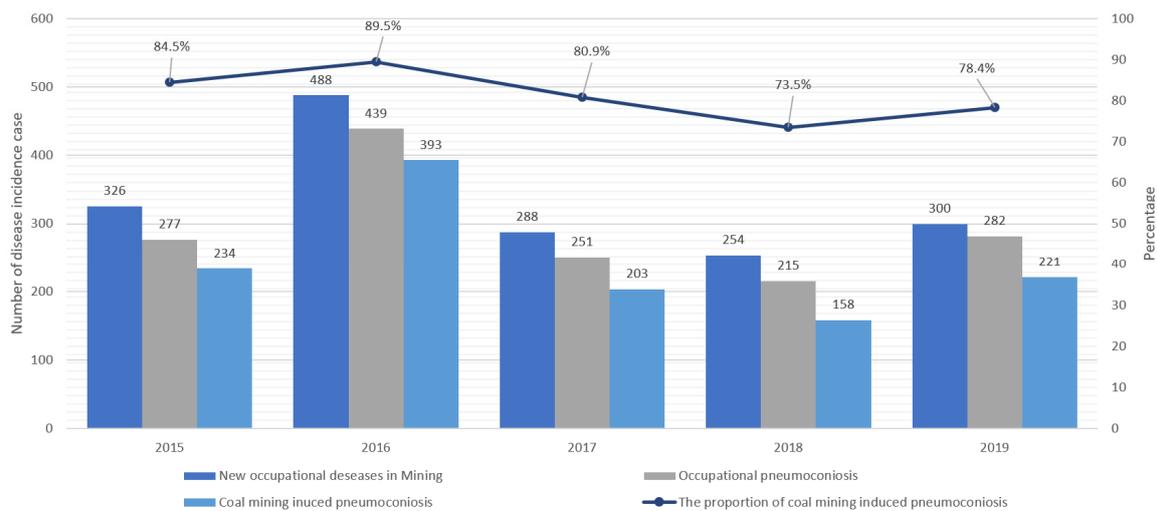
Figure 1. Share of new pneumoconiosis cases in Poland caused by coal mining in the years 2013–2017 [8].

The persistently high number of cases of disease makes it important to look for new, practical tools and methods to improve risk models, dust control, and workers protection, especially with regard to the finest fraction of dust, i.e., PM2.5. Forecasting and assessment of hazards related to mine dust are based mainly on epidemiological [9] and cohort studies [10], based on regional or national data. The intensity of dust settlement by measuring its concentration in the protection zone was tested [11,12]. The tests results were used to develop an empirical model of these relationships (Figure 2). These models, developed on the basis of the test results of the intensity of settlement and changes in the concentration of dust in the protection zone, allowed for the development of tools for the reduction in the risk of coal dust explosion.
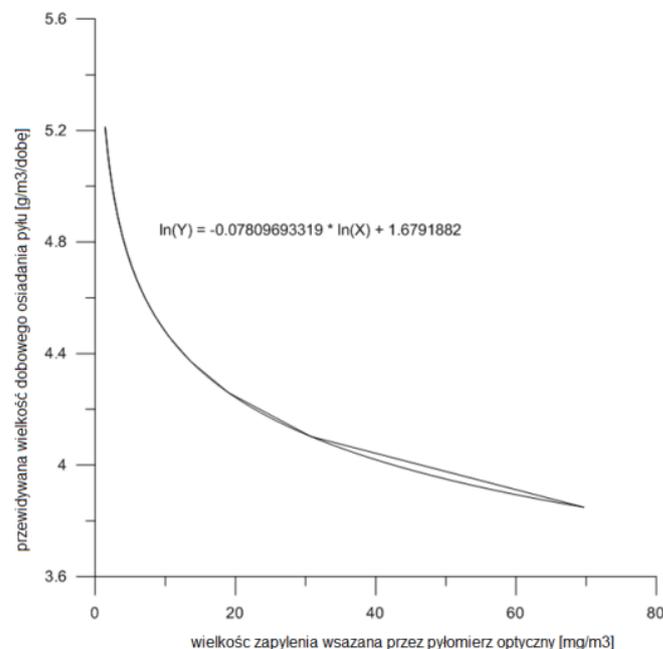
Figure 2. Empirical model of dust settlement in relation to dust concentration in air for longwall panel no. 551 and longwall no. 121 [11].

In turn, in [13], the flow of air with coal dust in a mine working was tested. Dust distribution in the mine workings was numerically analyzed (CFD).

The tests showed that it is possible to model dust concentrations using mathematical tools, with high compatibility with actual results. Due to the complexity of the process, the

analyses were focused on one type of workings, and their main objective was not to predict dust concentration but to assess the effectiveness of the dust removal equipment used.

In another work [14], the authors found a correlation between the rate of settling of dust particles and the aerosol parameters, which can be used to parameterize the mathematical models of air–dust mixture flow in mine ventilation networks. In [15], the diffusion of dust particles was tested based on the CFD-DEM coupling model and underground tests. In turn, the authors of [16], based on the theory of similarity and the theory of two-phase gas–solid flow, applied numerical simulation and similarity experiments to investigate the distribution of dust concentration and the characteristics of dust propagation in mine workings.

The main disadvantage of almost all known dust analyses is that they were based only on the inhalable fraction (nominally particulate matter <10 μm—PM10) or on the respirable fraction (nominally <4 μm—PM4). Little attention was paid to the fine fraction (PM2.5) that can penetrate into the gas exchange zone in the lungs [17,18]. An increase in PM2.5 dust concentration is associated with higher lung cancer incidences as well as cardiovascular mortality [19]. Exposure to dust and work in the hard coal mining industry caused over 4.5 thousand cases of pneumoconiosis in the last decade only in Poland [7,8]. In the United States, around the same time period, there was evidence of an increase in both the incidence and severity of pulmonary diseases associated with coal dust [2].

The situation is similar in China, where pneumoconiosis accounts for more than 90% of occupational diseases, where more than 85% of them are reported in the coal mining industry [20].

Within the project of ROCD (Reducing risks from Occupational exposure to Coal Dust) funded by the European Commission Research Fund for Coal and Steel, research work was carried out in the aspect of reducing dust concentration, protecting miners from dust, and many studies enabling dust prediction [21].

The dust hazard prevention tool was developed within the project. It was a prediction algorithm for monitoring the dust concentration, dust properties, and predicted concentrations, based on continuous dust measurements and gained knowledge. The algorithm for the prevention of excessive dust concentration is based on a much larger number of results and a broader spectrum of dust particle sizes compared to the previous methods, including coal mining technologies and the mine ventilation network system. The prediction algorithm is created by a procedure of actions and a special interactive application for predicting the dust concertation in any place of a mine working. In the first place of the procedure, characteristics of the average dust concentration distribution were developed, based on the determination of PM10, PM4, and PM2.5 dust concentration at different distances from the source of dust, in the tested mine workings. The next step is to determine the equivalent characteristics of the dust depending on the dust source. These functions make it possible to predict the propagation of dust concentration in the places for which we have no empirical data.

2. Test Methodology

Dust concentration measurements required for the prediction analysis were taken using three types of devices: CIP-10-R gravimetric dust meters, IPSQ particle analyzer, and the Pł-2 optical dust meter. Measurements were taken in the hard coal mines of Jastrzębska Spółka Węglowa S.A., Polska Grupa Górnicza S.A. and Premogovnik Velenje mine in Slovenia during normal mine operation. Dust concentration measurements were taken in longwall panels and roadways. The measuring points were set at a distance of about 50 m from each other, at least at three points. The first measuring point was placed just behind the dust source, i.e., behind a roadheader in a coal face or at the air outlet from a longwall face. Subsequent stationary measuring points were placed in the axis of the working, at the height of 1.5 m, at distances of 50 m, 100 m, 150 m, 200 m, etc., in accordance with the following scheme of measuring devices arrangement (Figure 3).

PM4 dust concentration was measured with the use of CIP-10R dust meters (Figure 4). Measurements of dust weight in the measuring cups of personal dust meters were performed by a body accredited in the scope of tests in the work environment. Measurements were taken in five coal faces and four gates.
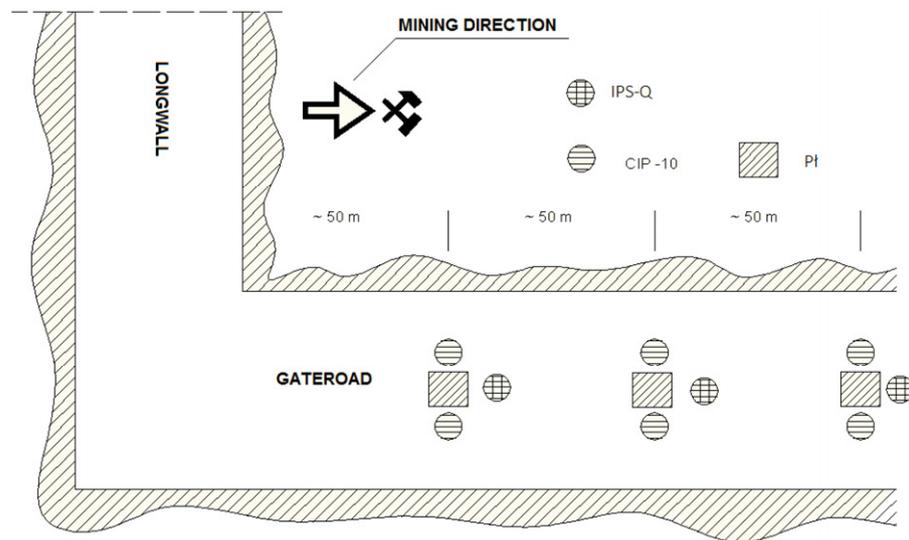
Figure 3. Arrangement of devices in the gateroad.

Figure 4. CIP-10R personal dust meter for measuring the PM4 dust respirable fraction of.

Measurements with the use of CIP-10R dust meters enabled calculating the average dust concentration at the given measuring points (1).

$$\overline{S} = \frac{m}{\dot{V} \times \tau} \tag{1}$$

where:

$\overline{S}$—dust concentration (mg/m^3).

$\dot{V}$—air flow in the CIP-10R (dm^3/min).

τ—measurement time (min).

m—dust mass in the measuring cup (mg).

Fractional distribution of dust and dust concentration at given points were measured using an IPSQ analyzer connected to a laptop recording the results (Figure 5).
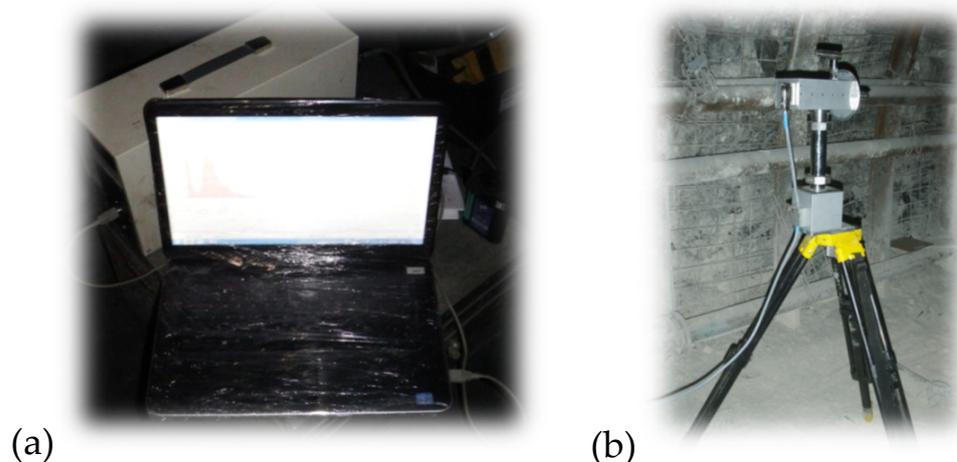
Figure 5. IPSQ analyzer, consisting of: (**a**) electronic measuring block with a computer; (**b**) measuring probe.

Due to the device not being ATEX manufactured, the measurements in accordance with the adopted measurement methodology could only be taken in workings of methane concentration below 0.5%. The following parameters were measured: temperature, humidity, airspeed, as well as the dimensions and concentration of dust particles suspended in the air. Size distribution and dust concentration were measured in the range from 0.4 to 300 µm, from which the particles below 2.5 µm were finally separated. To develop a mathematical model of the dust distribution for a given type of working, data from measurements in two mines (coal faces and gates) were used.

The last dust concentration measurements of PM10 dust were taken by the Pł-2/100 optical dust meter designed by ITI EMAG. The Pł-2 optical dust meter is an optical device operating on the basis of light scattering on dust particles. The physical principle of operation is based on the so-called Tyndall effect and consists in scattering light radiation of a constant wavelength in a colloidal solution, which in this case is a mixture of coal dust and air.

The Pł-2 dust meter (Figure 6) enables continuous measurement and recording of the PM10 dust concentration in the range of 0–100 mg/m^3.

Figure 6. The PŁ-2 optical dust meter used in testing.

The Pł-2 dust meter is approved for operation in potentially explosive atmospheres, and it could be used in workings with a risk of coal dust and methane explosion. The dust meters were located in accordance with the assumed testing methodology, and the measurements from dust meters were recorded through the mine's measuring system. Measurements were taken in three coal faces and three gates.

3. In Situ Tests

Changes in dust concentration in mine workings are stochastic, determined by many variables. The development of a proxy characteristic was based on several test trials carried out in different mines to develop a relationship that best reflects changes in concentrations of PM10, PM4, and PM2.5 in a given type of workings.

The results of the tests were divided into groups, depending on the type of working. Then, from the separated points, the characteristics of the dust concentration distribution depending on the distance from the dust source for each test in a given type of workings were developed.

Characteristics of the average distribution of PM4 dust concentration, depending on the distance from a dust source, obtained on the basis of dust concentration measurements with the use of CIP-10R in gates (Figure 7) are presented below. The characteristics are presented together with the functions describing them and are necessary to determine the mean value enabling the creation of the equivalent characteristics in further tests.
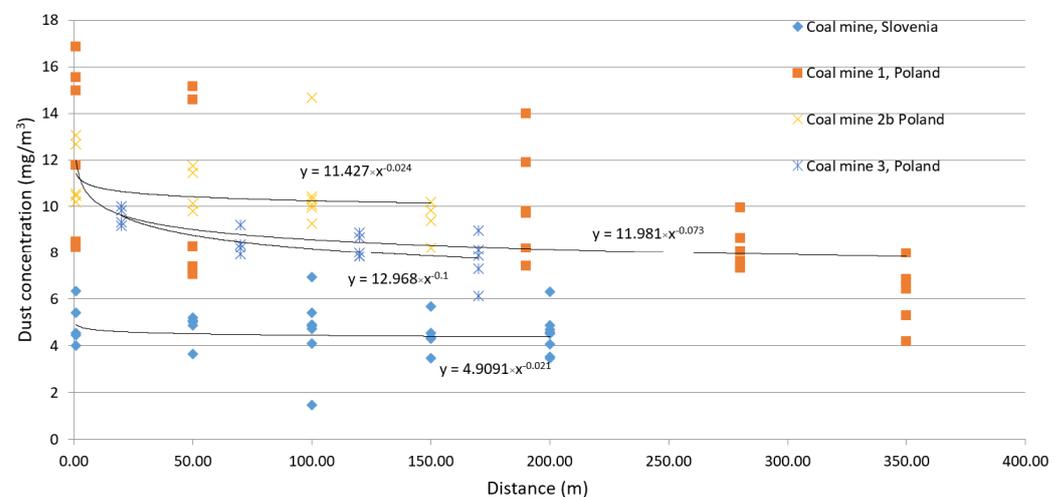
Figure 7. Characteristics of the average distribution of PM4 dust concentration in gates depending on distance from a source of dust, based on dust concentration measurements using the CIP10R with the functions describing them.

Similarly, the characteristics of the average distribution of PM4 respirable dust concentration depending on the distance from a dust source, based on dust concentration measurements using CIP-10R, in coal faces are presented below, together with the functions describing them (Figure 8).

The results of dust concentrations from the IPSQ analyzer allowed us to isolate particle fractions of sizes below 2.5 μm at given measuring points. The sample result of the quantitative share of particles in a given class at each of the three measuring points (coal face) in one of the mines is shown in Figure 9.

On the basis of the measurement results of PM2.5 dust concentration for the coal face and the gates, the characteristics of the average dust concentration distribution depending on the distance for each test in a given type of workings were developed. The characteristics of the average distribution of PM2.5 dust concentration depending on the distance, based on the results from the IPSQ analyzer in the gates with the functions that describe them, are presented below (Figure 10).

Similarly, the characteristics of the distribution of PM2.5 dust concentration depending on the distance, measured with the IPSQ analyzer in coal faces, together with the functions that describe them, are presented in Figure 11.
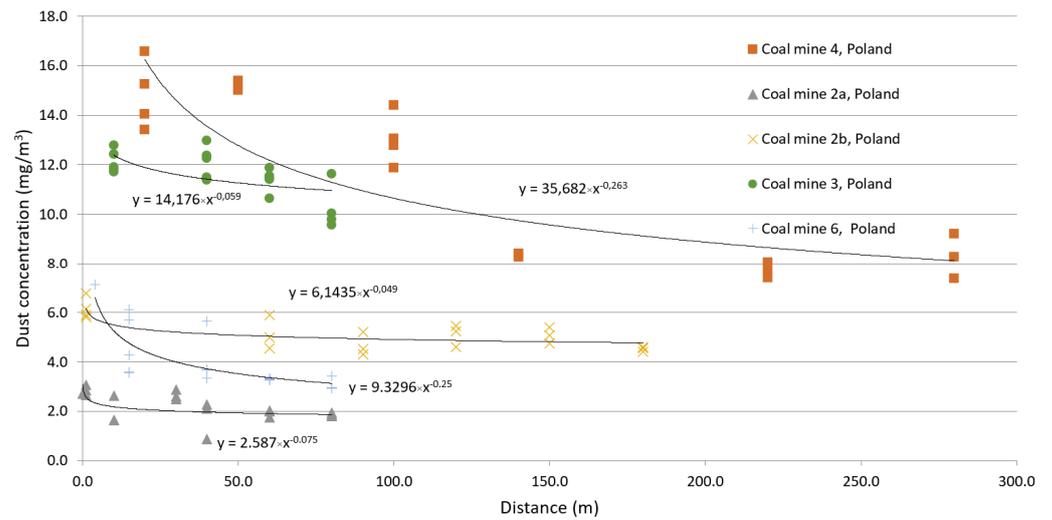
Figure 8. Characteristics of the average distribution of PM4 dust concentration in the coal face depending on the distance from a source of dust, based on dust concentration measurements with the use of CIP-10R dust meter together with the functions describing them.

(**a**)

(**b**)

(**c**)
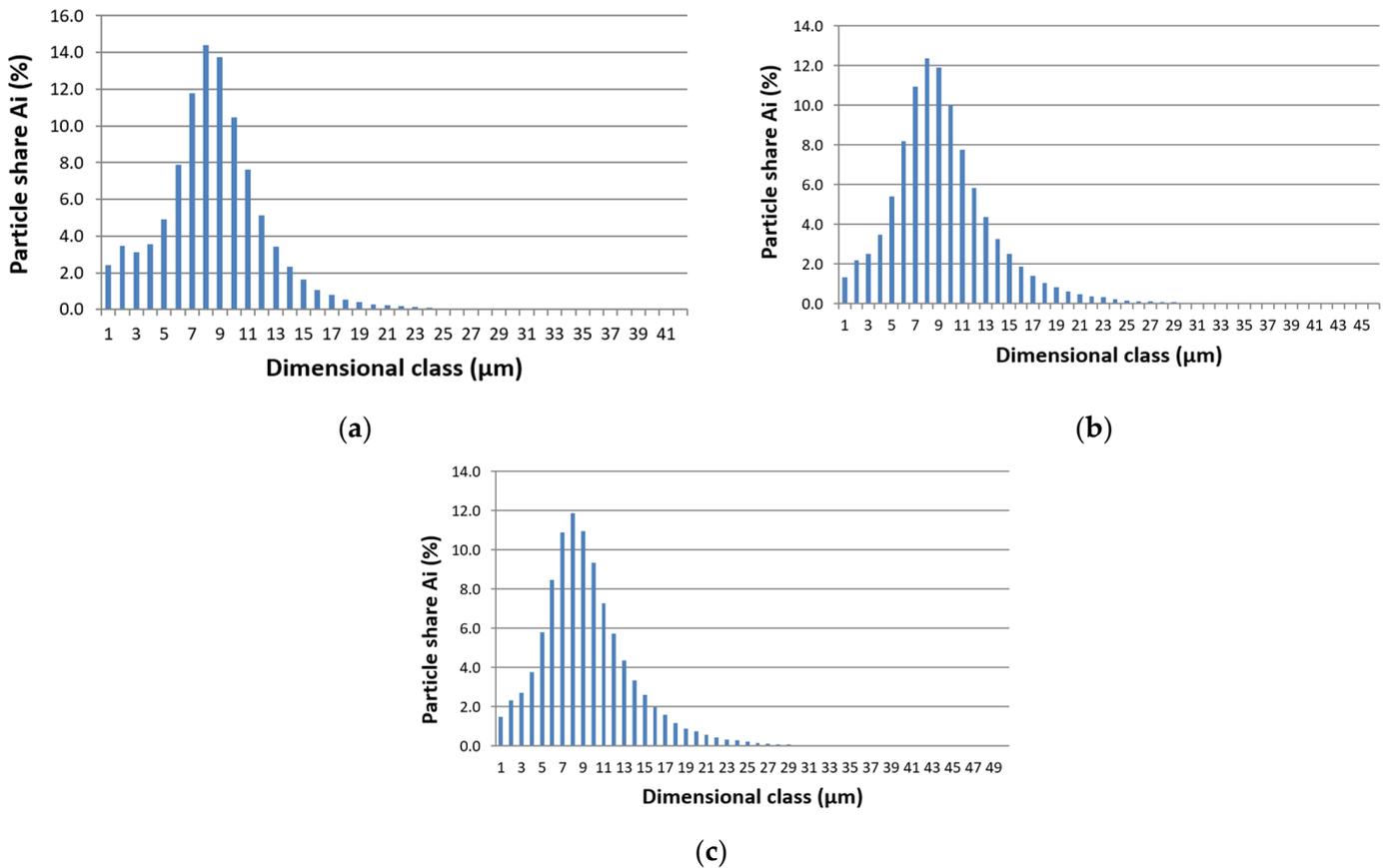
Figure 9. Sample result of the quantitative share of particles in a given class during measurements for the following measuring points: (**a**) nr 1; (**b**) nr 2; (**c**) nr 3.
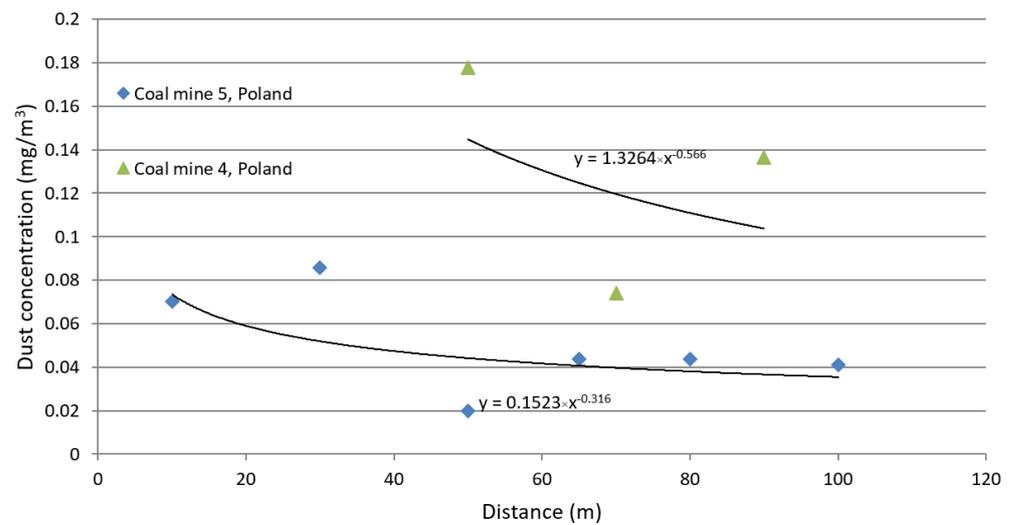
Figure 10. Characteristics of the average distribution of PM2.5 dust concentration in the gates depending on the distance, based on the results from the IPSQ analyzer with the functions describing them.
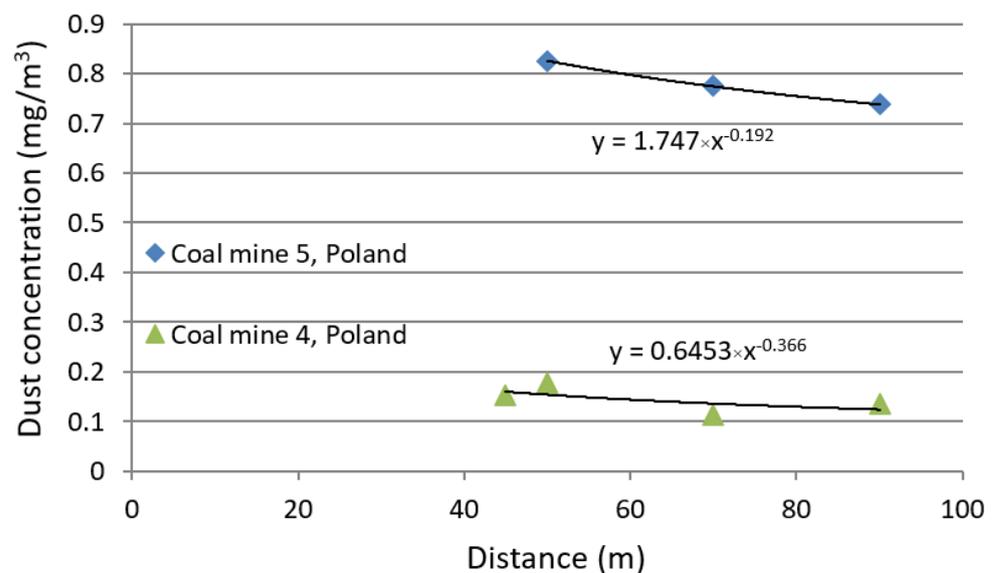
Figure 11. Characteristics of the distribution of PM2.5 dust concentration depending on the distance from a dust source, measured with the IPSQ analyzer in coal faces, together with the functions that describe them.

The results of measurements taken by the Pł-2/100 optical dust meter consist of the recorded momentary time processes of PM10 dust concentration in coal faces and gates. Sample waveforms of the momentary concentration of PM10 dust in one of the mines, obtained from three Pł-2 dust meters located in the coal face, are shown in Figure 12.

Based on the momentary time processes of PM10 dust concentrations, the average PM10 dust concentration distributions were determined. The characteristics of the average distribution of PM10 dust concentration depending on the distance in the coal faces with the functions that describe them are presented below (Figure 13).

Similarly, below the characteristics of the average distribution of PM10 dust concentration depending on the distance, in the gates with the functions that describe them are presented (Figure 14).
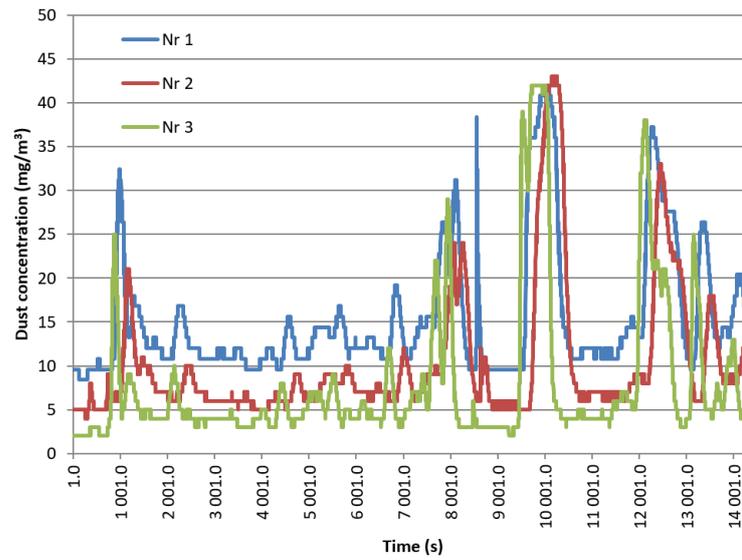
Figure 12. Momentary concentration of PM10 dust, obtained from three Pł-2 dust meters—coal face in one of the mines.
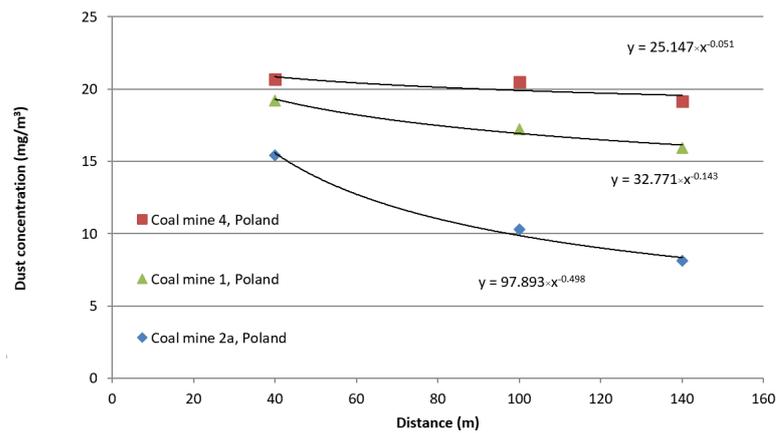
Figure 13. Characteristics of the average distribution of PM10 dust concentration depending on the distance in the coal faces, based on the results from Pł-2 dust meters with the functions that describe them.
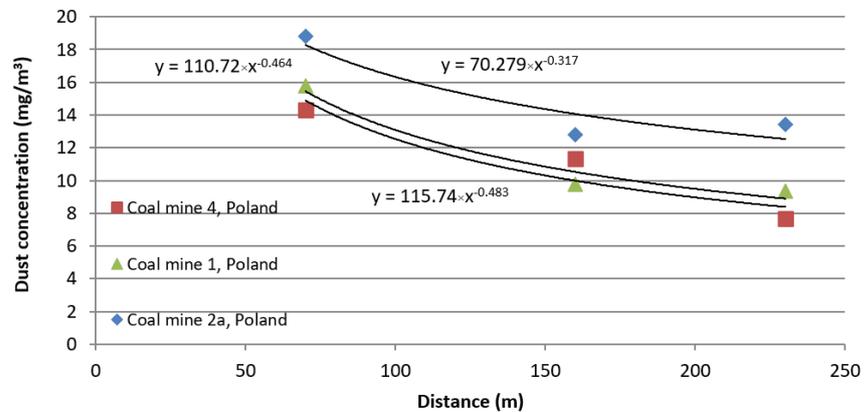
Figure 14. Characteristics of the average distribution of PM10 dust concentration depending on the distance in the gates, based on the results from Pł-2 dust meters with the functions that describe them.

4. Analysis of the Results

For different workings, the location of the measuring points was different. Hence, to develop a universal characteristic for each type of working, for each test with the use of a different type of measuring device (Pł-2, CIP-10R, and IPSQ), graphs of changes in dust concentration (PM10, PM4, and PM2.5), depending on the distance from the dust source, were created. They enabled the extrapolation of the results to the required working length equal to 300 m.

Examples of PM10 dust concentration measurements, extrapolated to a distance of 300 m from the dust source, for the gates, are presented in the table below (Table 1).

Table 1. Dust concentration measurements in the gates, extrapolated to a distance of 300 m from the dust source.

Distance, m	PM10 Dust Concentration, Mine No 1, mg/m^3	PM10 Dust Concentration, Mine No 2, mg/m^3	PM10 Dust Concentration, Mine No 3, mg/m^3
	$y = 70.279 \times x^{-0.317}$	$y = 115.74 \times x^{-0.483}$	$y = 110.72 \times x^{-0.464}$
1	70.73	115.74	110.72
50	20.47	17.49	18.03
100	16.43	12.52	13.07
150	14.45	10.29	10.83
200	13.19	8.96	9.47
250	12.29	8.04	8.54
300	11.60	7.36	7.85

On the basis of each dust concentration extrapolated to a distance of 300 m, the average value was determined, which was the base for the development of universal equivalent characteristics, and then the equivalent equation was determined for a given dust fraction and a given type of mine working (for a coal face and a gate).

Based on the results of dust concentration measurements in three gates, an equivalent equation for PM10 dust concentration (measured by Pł-2 dust meters) depending on the distance from the dust source, was obtained in the form of $y = 97.201 \times x^{-0.42}$ (Figure 15).
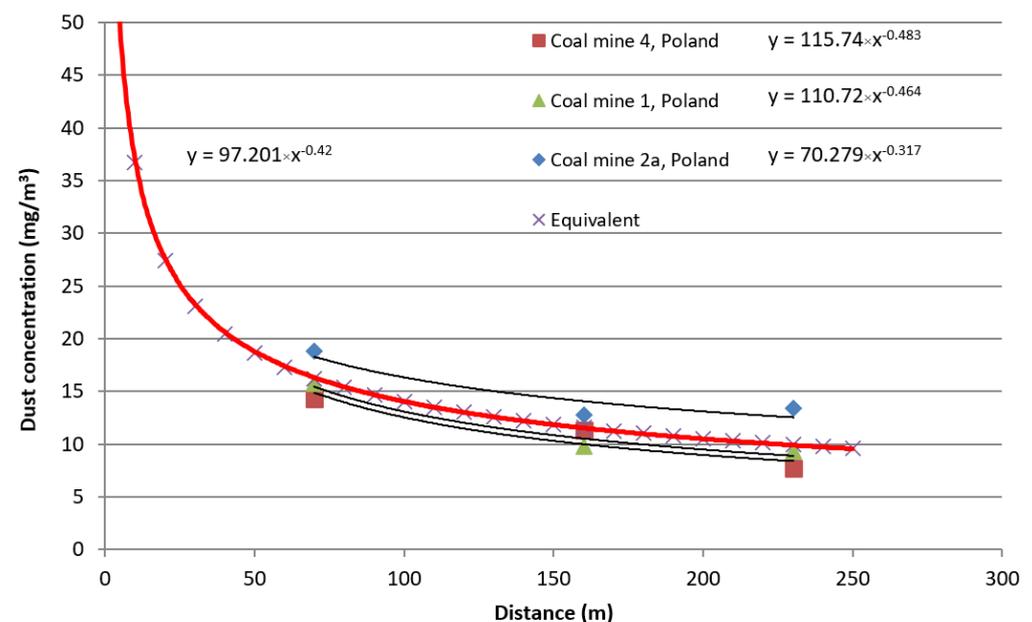
Figure 15. Equivalent characteristics of PM10 dust concentration (measured by the Pł-2 dust meters), depending on the distance from the dust source, determined on the basis of dust concentration measurements in three gates.

On the other hand, on the basis of dust concentration measurements in four gates, the equivalent equation for PM4 dust concentration (measured by CIP-10R), depending on the distance from the dust source, was $y = 10.276 \times x^{-0.058}$ (Figure 16).
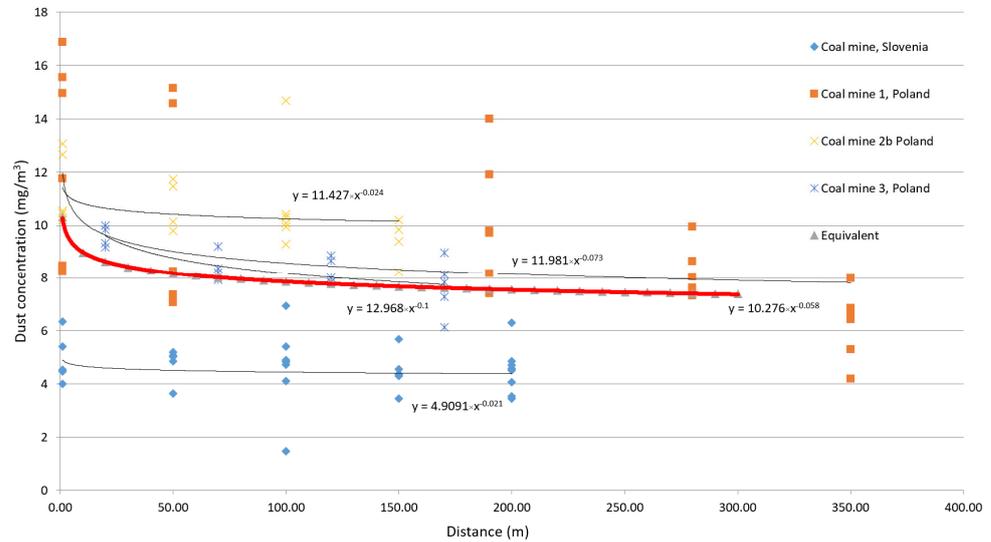
Figure 16. Equivalent characteristics of PM4 respirable dust concentration (measured by CIP-10R dust meter), depending on the distance from the dust source, determined on the basis of dust tests in four gates.

Based on dust concentration measurements in two gates, the equivalent equation for PM2.5 dust concentration (measured by the IPSQ analyzer), depending on the distance from a dust source, was $y = 0.6795 \times x^{-0.503}$ (Figure 17).
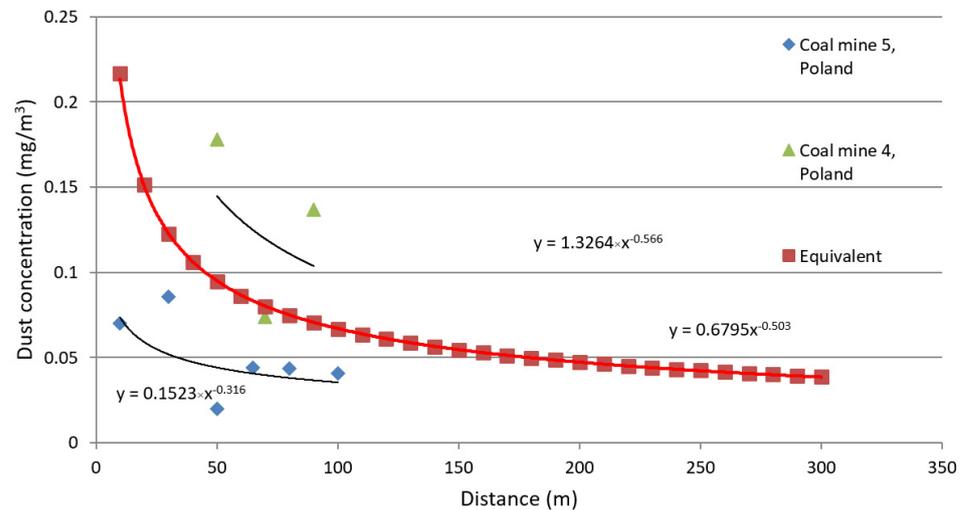
Figure 17. Equivalent characteristics of PM2.5 dust concentration (measured by IPSQ analyzer), depending on the distance from the dust source, were determined on the basis of dust measurements in two gates.

Based on the same method, characteristics and equivalent equations were determined for the coalface. Based on the measurements of dust concentration in three coal faces, the equivalent equation for PM10 dust concentration (measured by CIP-10R), depending on the distance from the dust source, was $y = 45.697 \times x^{-0.23}$ (Figure 18).
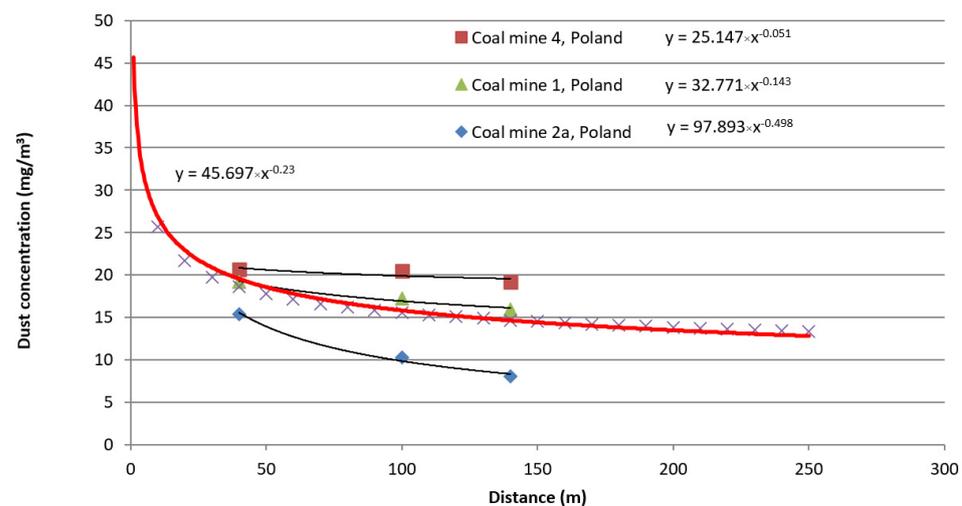
Figure 18. Equivalent characteristics of PM10dust concentration (measured by Pł-2 dust meter), depending on the distance from the dust source, determined on the basis of dust measurements in two coalfaces.

Based on the measurements of dust concentration in five coal faces, the equivalent equation for PM4 dust concentration (measured by CIP-10R), depending on the distance from the dust source, was $y = 13.037 \times x^{-0.159}$ (Figure 19).
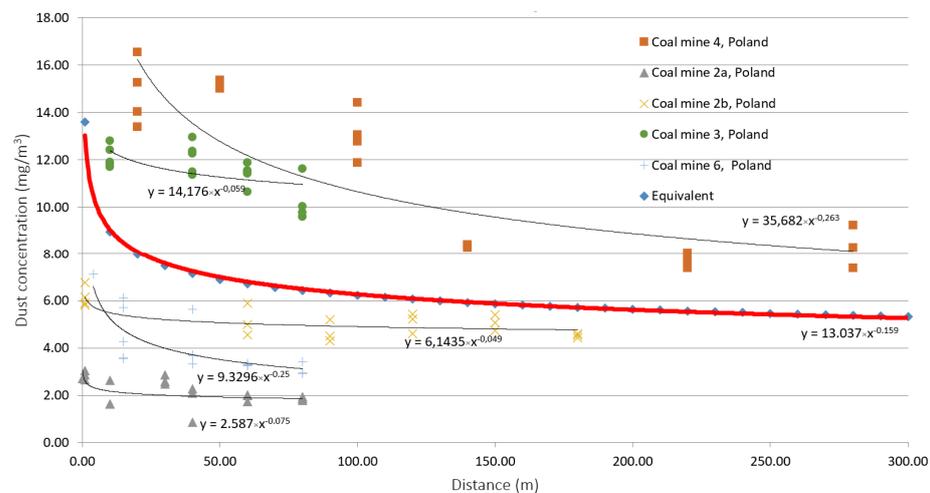
Figure 19. Equivalent characteristic of PM4 dust concentration (measured by CIP-10R dust meters) depending on the distance from a dust source, based on dust concentration measured in five coal faces.

Based on the dust concentration measurements, measured by the IPSQ analyzer in two coal faces, the equivalent equation for PM2.5 dust concentration depending on the distance from the dust source was $y = 1.1524 \times x^{-0.219}$ (Figure 20).

Based on equivalent equations of dust concentrations (PM10, PM4, and PM2.5) for coal faces and gates, a tool for dust concentration prediction was developed. This tool, together with the methodology, creates an algorithm for the prediction of dust distribution in hard coal mines.

Prediction of concentration of each type of dust: PM10, PM4, and PM2.5 (even if dust concentration from only one point is known), on the basis of the developed mathematical, empirical models, was possible, at any distance from the dust source. Dust concentration in the gates and coal faces tested within the project can be predicted on the basis of the obtained results (Figure 21). Data on the effectiveness in reducing the concentration of

each type of dust by the most frequently used spraying devices in the Polish mines were additionally implemented to the application. This allows for the assessment of their impact on dust concentration (different fractions) in the selected places of mine workings, and therefore to select the most preferable device with respect to the reduction in a given type of dust. The application for predicting the dust concentration is divided into a part showing the results of dust concentration depending on the distance from a dust source in the form of graphs (left side of the window) and in the form of a panel for entering input data for the simulation (right side of the window).
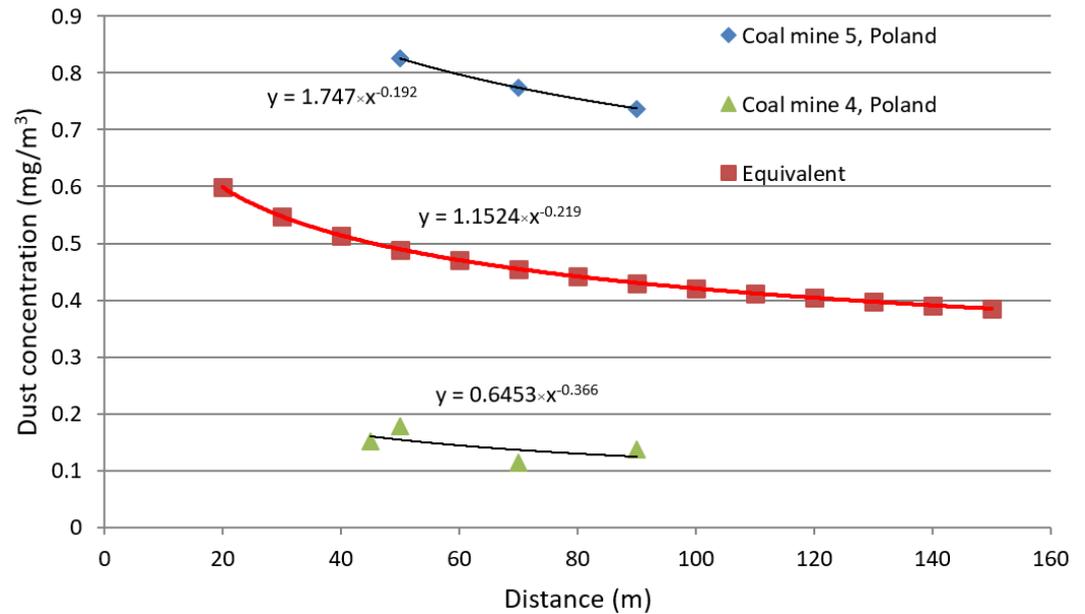
Figure 20. Equivalent characteristics of PM2.5 concentration (measured with an IPSQ analyzer), depending on the distance from the dust source, were determined on the basis of dust tests in two coal faces.
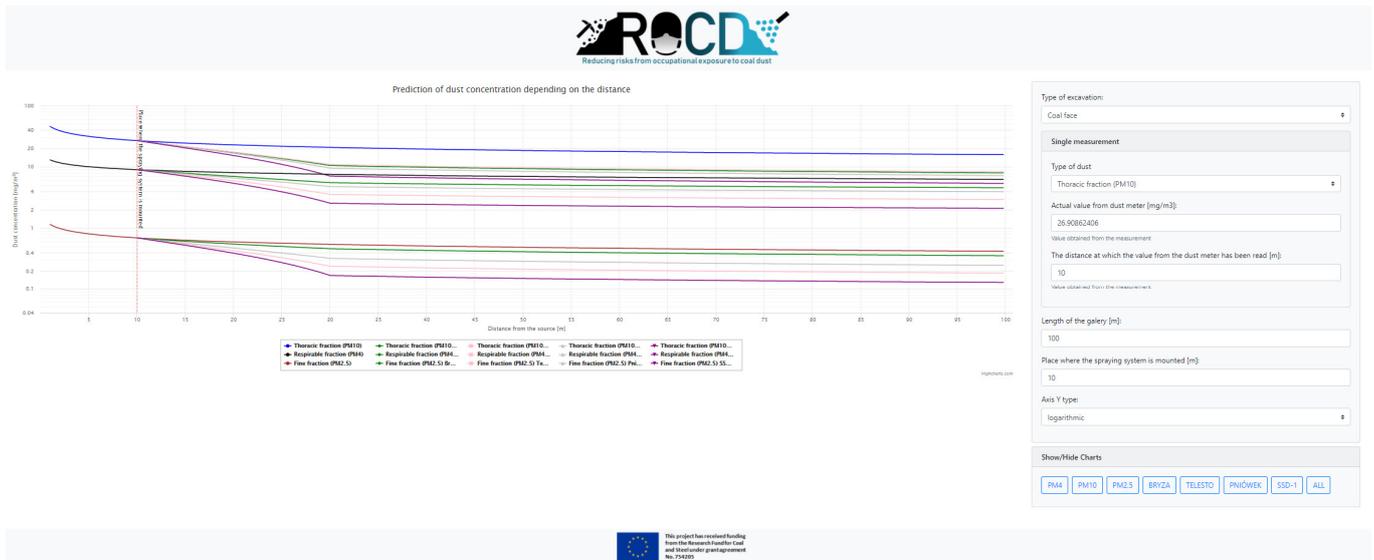
Figure 21. View of the dust prediction application, showing a graph of dust concentration depending on the distance from the dust source.

Entering the input data in the panel (Figure 22) starts from the selection of the type of mine working for which the dust concentration is predicted. Then, the panel allows

determining the type of dust and its concentration (mg/m^3) that has been measured, and on this basis, it enables us to predict concentration at other points of a given type of working. The panel also allows entering the length of the working in meters and the place of installation of dust control devices.

Figure 22. Window on the panel for entering the input data for prediction of dust concentration.

After entering the data into the application panel and turning on each characteristic to be displayed, the predicted dust concentration [mg/m^3] depending on the distance [m] are displayed in the graphic window (Figure 23). The graphic window displays the characteristics of the distribution of the PM10, PM4, and PM2.5 dust concentrations depending on the distance from a dust source. When determining the impact of the spraying device used (BRYZA, TELESTO, PNIÓWEK, SSD-1), additional characteristics are displayed showing their impact on a given type of dust. After moving the cursor over any of the characteristics, a window appears with the forecasted results of concentration for each type of dust, with and without spraying devices.
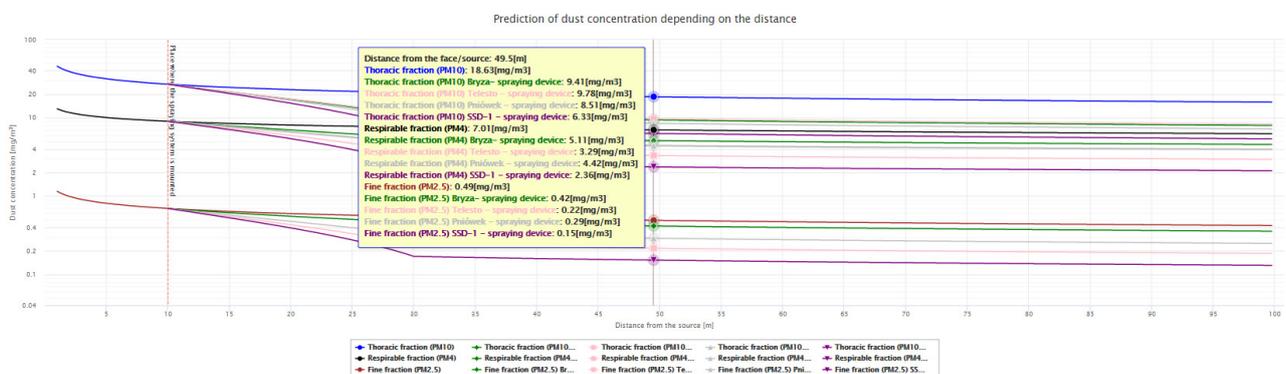
Figure 23. Graphical window to display the predicted dust concentration (PM10, PM4, and PM2.5) with and without spraying devices.

5. Conclusions

The methodology and the tool for the prediction of dust concentration in coal mines developed and presented in the article were based on a series of in situ tests carried out as part of a European project. Dust concentration with a wide spectrum of particle fractions, especially the fine dust fraction (PM2.5), in various types of workings, in several hard coal mines, has not been measured so far. Underground tests required coordination of activities and standardization of measurements. This enabled the development of dust concentration distribution characteristics (PM10, PM4, and PM2.5) depending on the distance from a dust source, and then the determination of empirical functions for them with high determination coefficients, indicating the high probability of correct description of the developed relationships. Based on the designated functions, the equivalent dust characteristics of PM10, PM4, and PM2.5 were developed for coal faces and gates (Figures 24 and 25).
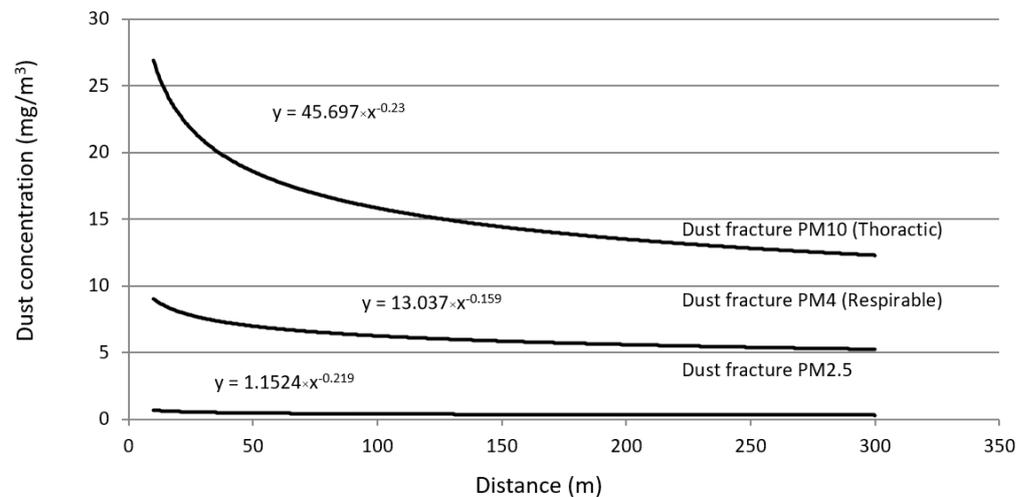
Figure 24. Characteristics and equations of PM10, PM4, and PM2.5 dust concentration for a coal face, depending on the distance from a dust source, developed on the basis of in situ tests.
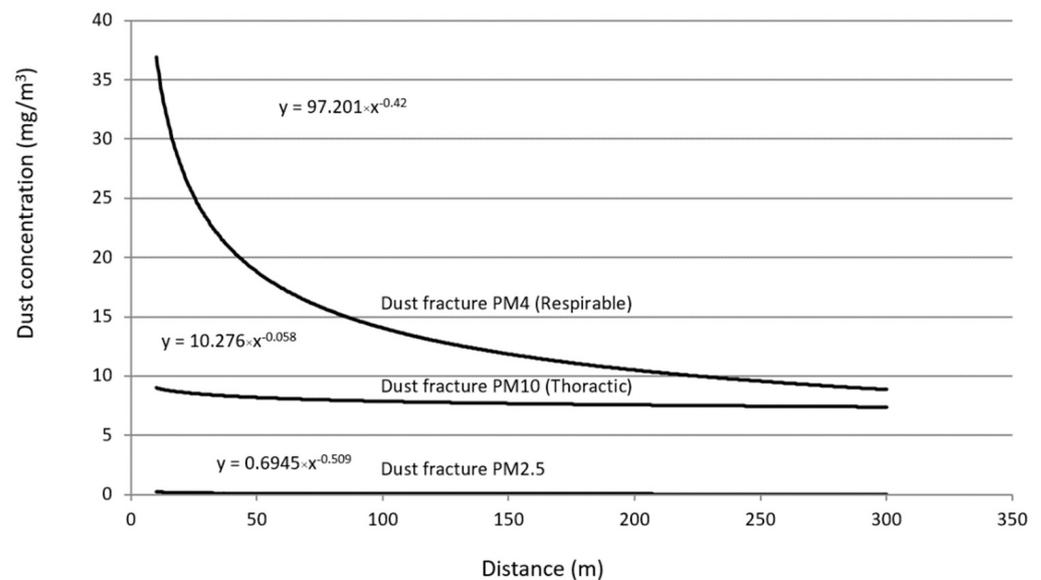
Figure 25. Characteristics and equations of PM10, PM4, and PM2.5 dust concentration for a gate, depending on the distance from the dust source, developed on the basis of in situ tests.

The developed equivalent characteristics show each dust fraction distribution depending on a distance from a dust source and type of mine workings.

The equivalent functions of the distribution of PM10, PM4, and PM2.5 dust concentrations enable their use to predict dust concentration in the tested types of mine workings. Predicting the concentration of various dust fractions in various types of workings, based on the dust concentration in one of the assessed coal faces or gates, is possible using the developed functions of the designed application. The suggested testing methodology allows to extend the developed database and increase the convergence of dust concentration measurements with the real results.

The presented methodology creates an algorithm for the prediction of dust concentration and will allow mine supervisors to better control mine workings in terms of the safety of the miners working there.

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