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The Impact of Moisture Content on Outburst Hazard of Sandstones in Coal-Bearing Strata

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ABSTRACT

The article theorizes the impact of the quantitative moisture content in rocks with two main factors of outburst hazard – their physical and mechanical properties and the gas factor. The impact of natural humidity and reservoir properties of sandstones on the degree of their outburst hazard and the depth of outburst manifestation in coal mines of the Donetsk Basin (Ukraine) is researched. The exploration targets were outburst-prone sandstones of the Lower and Middle Carboniferous age of the coal-bearing strata of Donbas in Ukraine. Sandstones lay in zones of middle and late catagenesis, within the distribution of gas, fatty, and coking coals in the depth range of 700–1200 m. The author evaluated the absolute humidity (weight moisture indicator), relative humidity (water saturation or the degree of pore filling with moisture), and open porosity of researched sandstones. It has been established that the weight moisture/open porosity ratio determines the degree of outburst hazard of sandstones. This indicator is proposed as a prognostic criterion for determining the degree of outburst hazard of sandstones. A connection has also been established between the manifestation depth of sandstone and gas outbursts with their water and gas saturation. Based on determining the critical values for the degree of pore filling with moisture for fixed stratification depths, an evaluation method of outburst hazard is proposed. Testing the use of the proposed methods for determining the outburst hazard of rocks, considering the natural moisture of sandstones, in the mines of Donbas, fully confirmed their reliability, validity, and the possibility of practical application.

1. Introduction

Rock and gas outbursts remain a pressing issue in the mining industry worldwide, they are unwanted complications of underground coal mining, which have occurred over the last 150 years and are still occurring. Rock and gas outbursts have been registered in China, Canada, Czech Republic, France, Germany, Ukraine, Russia (Lama and Saghafi, 2002), Poland, Japan, Hungary, and Great Britain (Baranov, 2021). A sudden rock and gas outburst is a dangerous and complex gas-dynamic phenomenon that occurs in gas-bearing rocks and is characterized by rapidly developing destruction of the massif with the rejection (displacement) of the rock mass and the release of gas into the mine workings.

An outburst is considered a spontaneous, fast-flowing process of fragile self-supporting destruction of the bottom-hole area of a rock massif, accompanied by gas release from destroyed coal and rocks and their movement through workings in a gas flow (Bolshinsky et al., 2003). Outburst intensity ranges from a few tons to tens of thousands of tons. As a result of outbursts, mine workings turn out to be filled with ejected rock for tens of meters, the support is destroyed, equipment is disabled, cavities are formed that protrude beyond the contour of the working, and the ventilation regime is disrupted due to the overturning of the air stream.

Outburst hazard is caused by the complex interaction of three main natural factors (stress state, gas, and physical-mechanical properties of rocks) with technological factors, and the formation of outburst-prone conditions occur in geological environments characterized by certain properties and states.

In Ukraine, rock and gas outbursts have been registered in coal mines of the Donetsk basin and occur in sandstones saturated with gas (methane). The characteristic features of rock and gas outbursts in Donbas coal mines are that they occur only in sandstones and, unlike coal and gas outbursts, are always triggered by an explosion. Experience in workings on outburst-prone sandstones in other regions has shown that outbursts also occur during the mechanical destruction of sandstone. In Germany, outbursts occurred when there was a shaft sinking with a combine (Bolshinsky et al., 2003).

In general, coal mining is associated with a few unfavorable natural phenomena, such as blowers, outbursts of coal, rocks, and gas, rock bumps, rushes, falls, rock inrushes and heaving, water irruptions, and increased water inflows into mine workings, etc. The reasons for the occurrence of most of them are directly or indirectly related to the geological activity of water and gas, and their complex interaction in a heterogeneous coal-rock massif. Water and gas in rock massifs are inextricably linked. Gas can occupy only that part of the pore space of coals and host rocks that are not filled with water. The gas saturation and gas content of coal-bearing strata is closely related to their moisture content. It should be noted that not only the amount of water affects gas saturation and gas content, but also the various forms of its presence in coal beds and host rocks. The thickness of a layer of bound water determines the active porosity (free pore space), which determines the permeability of the rock. The quantitative moisture content also largely determines the physical and mechanical properties of rocks and, consequently, the strength properties of the rock massif as a whole (Bulat and Bezruchko, 2015).

Humidity largely determines the strength properties of rocks. Many works have been devoted to the impact of moisture content on the strength properties of rocks. It is known that pore fluids impact the physical and mechanical properties of rocks, in particular, the strength (Cherblanc et al., 2016; Wong, et al., 2016; Shi et al., 2016; Petrov et al., 2017; Özdemir and Sarici, 2018; Majeed and Abu Bakar, 2018) and plasticity (Yilmaz, 2010; Malkowski et al., 2014; Yao et al., 2015; Zhou et al., 2016; Zhang et al., 2017).

An increase in the moisture content of rocks is accompanied by a decrease in their strength. Thus, the strength of many low-porosity rocks under uniaxial compression in a water-saturated state is often only 45 % of its value for the same material dried at high temperatures (Price, 1960; Colback and Wiid, 1965). It has been established that with an increase in the gravimetric moisture content to 2.5 %, the strength of outburst-prone sandstones in some Donbas coal mines decreases by 73-80 %, and of non-outburst-prone sandstones in the same mines – by 43-70 % (Bulat and Bezruchko, 2015).

This similar water impact can be explained based on the data obtained by Rutter (1970, 1974 and 1976). This researcher compared the results of testing the same samples in a water-saturated state and dried at high temperatures. When testing wet samples, the ratio of pore fluid pressure to confining pressure ranged from zero to unity. The effect of reducing the strength of rocks when exposed to water, as can be seen, is unusually sharp.

Thus, humidity has a significant impact on an important natural factor that determines the degree of outburst hazard of rocks – their physical and mechanical properties. It should be noted that humidity determines not only the physical and mechanical properties of coal beds and rocks, but also the properties of the rock massif as a whole (Bukowska and Bukowski, 2023). The work (Khanin, 1968) notes that if the pores of the rock are filled with water, then gas breakthrough and filtration become possible only at a certain pressure difference, the value of which depends on gas permeability. With an absolute gas permeability coefficient of the order of $1 \cdot 10^{-6}$ mD (fm^2), the pressure difference for the emergence of gas filtration must be at least 12.0 MPa. That is, bound moisture plays a dual role: on the one hand, it reduces the volume of pore space suitable for filtering free water and gas, and on the other hand, together with free water, it determines the phase permeability for the gas and liquid phases.

Permeability to gas in sandstones becomes zero when about 90% of the pore space is occupied by liquid. On the other hand, in order to completely stop the movement of liquid in sandstones, in most cases it is enough for 40–50 % of the pore space to be occupied by gas. Consequently, with this or a greater degree of pore filling with gas, the role of the gas factor increases significantly. Exactly within these limits, we can observe the ratio of the degree of pore filling with gas and moisture in outburst-prone sandstones. The maximum currently recorded degree of pore filling with moisture in outburst-prone sandstones of Donbas is about 46%, that is, the degree of pore filling with gas in outburst-prone sandstones is 54 percent or more (Bulat and Bezruchko, 2015). Consequently, the moisture content of rocks also has a very significant impact on the gas factor, and consequently, the degree of outburst hazard of rocks. Based on the connection between the gas content and strength properties of rocks and humidity, we can conclude that humidity plays a significant role in the formation of the properties of a gas-saturated rock massif, largely defining two of the three main natural factors that determine the occurrence of rock and gas outbursts.

The third main natural factor causing the occurrence of rock and gas outbursts is the stressed state of the rock massif. The combined impact of depth, tectonic forces, and the heterogeneity of the structure of fields leads to a complex stressed state of the rock massif. Vertical stresses increase with depth but are very sensitive to geological structures. Horizontal stresses are very variable and are also related to the structure of the field. As the depth increases, the pressure of the gas filling the free pore space of rocks also increases. One way or another, the impact of the occurrence depth of rocks on their outburst hazard is a proven fact and the depth should be considered in cases where there is no more reliable way to assess the stress state of the rock massif. The purpose of the paper is to research the sandstone moisture impact on the occurrence of rock and gas outbursts and substantiate predictive criteria for outburst hazards based on natural moisture indicators.

2. Methodology

Analysis of lithologic-and-facies conditions for the accumulation of coal-bearing strata, laboratory research of the physical and reservoir properties of rocks, determination of the mineralogical composition and petrographic characteristics by optical spectroscopy, probabilistic and statistical processing of experimental research results.

3. Characteristics of the Research Object

The object of research is the outburst-prone sandstones of the Lower and Middle Carboniferous age of the coal-bearing strata of Donbas in Ukraine. Sandstones occur in zones of middle and late catagenesis, within the distribution of gas, fatty and coking coals. All outbursts occur significantly deeper than the upper boundary of the methane gas zone; the mines in which they are noted are classified as supercategory for methane. The gas released during outbursts is predominantly represented by methane – it is more than 80%. The thickness of the beds in outburst-prone sandstones varies within a very wide range from 2.6 to 70.0 m, however, the outbursts are confined to individual layers of outburst-prone sandstones (Bulat and Bezruchko, 2015).

According to their genesis, these are channel sandstones, sandstones of underwater river drifts, coastal-marine sandstones, and lithogenic types transitional between them. Channel sandstones (Fig. 1) lie in sharp contact with erosion on underlying sediments of various origins. The formation of the described sandstones occurred within riverbeds below the water level. Sandstones of underwater river drifts (Fig. 2) lie with erosion on various facies types of rocks or gradually transform into channel sandstones. Their formation occurred under the predominant impact of river flows and the impact of coastal currents and waves. Under coastal-marine sandstones (Fig. 3) it is necessary to understand the sediments of the surf zone in the shallow part of the sea basin. The described sandstone in the section, as a rule, completes the sequence of mudstones and fine-grained siltstones deposited in the conditions of the deep and shallow parts of the sea basin.

According to their petrographic composition, they consist of quartz, feldspars, carbonates, micaceous and clay minerals, and accessory minerals. The main characteristics of the studied sandstones are given in Table 1. The sorting coefficient is the ratio of the third quartile to the first quartile of the cumulative particle size distribution plot. The quartz content is indicated as the total content of detrital quartz, which significantly predominates, and regenerated quartz. In terms of their properties, the most dangerous in terms of outbursts in the Donbas are channel sandstones. However, according to statistics, the largest number of outbursts occurs in sandstones of underwater river drifts, since this is the most common type of sandstone. Their share is up to 30% of the suite thickness of coal-bearing sediments in the Carboniferous period.

4. Results and Discussions

4.1. Impact of Natural Humidity of Sandstones and their Stratification Depth on Outburst Hazard

Based on the fact that modern depth is one of the factors that determine the stressed state of a rock massif and the gas pressure in it, and therefore influences the occurrence of sudden rocks and gas outbursts, it is of interest to research the natural moisture content of outburst-prone sandstones located at various depths. The minimum depth of outbursts recorded in Donbas is 677 m (Bulat and Bezruchko, 2015).

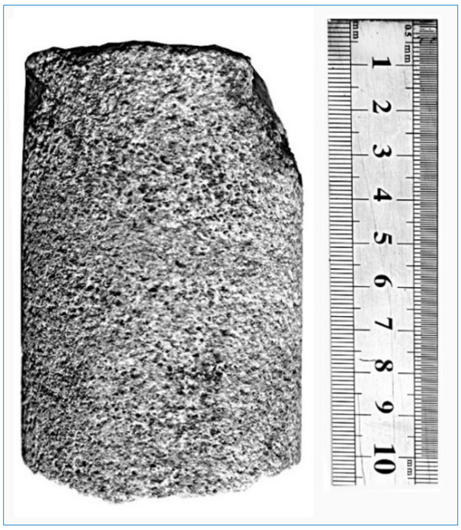

Fig. 1. Channel sandstone

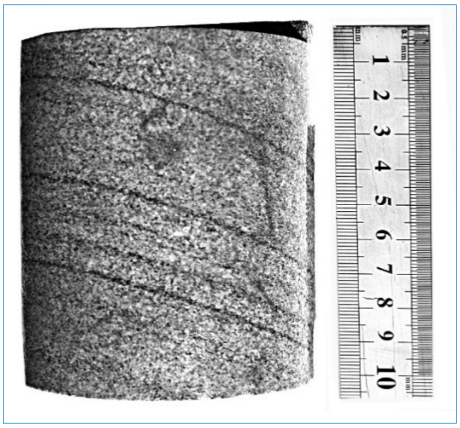

Fig. 2. Sandstone of underwater river drifts

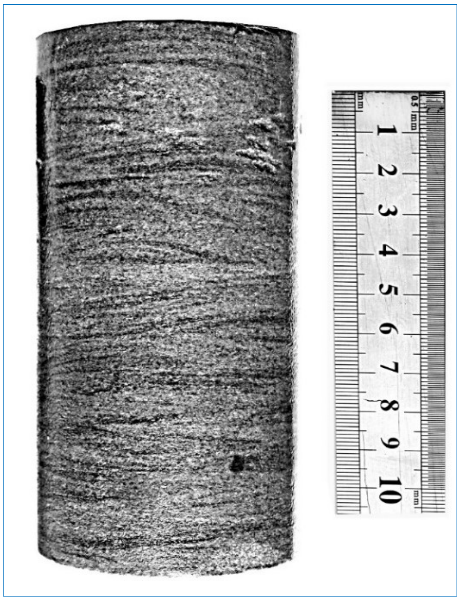

Fig. 3. Coastal-marine sandstone

The author carried out the analysis of samples of outburst-prone sandstones taken from rock and gas outburst sites in 5 coal mines in a wide range of depths from 700 to 1200 m. A total of 225 determinations of bulk density, porosity and natural moisture of outburst-prone sandstones were made. When comparing the degree of pore filling with moisture in outburst-prone sandstones with the depth of rock occurrence, attention is drawn to the fact that shallow mining depths, where rock and gas outbursts occur, are characterized by lower relative humidity values. Samples taken from outburst sites at great depths are characterized by increased values of the degree of pore filling with moisture (Fig. 4).

Table 1. Main characteristics of the researched sandstones

Indicators	Quantitative values		
	Minimal	Maximum	Average
Bulk density, g/cm^3	2.42	2.58	2.50
Density of the solid component, g/cm^3	2.66	2.75	2.70
Open porosity factror, %	3.3	11.0	7.0
Sorting coefficient, dimensionless	1.42	3.21	1.86
Grain size, mm	0.13	0.46	0.22
Quartz content, %	57.0	86.2	68.5
Carbonate content, %	0.0	9.0	2.3
Feldspar content, %	3.4	18.7	8.8
Content of rock fragments, %	1.49	7.53	4.17
Content of mica-clay minerals, %	0.0	21.9	15.3
Weight moisture indicator, %	0.2	1.2	0.6
The degree of pore filling with moisture (moisture saturation), %	5.0	46.0	24.0

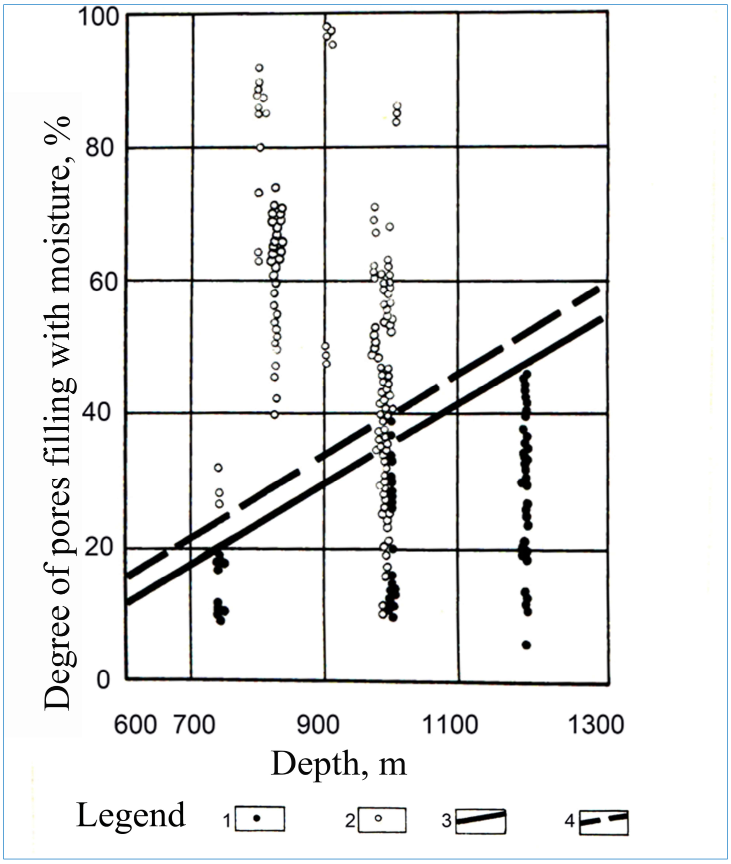

Fig. 4. The values field of relative humidity for samples of outburst-prone and non-outburst-prone sandstones: 1 – samples of outburst-prone sandstones; 2 – samples of non-outburst-prone sandstones; 3 – dependence of the maximum values of the degree of pore filling with moisture on the depth of rock and gas outbursts; 4 – upper confidence interval of the dependency at 5 % significance level

Consequently, with increasing depth, the critical values of the degree of pore filling with moisture naturally increase, at which rocks, and gas outbursts are still possible. That is, with increasing depth of occurrence, more and more moisture-saturated rocks become outburst-prone, or, similarly, with increasing depth of occurrence, less gas-saturated rocks become outburst-prone. The distribution area for samples of outburst-prone sandstones is the lower right part of the dependence graph of critical values of the degree of pore filling with moisture on absolute depth, and the distribution area for non-outburst-prone sandstones is the upper left part (Fig. 4).

To obtain a quantitative relationship characterizing the identified pattern, in each depth interval the maximum values of the degree of pore filling with moisture were selected and a correlation and regression analysis of the relative humidity values at which rock and gas outbursts still occur was carried out, with the corresponding depths of their occurrence.

The linear correlation coefficient characterizing the dependence of the maximum (critical) values of the degree of pore filling of outburst-prone sandstones with moisture (outbursts in more moisture-saturated rocks for these depths have not been recorded) on the depth of occurrence of rock and gas outbursts is 0.98. The reliability of the correlation factor is 73.7. This dependence is approximated by a straight line (Fig. 4):

$$G_{cv} = 0.061 \cdot H - 25.9 \quad (1)$$

where G_{cv} is critical value of the degree of pore filling with moisture for absolute depth H.

The resulting dependence allows us to determine the minimum depth at which rock and gas outbursts are possible. Extrapolating the obtained dependence to the region of shallow depths, we can assume that in absolutely dry rocks (the pore filling degree with moisture is 0) and completely gas-saturated rocks, outbursts can occur from a depth of 425 meters. However, if we take into account that absolutely dry rocks are practically never found, and the minimum values of the pore filling degree with moisture in Donbas sandstones are rarely less than 3-5%, a depth of 490-505 m should be taken as the minimum depth of possible outbursts for the Donetsk Basin.

The extrapolation method can also be used to obtain depths at which completely moisture-saturated sandstones should be considered outburst-prone, provided that when the degree of pore filling with moisture is equal to 100 %, outbursts are generally possible. These depths are 2060–2065 meters. However, the assumption that completely moisture-saturated rocks can be outburst-prone seems unlikely. Permeability to gas in sands and sandstones becomes zero when 90 % of the pore space is occupied by liquid. Consequently, with this or a greater degree of filling of the pores with moisture, the gas factor necessary for the occurrence of an outburst is absent. Thus, a value of 90 % can be considered as the maximum critical value for relative humidity. In this case, the calculated depth takes the value of 1900 meters.

The dependence of the maximum values of the degree of pore filling with moisture, at which outbursts can still occur, on the depth of rock and gas outbursts can be used to determine the outburst hazard of rocks. In order to exclude errors of the first type when predicting outburst hazard (erroneous classification of outburst-prone rocks as non-outburst-prone ones), the upper confidence interval of the obtained dependence should be taken as the separating area of outburst-prone and non-outburst-prone rocks. For a selected depth, the expected value can be estimated using an upper confidence interval. For modern development depths, with a confidence probability of 95 % (Fig. 4), the separating equation will take the form:

$$G = 0.061H - 21.3 \quad (2)$$

To determine the outburst hazard during sampling, it is necessary to determine the stratification depth of the rocks. Using the formula (2), the critical value for a given depth of the degree of filling of pore with moisture is calculated, with which the actual value of this indicator, determined from the selected samples, is compared. When the actual degree of pore filling with moisture is equal to or less than the calculated critical value, the rock should be considered outburst-prone, and when the degree of pore filling with moisture is greater than the critical value, the rock should be considered non-outburst-prone.

4.2. Researching the Impact of Natural Moisture and Reservoir Properties of Sandstones on Outburst Hazard

The most important characteristics of rocks as reservoirs of natural gases in coal fields are porosity and gas permeability. They determine the capacity of rocks and their filtering ability and are the initial parameters for solving problems related to the distribution of gases in an undisturbed massif, their secular migration, gas release into mine workings, degassing, and the outburst hazard of coal beds and rocks.

The gas capacity properties of rocks determine not only their porosity but also their moisture content. Therefore, in accordance with the above, the task was set to research the combined impact of porosity and moisture on the outburst hazard of rocks, and on this basis to propose new predictive indicators of outburst hazard.

A study was carried out on the joint effect of open porosity rocks and weight moisture on the outburst hazard. For this purpose, an analysis of samples taken from the sites of rock and gas outbursts in 5 mines was carried out. A total of 150 determinations of natural moisture and open porosity were performed.

When analyzing outburst-prone samples, a tendency for the weight moisture indicator to increase with an increase in the open porosity factor was noted (Fig. 5). A correlation-regression analysis was carried out of the maximum values for the gravimetric moisture indicator at which outbursts can still occur (outburst-prone rocks with a large value of the weight moisture indicator for a given porosity have not been established) and the corresponding to them values of the open porosity factor.

Correlation and regression analysis made it possible to identify the dependence of the maximum (critical) values of the weight moisture indicator on the open porosity factor, the graph of which separates the areas of predominant distribution of samples of outburst-prone and non-outburst-prone sandstones. The linear correlation coefficient is 0.95; the reliability of the correlation coefficient is 44.2. The revealed dependence is approximated by a straight line (Fig. 5):

$$W = 0.14\ K \quad (3)$$

where W is a weight moisture indicator and K is an open porosity factor.

The empirical coefficient of 0.14 is the slope of the straight line characterizing the dependence of the weight moisture on the open porosity of the outburst-prone sandstones and is the ratio of the weight moisture to the open porosity factor. Samples of outburst-prone sandstones are confined to the lower right part of the distribution field for the values of the open porosity factor and the weight moisture indicator (Fig. 5) and are characterized by low values of the weight moisture/open porosity ratio. Non-outburst-prone sandstones, on the contrary, are characterized by increased values of this ratio and are predominantly located in the upper left part of the distribution field of the values of the open porosity factor and the weight moisture indicator (Fig. 5). The average values of the ratio between weight moisture and open porosity (Table 2) of non-outburst-prone sandstones (0.2043) are twice the value of this indicator for outburst-prone sandstones (0.1006).

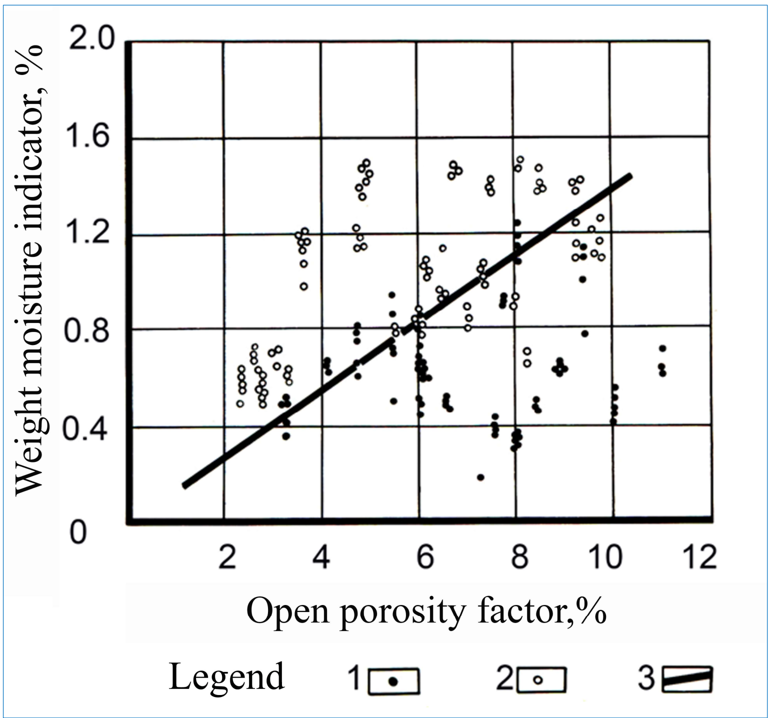

Fig. 5. Values distribution field of the open porosity factor and the weight moisture indicator for samples of outburst-prone and non-outburst-prone sandstones: 1 – samples of outburst-prone sandstones; 2 – samples of non-outburst-prone sandstones; 3 – approximating straight line

Table 2. Statistical characteristics of the weight moisture-open porosity indicator for outburst-prone and non-outburst-prone sandstones

Characteristics of sandstones	Sample volume	Average value of weight moisture/open porosity ratio	Dispersion	Standard deviation	Skewness	Kurtosis
outburst-prone	75	0.1006	$1.753x10^{-3}$	0.04	$7.821x10^{-2}$	-1.285
non-outburst-prone	178	0.2043	$6.010x10^{-3}$	0.08	$3.702x10^{-1}$	$3.904x10^{-2}$

The difference in the average values of the weight moisture-open porosity ratio between outburst-prone and non-outburst-prone sandstones was tested by comparing sampling means using the Student's t-test. First, the compliance of the experimental distribution of sample populations with the law of normal distribution was checked. For this purpose, sample estimates of the coefficients of skewness and kurtosis were calculated.

The results of statistical processing of both sample populations indicate the homogeneity of each sample; the experimental distribution in all cases does not contradict the law of normal distribution, since the estimates of the coefficients of skewness and kurtosis are quite small (Table 2). Therefore, assessing the significance of the difference between sample populations using the Student's t-test is legitimate.

The difference in the average values of the weight moisture-open porosity ratio of outburst-prone and non-outburst-prone sandstones, estimated by Student's t-test, is significant. The Student's t-test value is 11.25. It can be concluded that the weight moisture-open porosity ratio is a fairly reliable predictive criterion for assessing the outburst hazard of rocks. The proposed criteria were applied to predict the outburst hazard of sandstones in preparatory mine workings. In order to check the reliability and validity of determining the outburst hazard of rocks, a comparison of predicted data with the actual outburst hazard was carried out. The prediction was carried out in the mine workings of 14 coal mines.

Geographically, the mines are located in the western, central and eastern parts of the Donetsk basin, and are characterized by different mining and geological conditions for the development of coal beds. In the process of determining the outburst hazard of rocks based on an assessment of their moisture content, neither errors of the first type (erroneous classification of outburst-prone rocks as non-outburst-prone ones) nor errors of the second type (erroneous classification of non-outburst-prone rocks as outburst-prone ones) were detected. Taking into account the fulfilled prediction, more than 10,000 m of preparatory workings were covered.

5. Conclusion

It has been established that for shallow depths of coal minings, where rock and gas outbursts occur, lower values of relative humidity (the degree of pore filling with moisture) are characteristic. With increasing depth, the critical values of the degree of pore filling with moisture, at which outbursts of rocks and gas are still possible, naturally increase (according to a linear dependence). Consequently, with increasing depth of occurrence, more and more moisture-saturated rocks become outburst-prone, or, similarly, with increasing depth of occurrence, less gas-saturated rocks become outburst-prone. The obtained dependence served as the basis for assessing the outburst hazard of rocks, which comprehensively took into account the water and gas saturation of sandstones and the depth of their occurrence.

For outburst-prone and non-outburst-prone sandstones, a significant difference in the average values of the weight moisture-open porosity ratio is also found, which served as the basis for predicting the outburst hazard of rocks using this criterion.

Testing the use of methods for determining the outburst hazard of rocks, with regards to the natural moisture of sandstones in Donbas mines, fully confirmed their reliability, validity, and the possibility of practical application.

In the context of research and findings, the assessment of the outburst hazard of rocks, considering their moisture content and the experience of conducting mining operations on outburst-prone rocks in various coal basins of the world is of scientific interest. The dialogue on this issue can undoubtedly be useful for all interested parties.

Conflicts of Interest

The authors hereby state that they do not have any conflict of interest.

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