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# IMPACT OF MOISTURE ON THE PHYSICAL-MECHANICAL PROPERTIES OF DONBAS SANDSTONES

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**Abstract**. Ensuring the sustainable operation of the mining industry, in particular the coal and oil-gas industry, is connected with the prediction and research of natural and technogenic geomechanical processes occurring in rock massifs, which in turn involves the research and prediction of physical and mechanical properties of rocks and rock massifs in general. Given the well-known fact concerning the impact of rock moisture on their strength properties, it is necessary and relevant to determine the regularities of this impact on the formation of the properties of rocks and rock massifs as a whole. **The purpose** of the paper is to research the impact of the moisture content of sandstones in the coal-bearing strata on their physical and mechanical properties and to establish the regularities in the formation of their strength and elastic properties. Sandstones of the Lower and Middle Carboniferous age of the coal-bearing strata of the Donbas in the Central, Donetsk-Makiivskyi, and Pokrovskyi (formerly Krasnoarmiiskyi) geological and industrial districts were the object of the research. Sandstones lie in the zones of middle and late catagenesis, within the distribution of gas, fatty, and coking coal, which corresponds to the stages of $MK_2$–$MK_4$ mesocatagenesis. As a result in determining the impact of the moisture content of sandstones in the coal-bearing strata on their physical and mechanical properties, the presence of the impact of the sandstone compaction degree and moisture on their strength properties was confirmed, namely on their ultimate compression strength. The most significant relationships are based on the results of pairwise correlation for pairs of indicators: compression strength - open porosity ratio, and compression strength – mass moisture. According to the results of multiple correlations, the impact of moisture and open porosity on the ultimate compressive strength of sandstones has been proven with fairly high correlation coefficients of 0.81–0.82. Appropriate models reflecting this connection as much as possible are proposed. This is a cubic, mixed, and adaptive piecewise-linear model MARS. The established regularities of connection between the indicators of the physical and mechanical properties of rocks and the quantitative moisture content will make it possible to successfully simulate the geomechanical processes occurring in the geological environment to predict the mining and geological conditions in working out of coal deposits.

**Keywords**: Donbas, sandstones, moisture, strength properties.

## 1. Introduction

Ensuring the sustainable operation of the mining industry is connected with the prediction and research of natural and technogenic geomechanical processes occurring in rock massifs. In particular, for the coal industry, this is the support of effective and safe coal mining at productive mines, preparation of planned mines for conservation or liquidation, and the closure of mines.

Operating mines, planned to be decommissioned last, should work with mines that were closed earlier or are being closed. The closure of mines means decommissioning the drainage system and flooding its mine workings and surrounding rocks with the natural water influx [1]. Significant water reservoirs are formed in closed mines, and water can be used as a carrier of thermal or mechanical energy. The above-water spaces of reservoirs created in mine workings are also reservoirs of mine gases, most often methane, pushed by the groundwater level to the Earth's surface [1]. The closure of mines, due to the restriction of access to previously developed parts of the deposits is associated with the closure of the drainage system or the introduction of a shift, or restrictions in scale. After all, such measures are associated with an increase in the water level and their possible complete flooding.

An increase in the water saturation of the mine workings, caused by a change or closure of the drainage system, affects the water saturation conditions in the surrounding rock massif. Each new hydrodynamic state associated with the mine workings of a closed mine inevitably changes the geomechanical properties of the rock environment, which is of crucial importance for the coexistence of water bodies in the produced spaces (this should be considered as a potential source of water supply for geothermal systems) and for conducting underground mining operations in their outskirts [1].

For the oil and gas industry, the simulation of geomechanical processes occurring in coal-gas and gas fields around working or degassing wells during their development also involves researching the stress-strain state of the rock massif and the water and gas filtration process [2]. To simulate the work of wells during their operation, among other things, it is necessary to specify the parameters of the physical and mechanical properties of rocks for calculations.

In the absence of data on the physical and mechanical properties of exact rock layers, they can be estimated based on the known correlation dependences of the sought indicators with other known available parameters. In addition, the very sampling of rocks in mine workings or from wells and subsequent laboratory studies to determine physical and mechanical properties can be linked with significant material and time costs. Therefore, understanding the regularities of the relationship between the main indicators of physical and mechanical properties, in particular with the quantitative content of moisture, will allow us to successfully simulate geomechanical processes occurring in the geological environment.

Changes in the geomechanical properties of rocks under the action of water differ depending on the age of the rocks, their type, physical properties (especially porosity and density), petrographic structure and depth of occurrence.

Under certain mining conditions, understanding these changes is relevant for the mining industry, necessary for public and general safety, exploitation of mining operations, and decommissioning of mines, as well as for facilitating the drainage of rock massifs. [1].

The purpose of the research is to determine the impact of moisture content of rocks in coal-bearing strata on their physical and mechanical properties and establish regularities in the formation of their strength and elastic properties.

The object of research is the physical and mechanical properties of Donbas sandstones in the middle and late catagenesis zones.

## 2. Methods

We used laboratory methods in studying physical and mechanical properties of rocks, methods of optical spectroscopy, methods of probabilistic and statistical processing of experimental data. In the course of research, the following characteristics were determined: mass moisture, water saturation (the degree of pores filling with moisture), bulk density, density of the solid constituent, open porosity ratio, ultimate compression strength, and Young's modulus. The rest of the involved indicators were determined by calculation.

**3. The theoretical part**

The physical and mechanical properties of rocks are determined by the lithological and petrographic features of rocks (conditions of sedimentation and material composition, the degree of post-diagenetic changes), the depth of their pre-inversion immersion, ancient tectonic processes, the presence of residual tectonic stresses and modern conditions. The current depth of occurrence and hydrogeological conditions, particularly water and gas saturation, should be understood as modern conditions of occurrence.

The given information about the impact of various natural factors on the strength properties of sandstones fully applies to their elastic properties. Both with an increase in the degree of metamorphism and an increase in the current depth of sedimentary rocks, the propagation speed of elastic oscillations and the dynamic Young's modulus increase.

Moisture is one of the main factors affecting the strength of rocks [3]. The strength properties of undisturbed sandstones are determined by the degree of their post-diagenetic changes and their natural moisture (water saturation). With a decrease in porosity and moisture, the strength properties of rocks increase.

Many works are devoted to the issue of the moisture content impact on the strength properties of mining rocks. Pore fluids have been proven to affect rocks' physical and mechanical properties, particularly strength and plasticity [4–9].

An increase in the moisture content of rocks is accompanied by a significant decrease in their strength. Thus, the strength of many low-porous rocks under uniaxial compression in a water-saturated state is often only 45% of its value in the same material dried at high temperatures [10–11]. It has been established that with an increase in the weight moisture index up to 2.5%, the strength of outburst-prone sandstones at coal mines of the Donetsk-Makiiv geological and industrial district of Donbas decreases by 73–80%, and of outburst-prone sandstones at the same mines – by 43–70% [12].

A similar effect of water can be explained based on the obtained data by E. Rutter [13–15]. This researcher compared the test results of the same samples in a water-saturated state and dried at high temperatures. When testing wet samples, the ratio of the pore fluid pressure to the overall pressure varied from zero to one. The effect of reducing the strength of rocks under the effect of water, as can be seen, is extremely sharp.

Thus, water significantly affects the physical and mechanical properties of rocks. It is worth noting that moisture determines not only the physical and mechanical properties of coal beds and rocks but also the properties of the rock massif in general [1,12].

Characteristics of the research object. The Lower and Middle Carboniferous age sandstones in the coal-bearing strata of the Central, Donetsk-Makiivskyi, and Pokrovskyi (former Krasnoarmiiskyi) geological and industrial districts of the Donbas were the object of the research. Sandstones lie in the zones of middle and late catagenesis, within the distribution of gas, fatty, and coking coal, which corresponds to the stages of $MC_2$–$MC_4$ mesocatagenesis.

The main characteristics of the properties and material composition of the researched sandstones are given in Table 1.

Table 1 – Main characteristics of the researched sandstones

| Indicators | Quantitative values | | |
|---|---|---|---|
| | minimum | maximum | average |
| Bulk density, $g/cm^3$ | 2.42 | 2.58 | 2.50 |
| The density of the solid constituent, $g/cm^3$ | 2.66 | 2.75 | 2.70 |
| Open porosity ratio, % | 3.11 | 14.30 | 8.31 |
| Sorting factor, dimensionless (d/l) | 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 |
| Mass moisture, % | 0.06 | 2.71 | 1.00 |
| Degree of pores filling with moisture (water saturation), % | 2.27 | 88.0 | 29.6 |

## 3. Results and discussion

The conversion degree of sandstones in the process of post-diagenetic changes is quantitatively characterized by such indicators as the open porosity ratio and the compaction factor.

The compaction factor is the ratio of the bulk density to the density of the solid constituent of the rock. The variation range of the compaction factor in general for Donbas sandstones is from 0.6 in the development zone of coal of low-staged metamorphism, and almost to 1.0 in the development zone of highly metamorphosed coal. The averaged quantitative indicators for the degree of post-diagenetic changes for different groups of metamorphism of Donbas sandstones are given in Table 2.

Natural moisture is characterized by two indicators – mass moisture (absolute) and the degree of pores filling with moisture or water saturation (so-called relative moisture).

The main numerical characteristics of the researched indicators are given in Table 3.

Table 2 – Average quantitative indicators of the degree of post-diagenetic changes for different groups of metamorphism in Donbas sandstones

| Group of metamorphism | Bulk density, $10^3$ $kg/m^3$ | Density of the solid phase, $10^3$ $kg/m^3$ | Open porosity ratio, % | Compaction factor, d/l |
|---|---|---|---|---|
| LF | 2.36 | 2.63 | 11.9 | 0.897 |
| G | 2.42 | 2.66 | 10.9 | 0.910 |
| F | 2.55 | 2.68 | 5.6 | 0.951 |
| C | 2.58 | 2.68 | 3.8 | 0.962 |
| ML | 2.60 | 2.70 | 3.6 | 0.962 |
| L | 2.60 | 2.70 | 3.0 | 0.962 |

Table 3 – The main numerical characteristics of indicators for sandstone properties

| Indicators (samples quantity) | Indicator value min.-max. / average | Dispersion | Root-mean-square deviation | Coefficient of variation | Coefficient of asymmetry | Kurtosis |
|---|---|---|---|---|---|---|
| Mass moisture, % (170) | 0.06-2.71 / 1.00 | 0.313 | 0.561 | 55.96 | 0.27 | -0.470 |
| Degree of pores filling with moisture, % (131) | 2.27-88.00 / 29.56 | 377.08 | 19.49 | 65.92 | 0.47 | -0.437 |
| Compaction factor, d/l (170) | 0.82-0.97 / 0.91 | 0.001 | 0.024 | 2.70 | 0.04 | 0.503 |
| Ultimate compression strength, kgf/sm$^2$ (108) | 384-1758 / 902 | 49241.8 | 221.91 | 24.60 | 1.044 | 2.895 |
| Open porosity ratio, % (133) | 3.11-14.30 / 8.31 | 3.60 | 1.905 | 22.93 | 0.01 | 0.582 |

A statistical analysis was carried out based on the obtained indicators of physical and mechanical properties. Mathematical processing of research results included determining the main statistical characteristics of random variables, testing the hypothesis regarding normal distribution, correlation, and regression analysis, and checking, if necessary, the homogeneity of two sample populations.

The determination of the main statistical characteristics consisted of estimating the average value, dispersions, root-mean-square deviation, variability index, coefficient of asymmetry, and kurtosis and was carried out according to the methods outlined in works [16–18].

As a criterion for checking the agreement of the experimental distribution with the theoretically predicted normal distribution, sample estimates of the asymmetry and kurtosis coefficients were used. The distribution was considered not contrary to normal if the ratios of the asymmetry and kurtosis coefficients to their standard errors were small enough.

The correlation-regression analysis included the determination of the linear correlation coefficient, the root-mean-square deviation of the correlation coefficient, the reliability coefficient of the correlation coefficient, the significance of linear and non-linear dependence, the significance of the difference between non-linear and linear dependence. The significance of linear (non-linear) dependence was checked under the assumption that the linear correlation coefficient (or correlation ratio) is not equal to zero. The essence of the difference between a nonlinear relationship and a linear one was assessed by the linearity index, which is the difference between the squares of the correlation ratio and the linear correlation coefficient. The optimal equation of constraints was chosen based on the minimum value of the root-mean-square deviation of the empirical data from the theoretical curve calculated by the least square method. The correlation-regression analysis was carried out following the well-known methods given in the works [16–18].

Table 4 presents the results of the correlation-regression analysis of the data – the results of the pairwise correlation of the researched indicators. Both pairwise correlation coefficients and correlation ratios are not too significant. More or less satisfactory are the values of the obtained coefficients for a pair of indicators: open porosity ratio – compaction factor (-0.75 – feedback), Ultimate compression strength – open porosity ratio (-0.65 – feedback), and Ultimate compression strength – mass moisture (-0.52 also feedback). The resulting relationship equations, determined by the results of the regression analysis, both linear and non-linear, are shown in Table 5.

Table 4 – Results of correlation-regression analysis (pairwise correlation) for indicators of physico-mechanical properties for sandstones

| Indicators | Number of paired observa tions | Correlation coefficient | The root-mean-square deviation of the correlation coefficient | The reliability coefficient of the correlation coefficient | Correlation ratio |
|---|---|---|---|---|---|
| Degree of pores filling with moisture *(G)* – Compaction factor *(Fcom)* | 131 | 0.40 | 0.0736 | 5.39 | 0.44 |
| Absolute moisture (*W*) - compaction factor *(Fcom)* | 170 | 0.11 | 0.0758 | 1.45 | 0.22 |
| Ultimate compression strength ($\sigma_{com}$) - compaction factor *(Fcom)* | 95 | 0.50 | 0.0775 | 6.38 | 0.51 |
| Open porosity ratio ($n_o$) - compaction factor *(Fcom)* | 134 | -0.75 | 0.0384 | 19.39 | 0.75 |
| Degree of pores filling with moisture *(G)* - Open porosity ratio ($K_{op}$) | 131 | -0.44 | 0.0700 | 6.28 | 0.44 |
| Ultimate compression strength ($\sigma_{com}$) – mass moisture (*W*) | 108 | -0.52 | 0.0700 | 7.42 | 0.56 |
| Ultimate compression strength ($\sigma_{com}$) - Degree of pores filling with moisture *(G)* | 74 | -0.19 | 0.0737 | 2.59 | 0.27 |
| Ultimate compression strength ($\sigma_{com}$) - open porosity ratio ($K_{op}$) | 84 | -0.65 | 0.0630 | 10.31 | 0.69 |

Table 5 – Relationship equations determined by the results of correlation-regression analysis

| Indicators | Linear relation equation | Nonlinear relation equation |
|---|---|---|
| Degree of pores filling with moisture *(G)* – Compaction factor *(Fcom)* | $G = 288.37F_{com} - 233.23$ | $G = 74.209F_{com}^{1.116}$ |
| Mass moisture (*W*) – Compaction factor *(Fcom)* | $W = 2.48F_{com} - 1.258$ | $W = 1.4063F_{com}^{5.933}$ |
| Ultimate compression strength ($\sigma_{com}$) – Compaction factor *(Fcom)* | $\sigma_{com} = 4217.2F_{com} - 2956.7$ | $\sigma_{com} = 23172F_{com}^2 - 37850F_{com} + 16128$ |
| Open porosity ratio ($K_{op}$) – Compaction factor *(Fcom)* | $K_{op} = 56.82 - 53.32K_{com}$ | $K_{op} = 90.39F_{com}^2 - 217.7K_{op} + 131.49$ |
| Degree of pores filling with moisture *(G)* – Open porosity ratio ($K_{op}$) | $G = 68.64 - 4.752K_{op}$ | $G = 0.1545K_{op}^2 - 7.2496K_{op} + 78.24$ |
| Ultimate compression strength ($\sigma_{com}$) – Mass moisture (*W*) | $\sigma_{com} = 199.9W + 1111.5$ | $\sigma_{com} = 1125e^{-0.238W}$ |
| Ultimate compression strength ($\sigma_{com}$) – Degree of pore filling with moisture *(G)* | $\sigma_{com} = 993.28 - 2.403G$ | $\sigma_{com} = 5.555G - 0.1144G^{\cdot 2} + 895.88$ |
| Ultimate compression strength ($\sigma_{com}$) – Open porosity ratio ($K_{op}$) | $\sigma_{com} = 1630.6 - 87.592K_{op}$ | $\sigma_{com} = 11.446K_{op}^2 - 285.45K_{op} + 2441.4$ |

To identify a more significant relationship, a multiple regression of the researched indicators was conducted. Namely, the dependence of the Ultimate compression strength on moisture indicators and the degree of post-diagenetic changes. The obtained results made it possible to reveal to a greater extent the nature of the existing relationship between the sought indicators.

Linear, quadratic, cubic, mixed, and piecewise-linear models were used during the statistical analysis. The quality indicators of the researched statistical models are given in Table 6.

The obtained indicators of the correlation and determination coefficients of the models are sufficiently high. The cubic model (Fig. 1) has satisfactory predictive quality, but it is complex and therefore theoretically can give inadequate predictions for an independent test sample. The cubic model characterizes the dependence of the Ultimate compression strength on the open porosity ratio and mass moisture and has the form:

$$\sigma_{com} = 875.8K_{op} + 82.7K_{op}^2 - 2.6K_{op}^3 - 72.9W^2 + 4037.5\,.$$

The mixed linear model (Fig. 2) gives comparable results and is probably the most adequate. It characterizes the relationship between the Ultimate compression strength and the open porosity ratio and the complex indicator of water content, as the product of mass moisture and the degree of pores space filling with water ($W \cdot G$) and has the form:

$$\sigma_{com} = 319.2 - 255.4WG + \frac{5428.8}{K_{op}}.$$

Table 6 – Quality indicators of the researched statistical models

| Indicators | Types of models | | | | | |
|---|---|---|---|---|---|---|
| | Linear | Quadratic | Cubic | Hyperbolical | Mixed | Piecewise-linear |
| Correlation coefficient | 0.746327 | 0.795091 | 0.815531 | 0.803844 | 0.814917 | 0.820614 |
| Determination coefficient | 0.557005 | 0.63217 | 0.66509 | 0.646166 | 0.664089 | 0.6734 |
| Adjusted coefficient of determination | 0.544348 | 0.616177 | 0.64539 | 0.636056 | 0.654492 | 0.6542 |
| Significance level | 4.21E-13 | 5.56E-15 | 1.66E-15 | 1.61E-16 | 2.62E-17 | – |

The adaptive piecewise-linear model MARS (multivariate adaptive regression splines) [19] (Fig. 3) is more flexible and valuable because it indicates the position of the inflection lines, they are clearly visible on the graph ($W\ G$=28.6; 1/$K_{op}$=1.49).

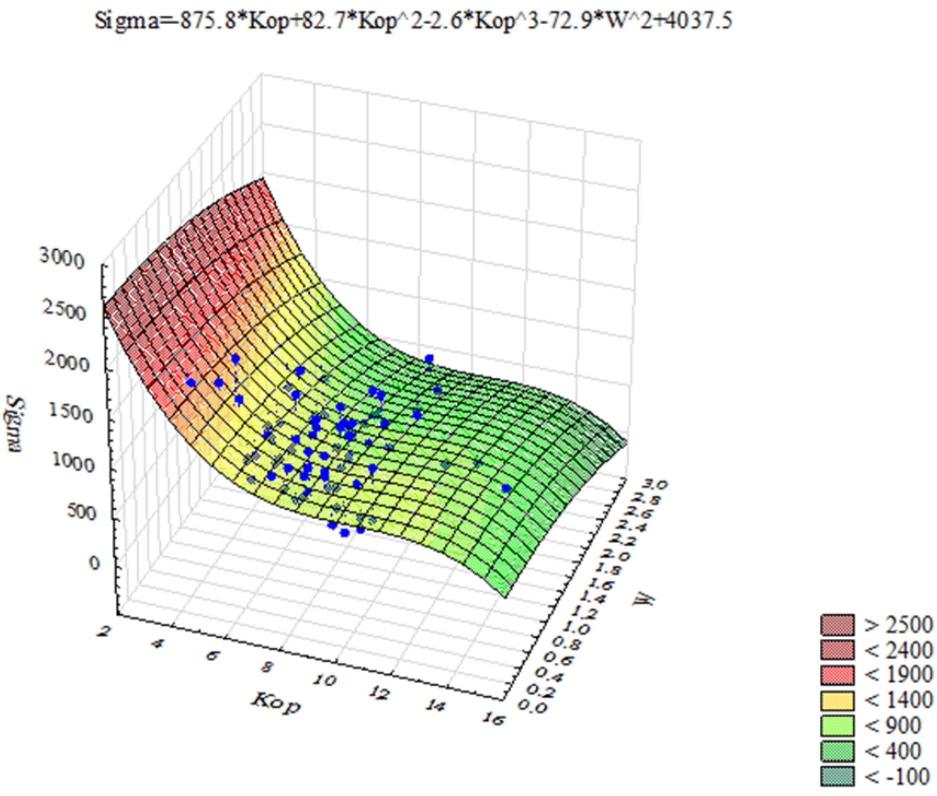


Figure 1 – The graph for the cubic model of the ultimate compression strength dependence on the open porosity ratio and mass moisture

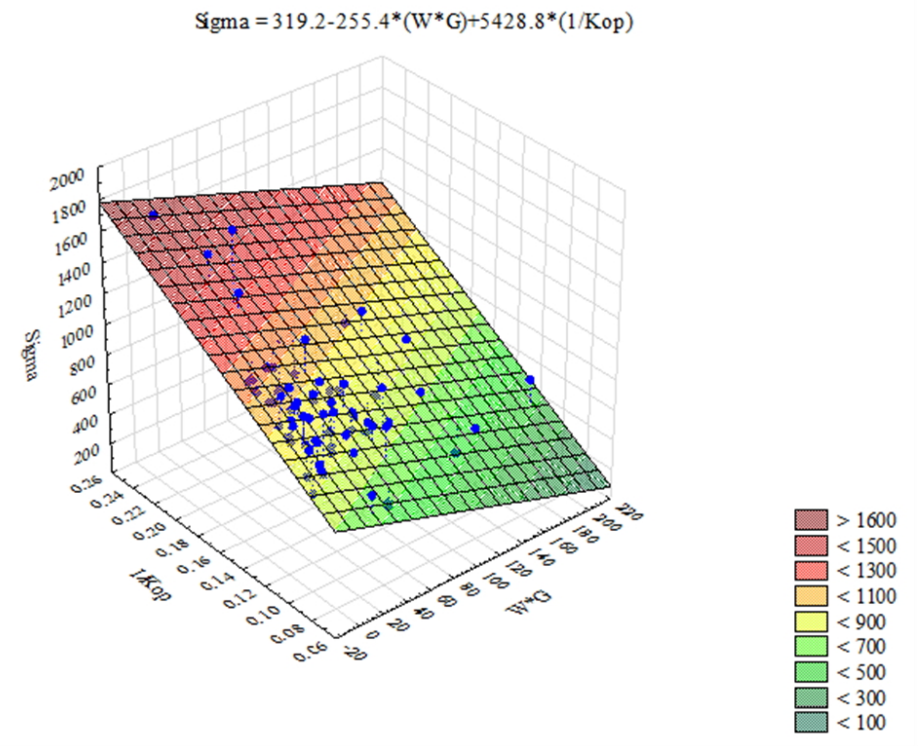


Figure 2 – The graph for the mixed model of the the ultimate compression strength dependence on the open porosity ratio and the product of mass moisture and the degree of pores filling with water

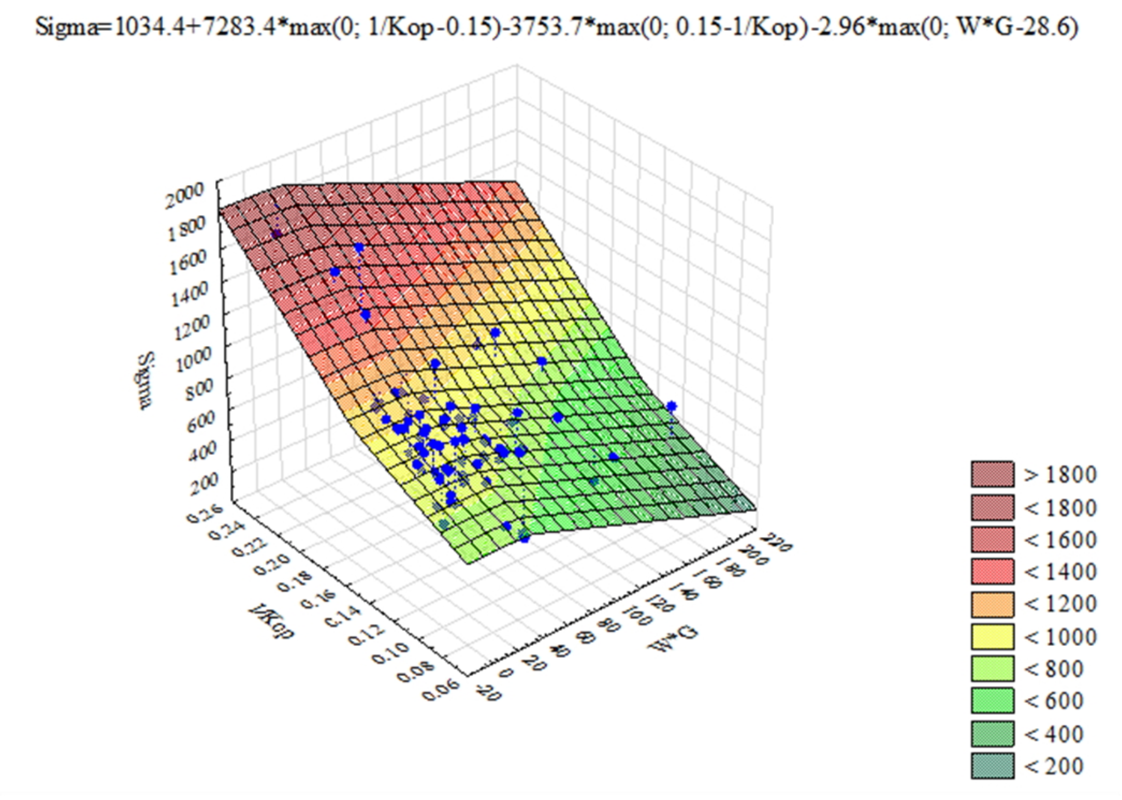


Figure 3 – The graph for the adaptive piecewise-linear MARS-model of the ultimate compression strength dependence on the open porosity ratio and the product of moisture and the degree of pores filling with water

## 4. Conclusions

As a result of determining the impact of the moisture content of sandstones in coal-bearing strata on their physical and mechanical properties and establishing the regularities in the formation of their strength and elastic properties, the presence of the impact of the sandstone compaction degree and moisture on their strength properties, namely on their ultimate compression strength, were confirmed. At the same time, the degree of compaction is characterized by the open porosity ratio and moisture – by mass moisture and the degree of pores filling with moisture.

The most significant are the connections based on the results of pairwise correlation for pairs of indicators:

– ultimate compression strength – open porosity ratio (correlation coefficient is -0.65 – feedback)

– ultimate compression strength – mass moisture (correlation coefficient is -0.52 also feedback).

According to the results of multiple correlations, the impact of moisture and open porosity on the ultimate compression strength of sandstones has been proven with fairly high correlation coefficients – 0.81 – 0.82. Appropriate models reflecting this relationship as much as possible are proposed. It is a cubic, mixed and adaptive piecewise-linear MARS model.

The cubic model characterizes the dependence of the ultimate compression strength on the open porosity ratio and mass moisture. The mixed linear model and the adaptive piecewise-linear MARS model characterize the relationship between the ultimate compression strength and the open porosity ratio and the complex indicator of water content, as a product of mass moisture and the degree of pore space filling with water.

The last two models prove the expediency of using (when determining the effect of moisture on the strength properties of rocks) the indicator of the degree of pores filling with moisture, that is, the degree of water saturation in addition to the mass moisture indicator.

The established regularities of the connection of indicators of physical and mechanical properties of rocks with quantitative moisture content will allow us to successfully simulate geomechanical processes occurring in the geological environment, aiming to predict the mining and geological conditions for mining the coal deposits. In the future, these models can be used to predict the strength properties of rocks for specific areas (mine fields or geological exploration sites).

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## ВПЛИВ ВОЛОГОСТІ НА ФІЗИКО-МЕХАНІЧНІ ВЛАСТИВОСТІ ПІСКОВИКІВ ДОНБАСУ

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**Анотація.** Забезпечення сталої роботи гірничо-добувної галузі, зокрема вугільної та нафто-газової пов’язано з прогнозом та дослідженням природних та техногенних геомеханічних процесів, що протікають в масивах гірських порід, що в свою чергу передбачає дослідження та прогноз фізико-механічних властивостей порід та гірських масивів в цілому. З огляду на відомий факт впливу вологості порід на їх міцнісні властивості необхідним та актуальним є визначення закономірностей цього впливу на формування властивостей порід та породних масивів в цілому. Мета роботы – дослідження впливу вмісту вологи пісковиків вугленосної товщі на їх фізико-механічні властивості та встановлення закономірностей формування їх міцнісних та пружних властивостей. Об’єктом досліджень були пісковики нижньо- та середньокам'яновугільного віку вугленосної товщі Донбасу Центрального, Донецько-Макіїївського та Покровського (колишнього Красноармійського) геолого-промислових районів. Пісковики залягають у зонах середнього та пізнього катагенезу, в межах поширення газового, жирного та коксового вугілля, що відповідає стадіям мезокатагенезу $МК_2$–$МК_4$. В результаті визначення впливу вмісту вологи пісковиків вугленосної товщі на їх фізико-механічні властивості, підтверджено наявність впливу ступеня ущільнення пісковиків та вологості на їх міцнісні властивості, а саме на їх межу міцності при стисканні. Найбільш значними є зв'язки за результатами парної кореляції для пар показників: межа міцності при стисканні – коефіцієнт відкритої пористості, межа міцності при стисканні – масова вологість. За результатами множинної кореляції доведено вплив вологості та відкритої пористості на межу міцності пісковиків при стисканні за досить високими показниками коефіцієнтів кореляції – 0.81–0.82. Запропоновані відповідні моделі, що якнайбільше віддзеркалюють цей зв'язок. Це кубічна, змішана та адаптивна кусково-лінійна модель MARS. Встановлені закономірності зв'язку показників фізико-механічних властивостей гірських порід з кількісним вмістом вологи, дозволять успішно моделювати геомеханічні процеси, що відбуваються у геологічному середовищі, з метою прогнозування гірничо-геологічних умов відпрацювання вугільних родовищ.

**Ключові слова:** Донбас, пісковики, вологість, міцнісні властивості.