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## About the connection of the total porosity of fossil coal with metamorphic transformations of coal seams

**Abstract.** Studying the porosity of minerals, in particular coal, and understanding the relationship between its structure and characteristics and properties is necessary for rationalising the use of coal, optimising processing processes, and finding new methods of combating sudden emissions or gas release. The goal was to establish the level of correspondence between the calculated values of the total porosity of coal (according to the empirical equation) and their experimental determination by standard methods, as well as to determine the indicators of the closeness of the correlation dependence of the total porosity on the degree of metamorphic transformations. The research methodology was based on the analysis of the comparison of the compliance of the calculated values of the total porosity for each separate coal seam according to the empirical equation with their values established by standard methods. The results indicated that the physical characteristics of coal, in particular density and porosity, change with the increase in the degree of metamorphism. The porosity of coal, the structure of its porous system and the specific surface determine the filtration, diffusion and sorption processes both in natural conditions of occurrence and during their changes under the influence of various physical and chemical factors. It has been proved that there is a practical absence of correlation between the total porosity of fossil coal and metamorphic transformations of coal seams when assessing the impact of these processes, taking into account the volatile substances yield. The total porosity is a unique characteristic of a particular coal seam within a mine field and is only partially determined by the volatile content. The averaged empirical dependencies on the volatile matter yield provide only a general idea of the trends in coal porosity during metamorphic transformations of coal seams. The results of the experiments make it possible to develop proposals for improving the regulatory

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framework for predicting the manifestation of dangerous properties of coal seams during mining operations. The facts revealed in the research can be used in regulatory documents to predict the dangerous properties of coal seams, as they allow the development of proposals and methods for improving the regulatory framework for safe mining operations. This will lead to a decrease in the level of accidents with serious consequences, industrial injuries at coal mining enterprises

● **Keywords:** coal seam; dangerous properties; coalification; labour protection

## ● Introduction

The issue of coal porosity and related phenomena is of great practical importance, as it relates to the problems of gas capacity and gas carrying capacity of coal seams, the solution of which would make it possible to predict and manage the release of gases in mining operations. Management of gas release directly depends on the content of methane in mining products, the amount of which can be contained under certain conditions in fossil coal, is closely related to the structure of the coal substance. Porosity defines the physical properties of the rock, its overall strength, rate of propagation of elastic waves, compressibility, electrical and other characteristics.

Scientists T. Wang *et al.* (2023) emphasised in their work that the pore-related characteristics of coal include porosity, specific surface area, pore volume, pore size distribution and their relationship. Studying the porous structure of various fossil coals and establishing its relationship with other characteristics or features of coal, their properties is necessary for the rational use of coal, optimisation of their processing processes, and also, as noted by O. Bazaluk *et al.* (2024), to develop effective methods for suppressing hazardous emissions in coal or preventing emissions.

The nature of the hazardous properties of coal seams, namely the release of explosive gas and dust, unexpected gas and coal emissions, spontaneous combustion of coal, explosiveness of coal dust and other undesirable phenomena, has not been fully disclosed by 2024, therefore, ignoring occupational safety, using outdated mining technologies and methods results in accidents with serious consequences for workers. The problem of injuries and accidents at enterprises has been considered by many scientists (Nosal *et al.*, 2021), and is still at a fairly high level. As noted by V. Tarasov *et al.* (2021), the problem of endogenous fires and explosions of methane-air mixtures, which lead to deaths, is of particular importance in coal mining. M. Onifade & B. Genc (2020) noted that a number of different methods have been applied to minimise these cases, but the problem still remains. Accordingly, scientific research aimed at solving these problems is relevant for all coal-mining countries of the world.

The aim of the work was to evaluate the strength of the correlation between total porosity and the degree of metamorphic changes in coal.

## ● Materials and Methods

All types of solid fuel have a porous structure. The actual sample density ( $d_r^d$ ) is always greater than the apparent density ( $d_a^r$ ). Their difference refers to the value of the actual density and is expressed as a percentage, which characterises the total porosity ( $P_r$ ) of the coal:

$$P_r = \frac{d_r^d - d_a^r}{d_r^d} \cdot 100. \quad (1)$$

According to the same dependence, the value of  $P_r$  was calculated for a set of 590 coal seams according to the catalogue of collector properties of hard coal and anthracite (Makiyivka State Research..., 1985). For this set of coal seams, the values of  $d_r^d$  and  $d_a^r$  were determined experimentally according to DSTU GOST No. 2160:2019 (2019) and ISO No. 5072:2021 (2021). For the second set of 186 coal seams, the values of  $P_r$  were calculated according to equation (1), but using the estimated values of  $d_r^d$  and  $d_a^r$  according to empirical dependencies. The catalogue (Makiyivka State Research..., 1985) does not provide indicators of the closeness of correlation for these dependencies. The total volume of pores  $P_{r(p)}$  in absolute terms for coal unloaded from rock pressure according to the catalogue (Makiyivka State Research..., 1985) was determined using the values of the actual ( $d_r^d$ ) and apparent ( $d_a^r$ ) densities according to equation (2):

$$P_{r(p)} = \frac{d_r^d - d_a^r}{d_r^d \cdot d_a^r}, \text{ cm}^3/\text{g}. \quad (2)$$

When determining  $P_{r(p)}$  according to equation (2) for a set of 590 coal seams, the experimental values of  $d_r^d$  and  $d_a^r$  were used, established in a standard way in accordance with the requirements specified by V. Tarasov *et al.* (2021). For the second set of 186 coal seams, their values were calculated according to empirical equations. In addition, the values of  $P'_{r(p)}$  were calculated in parallel to control the accuracy of calculations, according to empirical equation (3), depending on the yield of volatile substances during the thermal decomposition of coal in a vacuum ( $V^{\text{daf}}$ ):

$$P'_{r(p)} = 0.114 - 0.006V^{\text{daf}} + 0.00013(V^{\text{daf}})^2, \text{ cm}^3/\text{g}. \quad (3)$$

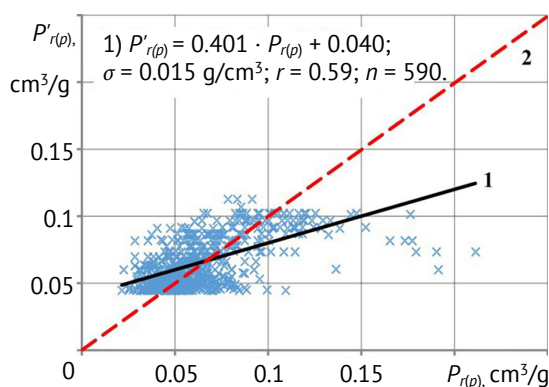
The degree of compliance of the calculated values of  $P_{r(p)}$  according to empirical equation (3) with their experimental determinations by standard methods was not established. For a long period of time,  $V^{\text{daf}}$  was the only indicator of metamorphic transformations

of seams when determining the consumer qualities of coal in accordance with the geological and coal-chemical map of the Donetsk basin (Donetsk State Coal Research Institute, 1954). It remains one of the main criteria in the modern classification of coal by genetic and technological parameters according to DSTU No. 3472:2015 (2015), and is also the main indicator of metamorphism in determining the susceptibility of coal seams to gas-dynamic phenomena (Order of the Ministry of Energy and Coal Industry of Ukraine No. 868, 2011). For these reasons, the  $V^{daf}$  indicator has been studied to a greater extent than other criteria, and its values are given in the catalogue (Makiyivka State Research..., 1985). This makes it possible, using the value of  $V^{daf}$ , to estimate the degree of influence of metamorphic transformations of the seams on changes in the total porosity of coal.

The methodology is based on a comparative analysis of the relationship between the calculated values of the total porosity  $P'_{r(p)}$  for each of the set of 590 coal seams according to empirical equation (3) and their value  $P_{r(p)}$ , determined by standard methods using equation (2). For the analysed set of 590 coal seams, the closeness of the correlation with the volatile yield  $V^{daf}$  was determined by statistical processing by the least squares method of the total porosity values calculated using the experimental values of the real ( $d_r^d$ ) and apparent ( $d_a^r$ ) densities according to equations (1) and (2).

### Results and Discussion

The graph comparing the calculated values of the total porosity  $P'_{r(p)}$  according to empirical equation (3) with their determination by standard methods  $P_{r(p)}$  according to equation (2) showed significant differences in the analysed ratios, as shown in Figure 1.

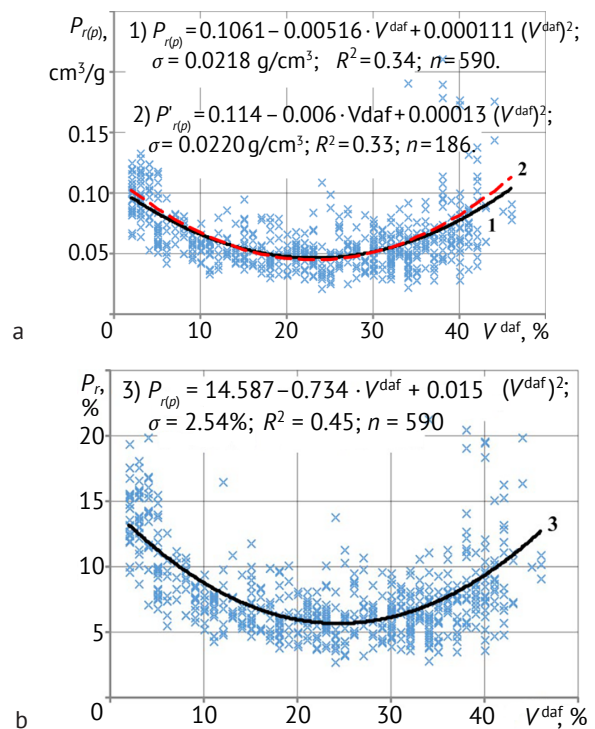


**Figure 1.** Interrelation between the calculated values of total porosity and their determination for a set of 590 coal seams according to the methodology of current standards

**Notes:** x – the established ratio for each coal seam between the values of  $P'_{r(p)}$  and  $P_{r(p)}$ ; 1 – averaging line; 2 – bisector of the coordinate grid; r – correlation coefficient;  $\sigma$  – root mean square deviation; n – the number of processed data pairs

**Source:** authors' development

In this case, there is no presence of high correlation interdependence ( $r = 0.59$ ). The presence of maximum distances of points in relation to the bisector of the coordinate grid when  $P_{r(p)} > 0.15 \text{ cm}^3/\text{g}$  (2), which determines the equality of  $P'_{r(p)}$  and  $P_{r(p)}$ , indicates insufficient accuracy in determining the total porosity of  $P'_{r(p)}$  using the empirical equation (3). The direction of changes in the total porosity of coal ( $P_{r(p)}$  – equation (1) and  $P'_{r(p)}$  – equation (2)) during metamorphic transformations for a set of 590 coal seams is illustrated by graphs of their dependence on the yield of volatile substances ( $V^{daf}$ ), which are shown in Figure 2.



**Figure 2.** Dependence of the values of the total porosity of coal ( $P_{r(p)}$  and  $P_r$ ), determined according to the methods of generally accepted standards for a set of 590 coal seams on the release of volatile substances ( $V^{daf}$ )

**Notes:** x – values of total porosity  $P_{r(p)}$  (a) and  $P_r$  (b), determined according to equations (2) and (1) using real ( $d_r^d$ ) and imaginary ( $d_a^r$ ) density; 1 – empirical average curve of the second-order polynomial obtained by the least squares method for a set of 590 coal seams; 2 – the average curve of the calculated values of the total density ( $P'_{r(p)}$ ) for a set of 186 coal seams according to equation (3); 3 – the empirical average curve of the second-order polynomial obtained by the least squares method for a set of 590 coal seams;  $\sigma$  – root mean square deviation;  $R^2$  – coefficients of determination; n – number of processed data pairs

**Source:** authors' development

The second-order polynomial shown in Figure 2(a), curve 1, characterises a rather low, practically absent, correlation between total porosity and volatile yield. The tightness of the connection ( $R^2$  and  $\sigma$ ) for the analysed complex of 590 coal seams is 0.34 and

0.0218 cm<sup>3</sup>/g, respectively. Curve 2 is characterised by approximately the same correlation indices ( $R^2 = 0.33$  and  $\sigma = 0.0220$  cm<sup>3</sup>/g), in relation to the set of 590 coal seams. This curve corresponds to empirical equation (3). Almost identical correlation indicators for curves 1 and 2 indicate that the use of averaged calculated values of  $P'_{r(p)}$  according to equation (3) did not affect the overall accuracy of determining  $P_{r(p)}$  according to equation (2).

The obtained results show that the total porosity of fossil coal is a strictly individual characteristic of a particular coal seam, which is slightly dependent on the yield of volatile substances. The average empirical dependences on this indicator give only partial insight about the direction of change in the total porosity of fossil coal during metamorphic transformations of coal seams.

The task of determining the volume of fossil coal is characterised by the problems of gas capacity and gas content of coal seams. The work by W. Han *et al.* (2020) indicate that the pore structure of coal is an important indicator for measuring the occurrence of coalbed methane and the actual operational capacity of coal mines. Despite a huge number of works in the field of coal physics, there is no single theory for the structure of fossil coals. According to the most general idea, based on X-ray diffraction and electron microscopy, coals of various modifications are considered as systems constructed of small graphite-like fragments (crystallites) randomly oriented in volume and chain non-aromatic part, as indicated by J.H. Shinn (1984) and A. Oberlin (2021).

The porosity of coal, together with the structure of its pore system and specific surface area, plays a key role in regulating the processes of filtration, diffusion and sorption. These processes take place both in the natural conditions of coal deposits and during coal transformation as a result of various physical and chemical effects. In some cases, these factors include the processes of metamorphic transformations of coal seams. Under the influence of these processes, the ratio between porosity types may change. It is divided into three main types: general (or physical), effective and open. Physical porosity includes the volume of isolated and connected pores. An open porosity refers to the volume of interconnected pores that are filled with gaseous or liquid fluids when the rock is saturated in a vacuum. Open porosity is less than the total porosity per volume of isolated pores. The effective porosity determines the fraction of the volume occupied by a moving fluid when the pore space is sufficiently saturated with this fluid. B. Ma *et al.* (2020) noted that

the effective porosity is defined as the ratio of the volume of interconnected pore space to the total volume of the porous sample.

The porous structure of fossil coal is directly related to its crystal structure. T. Wang *et al.* (2023) found that coal pores are mostly micropores and account for more than 90% of the total pores. As of 2024, the presence of pores with a size of  $10^{-3}$ - $10^{-9}$  m in the structure of fossil coal can be considered proven. Porosity determination methods based on grinding and pycnometry experiments give misleading results without taking into account closed porosity. The problem of closed porosity is studied from the standpoint of gas adsorption, small-angle X-ray and neutron scattering techniques.

## Conclusions

The insufficient accuracy of determining the total porosity using the empirical equation was established, which is confirmed by the presence of maximum point removals with respect to the bisector of the coordinate grid at  $P_{r(p)} > 0.15$  cm<sup>3</sup>/g, which determines the equality  $P'_{r(p)}$  and  $P_{r(p)}$ . The almost identical correlation coefficients of the dependences of the total coal porosity ( $P_{r(p)}$  and  $P_r$ ) on the volatile matter yield indicate that the use of the averaged calculated values of  $P'_{r(p)}$  did not affect the overall accuracy of the determination of  $P_{r(p)}$ . The total porosity of fossil coal is a strictly individual characteristic of a particular coal seam, which to some extent depends on the volatile matter yield. Based on the averaged empirical dependences on ( $V^{daf}$ ), it is possible to state the direction of change in the total porosity of fossil coal during metamorphic transformations of coal seams. For the first time, the practical absence of correlation between the total porosity of fossil coal and metamorphic transformations of coal seams was proved when assessing the impact of these processes using the volatile substance yield. Prospects for further research are the need to develop more accurate methods for determining the total and closed porosity of coal, in particular, taking into account its micropore structure and metamorphic changes, as well as studying the effect of porosity on filtration and sorption processes in mine operation conditions.

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## Conflict of Interest

None.

## References

- [1] Bazaluk, O., *et al.* (2024). Changes in the stability of coal microstructure under the influence of weak electromagnetic fields. *Scientific Reports*, 14(1), article number 1304. doi: 10.1038/s41598-024-51575-w.
- [2] Donetsk State Coal Research Institute. (1954). *Geological and coal-chemical map of the Donetsk Basin* (Vol. 8). Moscow: Ugletekhizdat.

- [3] Han, W., Zhou, G., Gao, D., Zhang, Z., Wei, Z., Wang, H., & Yang, H. (2020). Experimental analysis of the pore structure and fractal characteristics of different metamorphic coal based on mercury intrusion-nitrogen adsorption porosimetry. *Powder Technology*, 362, 386-398. doi: 10.1016/j.powtec.2019.11.092.
- [4] International Standard (ISO) No. 5072:2021 "Brown Coals and Lignites. Determination of True Relative Density and Apparent Relative Density". (2021, December). Retrieved from <https://www.iso.org/standard/79743.html>.
- [5] Ma, B., Hu, Q., Yang, S., Yin, N., Qiao, H., Zhang, T., & Meng, M. (2020). Multiple approaches to quantifying the effective porosity of lacustrine shale oil reservoirs in Bohai Bay Basin, East China. *Geofluids*, 2020, article number 8856620. doi: 10.1155/2020/8856620.
- [6] Makiyivka State Research Institute for Occupational Safety in the Mining Industry. (1985). *Catalog of collector properties of hard coals and anthracites of the Donetsk and Lviv-Volyn Basins*. Makiyivka: Donbas.
- [7] Nosal, D., Konovalov, S., & Shevchenko, V. (2021). Determination the injuries probability of coal mines workers. *Mining of Mineral Deposits*, 15(2), 47-53. doi: 10.33271/mining15.02.047.
- [8] Oberlin, A. (2021). *High-resolution TEM studies of carbonization and graphitization*. Retrieved from <https://www.semanticscholar.org/paper/High-Resolution-TEM-Studies-of-Carbonization-and-Oberlin/f8cb5121def57d24ee047df6c13075335e4fa7d8>.
- [9] Onifade, M., & B. Genc. (2020). A review of research on spontaneous combustion of coal. *International Journal of Mining Science and Technology*, 30(3), 303-311. doi: 10.1016/j.ijmst.2020.03.001.
- [10] Order of the Ministry of Energy and Coal Industry of Ukraine No. 868 "On Approval of Amendments to the Standard of the Ministry of Coal Industry SOU 10.1.00174088.011-2005 'Rules for Mining Operations in Seams Subject to Gas Dynamic Phenomena'". (2011, December). Retrieved from <https://zakon.rada.gov.ua/rada/show/v0868732-11#Text>.
- [11] Shinn, J.H. (1984). From coal to single-stage and two-stage products: A reactive model of coal structure. *Fuel*, 63(9), 1187-1196. doi: 10.1016/0016-2361(84)90422-8.
- [12] State Standard of Ukraine (DSTU GOST) No. 2160:2019 "Solid Mineral Fuel. Determination of Real and Imaginary Density". (2019, December). Retrieved from [https://online.budstandart.com/ua/catalog/doc-page.html?id\\_doc=88790](https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=88790).
- [13] State Standard of Ukraine (DSTU) No. 3472:2015 "Lignite, Stone and Anthracite Coal. Classification". (2015, May). Retrieved from [https://online.budstandart.com/ua/catalog/doc-page?id\\_doc=61974](https://online.budstandart.com/ua/catalog/doc-page?id_doc=61974).
- [14] Tarasov, V., Antoshchenko, M., Rudniev, Y., Zolotarova, O., & Davidenko, N. (2021). Metamorphism indicators for establishing the endogenic fire hazard of coal mining plants in mining. *International Journal of Environmental Science and Development*, 12(8), 242-248. doi: 10.18178/ijesd.2021.12.8.1346.
- [15] Wang, T., Tian, F., Deng, Z., & Hu, H. (2023). The characteristic development of micropores in deep coal and its relationship with adsorption capacity on the Eastern Margin of the Ordos Basin, China. *Minerals*, 13(3), article number 302. doi: 10.3390/min13030302.

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## Про зв'язок загальної пористості викопного вугілля з метаморфічними перетвореннями шахтопластів

● **Анотація.** Вивчення пористості корисних копалин, зокрема вугілля, та розуміння зв'язку його структури з характеристиками та властивостями необхідне задля раціоналізації застосування вугілля, оптимізації переробних процесів та знаходження нових методів боротьби з раповими викидами або газовиділенням. Мета полягала у встановленні рівня відповідності розрахункових значень загальної пористості вугілля (відповідно до емпіричного рівняння) їх експериментального визначення стандартними методами, а також визначити показники тісноти кореляційної залежності загальної пористості від ступеня метаморфічних перетворень. Методика досліджень ґрунтується на аналізі порівняння відповідності розрахункових значень загальної пористості для кожного окремого шахтопласту відповідно до емпіричного рівняння їх значенням, встановленим стандартними методами. Результати свідчать, що з підвищенням ступеня метаморфізму змінюються і фізичні характеристики вугілля, зокрема щільність і пористість. Пористість вугілля, структура його пористої системи та питома поверхня визначають фільтраційні, дифузійні й сорбційні процеси як у природних умовах залягання, так і під час їх змін під впливом різноманітних фізичних та хімічних факторів. Було доведено практичну відсутність кореляційної залежності загальної пористості викопного вугілля від метаморфічних перетворень шахтопластів при оцінці впливу цих процесів, враховуючи показник виходу легких речовин. Загальна пористість є унікальною характеристикою конкретного вугільного пласта в межах шахтного поля і лише частково визначається вмістом легких речовин. Усереднені емпіричні залежності від показника виходу легких речовин надають лише загальне уявлення про тенденції зміни пористості вугілля під час метаморфічних перетворень шахтопластів. Результати дослідів дозволяють розробити пропозиції задля удосконалення нормативної бази щодо прогнозування прояву небезпечних властивостей шахтопластів при гірничих роботах. Виявлені у дослідженні факти можна використовувати у нормативних документах для прогнозу небезпечних властивостей шахтопластів, оскільки вони дозволяють розробити пропозиції та методики щодо удосконалення нормативної бази з безпечного ведення гірничих робіт. Це призведе до зниження рівня аварійності з тяжкими наслідками, виробничого травматизму на вугледобувних підприємствах

● **Ключові слова:** вугільний пласт; небезпечні властивості; вуглефікація; охорона праці