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Chronostratigraphic and Depth Variability of Porosity and Strength of Hard Coals in the Upper Silesian Basin

Introduction

Hard coal is sedimentary rock of organic origin. It was formed as a result of the accumulation of plant material under suitable environmental conditions. Organic matter was subjected to long-term processes, initially biochemical metamorphosis, and later geochemical (Gabzdyl 1989) (Fig. 1). The progressing carbonisation process leads to an increase

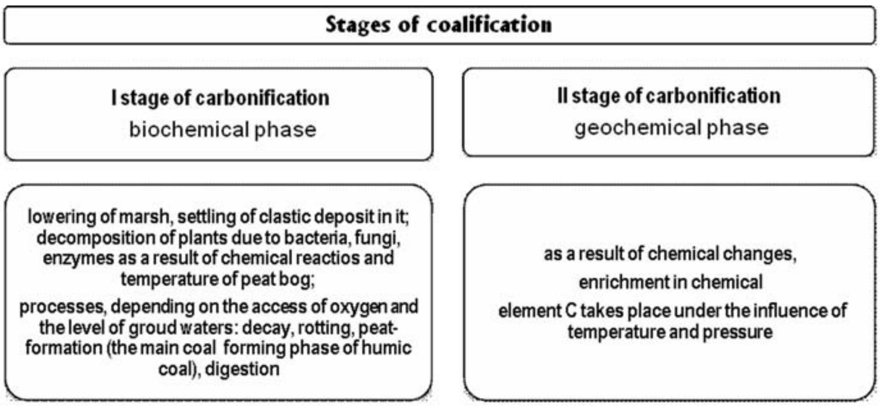

Fig. 1. Stages of coalification of coal generating organic matter

Rys. 1. Stadia uwęglenia węglotwórczej substancji organicznej

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in the content of the chemical element C. The process sees the simultaneous decrease in the percentage of oxygen, hydrogen, and volatile elements in coal generating organic matter.

The regularity of coalification with the increase in the value of pressure and temperature within the earth's interior is known. The progressive carbonization process is responsible for the formation of a series of types of coal (Fig. 2).

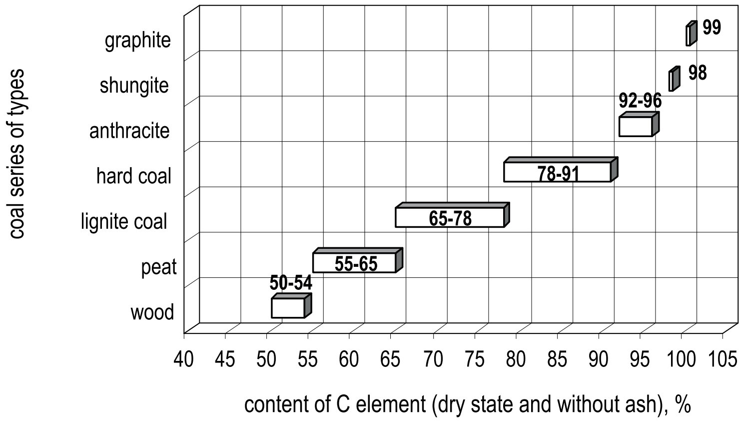


Fig. 2. Content of chemical element C in series of types of coal

Rys. 2. Zawartość pierwiastka C w typoszeregu węglowym

Coal, depending on the stage of carbonization, differs with respect to elementary composition (Chodyniecka, Gabzdyl, Kapuściński 1993) and properties, including physical properties.

This article presents the results of testing the porosity and compression strength of hard coals of the USCB, which are recognized as the group of physical parameters. Coals were collected from various stratigraphic cells of productive Carbon. These are coals of the Cracow Sandstone Series, the Mudstone Series, the Upper Silesian Sandstone Series, as well as the Paralic Series.

The Upper Silesian Coal Basin is characterized by its complex structure. This is a reference to its lithostratigraphy and tectonics. The complex structure of the basin results in the coal seams' order of occurrence over time not corresponding to an increase in the depth of their occurrence. Taking into account the complete lithostratigraphic profile of the USCB, in general, numbering of seams increases with depth. However, one cannot assign a constant range of deposition depth to any of the groups of seams (Bukowska 2012). Deposition depth is formed differently in various parts of the USCB and mining areas. Taking this into account, the article presents the variability of porosity and strength of the Upper Silesian coals from the aspect of age and depth.

1. Effective porosity of hard coals in the USCB

An important physical property of hard coals, on which other physical properties depend, is density (Krzesińska, Pilawa, Pusz 2004; Bukowska et al. 200; Bukowska 2012). Porosity is directly connected with density and determines the content of empty spaces in rock. These spaces are called pores or crevices. Pores in rocks are of different sizes (Table 1). The possibility of gas and fluid flow in a rock medium is dependent on the size of connected pores (Fig. 3).

Coal demonstrates a porous structure. It is marked by considerable heterogeneity. Pores differ in shape and size. The structure of coal is subject to change with the increase in the degree of coalification. Within the porous structure of coal there are macropores (diameter above 50 nm) and fracturing, mezopores (diameter from 2 to 50 nm), and micropores (diameter below 2 nm) distinguished (IUPAC 1982). In hard coals, the volume of macropores and mezopores is small in comparison with the total volume of pores (Mahajan 1991;

TABLE 1

Classification of pores relative to size (Ryncarz 1993)

TABELA 1

Klasyfikacja porów pod względem rozmiarów (Ryncarz 1993)

Name of pores	Size of pores [m]	Movement of fluid and gases particles
Ultramicropores	$< 10^{-9}$	Movement of larger particles of gases and fluid is not possible
Micropores	10^{-9}–10^{-7}	Movement of fluid and gas particles takes place by means of diffusion of a character close to diffusion in solid bodies
Mezopores	10^{-7}–10^{-4}	Unbounded diffusion of fluid and gas particles, movement of fluid and slow laminar flow of fluids and gases
Macropores	10^{-4}–10^{-1}	Possible laminar and turbulent flow
Megapores	$>10^{-1}$	Free flow of fluids and gases

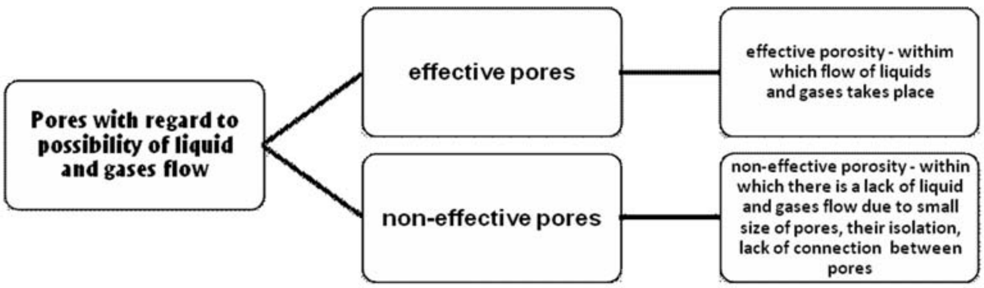


Fig. 3. Division of pores in rock with regard to possibility of fluids and gases flow

Rys. 3. Podział porów w skale ze względu na możliwość przepływu cieczy i gazów

Chudzik, Nodzeński 1993). Macropores and fracturing form a network of flow channels for fluids and gases. They have significance in the processes of diffusion and filtration. Gases (methane, carbon dioxide, water vapour) are formed in the process of diagenesis and metamorphism. The main volume of gases is sorbed by coal and deposited in pores of the smallest size. Micropores and submicropores play the main part in the sorption process (Mahajan 1991).

Many reference books describe different models of the porous structure of hard coal (Krevelen, Schuyer 1959; Krevelen 1961; Nelson 1983; Walker et al. 1988; Lasoń, ed. 1988, part I; Jasienko, ed. 1995; Czapliński, ed. 1994; Ndaji et al. 1997; Żyła (ed.) 2000). The model of the so called biporous structure of coal and some factors which influence it are presented in Fig. 4 (vide Orzechowska-Zięba, Nodzeński 2008). Strugała (2001) indicated that there is relationship between the volume of pores of a radius below 7.5 nm and the fraction and structure of the organic matter of coal. In the case of larger pores, he demonstrated that there is a relation between porosity and the fraction of organic matter and mineral impurities in coal.

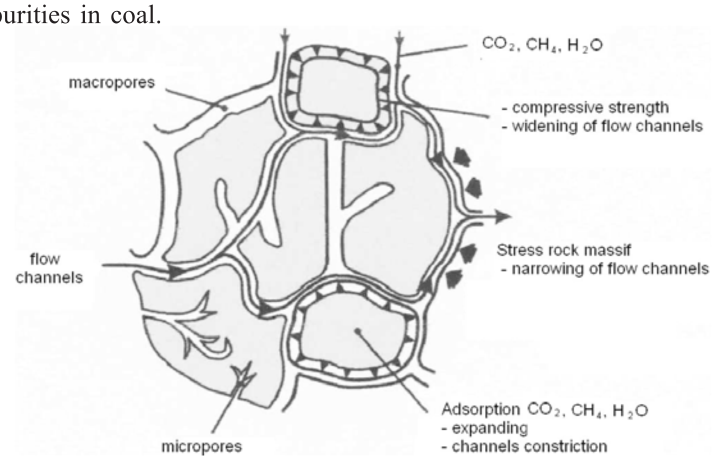


Fig. 4. Model of porous structure of coal and some factors which influence it (Seewald, Klein 1985)

Rys. 4. Model porowatej struktury węgla i niektóre czynniki, które mają na nią wpływ (Seewald, Klein 1985)

The porosity of hard coals was the subject of much research which has shown that hard coal porosity varies in a range from a few to several dozen per cent (Fig. 5). Testing of porosity, carried out on 14 samples of various types of hard coal from type 31 to 42 (Ceglarska-Stefańska et al. 1995) demonstrated that their porosity changes in value ranging from 3.65 to 16.92%.

Moreover, in the Central Mining Institute (Polish acronym: GIG), investigations of the porosity in USCB coals with various degrees of coalification were also carried out (Bukowska 2012). It was shown that open porosity of hard coals is shaped on a level from a few to a dozen or so per cent. The course of the porosity curve of bright coals of the Cracow Sandstone Series and the Mudstone Series in the USCB demonstrate a minimum content of the chemical element C of about 75% (Fig. 6).

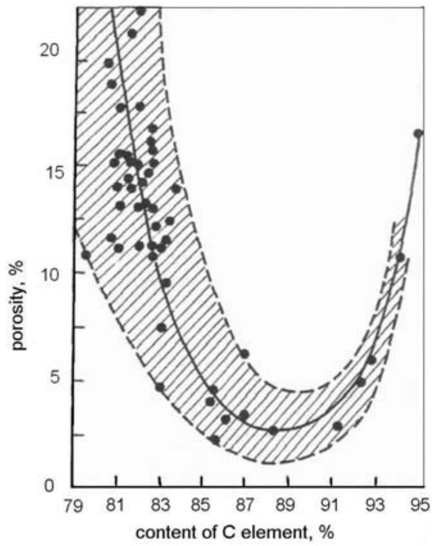


Fig. 5. Changes in porosity of hard coals versus metamorphism stage (Kawęcka 1988)

Rys. 5. Zmiany porowatości węgli kamiennych od stopnia metamorfizmu (Kawęcka 1988)

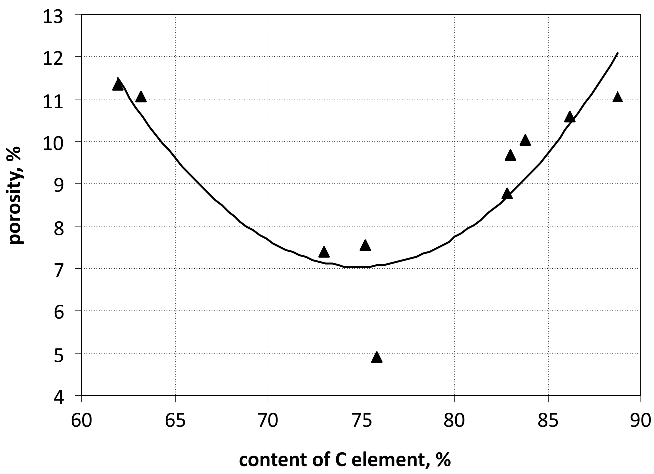


Fig. 6. Relation between effective porosity of bright coal of the Cracow Sandstone Series as well as the Mudstone Series in the USCB and carbonification degree (Bukowska 2012)

Rys. 6. Zależność porowatości efektywnej węgla błyszczącego krakowskiej serii piaskowcowej i serii mułowcowej w GZW od stopnia uwęglenia (Bukowska 2012)

The Authors of the article investigated coals of the Cracow Sandstone Series, the Mudstone Series, the Upper Silesian Sandstone Series, and the Paralic Series from the depth range of about 350 m to 1200 m (Table 2).

Investigations of porosity were conducted in compliance with the PN-EN 1936 (2010) standard "*Natural stone test methods: determination of real density and apparent density,*

TABLE 2

List of examined coals of the Upper Carbon formation of the USCB according to stratigraphic cells

TABELA 2

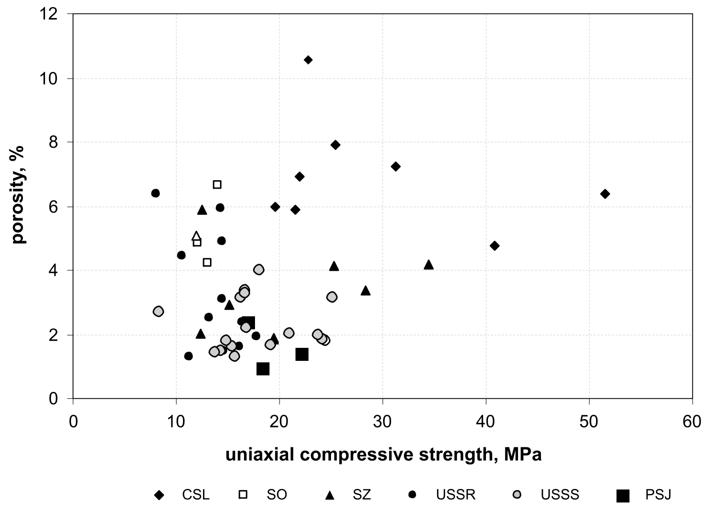
Zestawienie badanych węgli formacji górnego karbonu GZW według ogniw stratygraficznych

Stratigraphic cells, mine	No. of seam
Cracow Sandstone Series, Laziskie Beds (Piast Mine, Ziemowit Mine)	205/1–2, 206/1, 206/1–2, 207, 208, 209, 211/1
Siltstone Series, Orzeskie Beds (Boleslaw Smialy Mine)	324/3, 325, 325/2
Siltstone Series, Zaleskie Beds (Bielszowice Mine, Brzeszcze Mine, Sosnica Mine, Szczyglowice Mine, Ziemowit Mine	352, 364, 308, 401, 403/1, 405/2
Upper Silesian Sandstone Series, Rudzkie Beds (Halemba Mine, Jankowice Mine,Knurow Mine, MakoszowyMine, Sosnica Mine, Szczygłowice Mine)	407/3, 408/4, 409/1, 409/2, 410, 413/1, 414/2, 417/1, 418/1
Upper Silesian Sandstone Series, Siodlowe Beds (Bielszowice Mine, Bobrek Mine, Brzeszcze Mine, Halemba Mine, Jankowice Mine, Piekary Mine, Sosnica Mine)	501, 501/3, 502/1, 503, 504, 506, 510
Paralic Series, Porebskie Beds (Piekary Mine)	615
Paralic Series, Jaklowieckie Beds (Rydultowy Anna Mine)	706, 713

and of total and open porosity". Measurements were performed on samples in the form of nodules cut out of parent material. In accordance with the standard, samples desiccated to constant mass were placed in a vacuum vessel and subject to conditions of subatmospheric pressure in order to remove the air included in the open pores of samples. Next, samples were inundated with water to total immersion for the period of about 24 hours. After the time determined by the standard, the mass of a sample in water was determined as well as the mass of a saturated sample. Open porosity (effective) was calculated from the relation between the volume of open pores and the volume of the tested sample.

On the basis of the conducted examinations of coals, values of effective porosity within the value range from 0.96 to 10.54% were obtained. Compression strength from 8.1 to 51.5 MPa corresponds to these values. The most numerous group constituted samples of coal with strength between 10–30 MPa.

Based on the results of this research, it can be stated that with the increase in compression strength, values of porosity in the respective stratigraphic groups generally show a downward tendency. At this stage of the research, functional dependencies cannot be given for any of the stratigraphic groups between porosity and compressive strength of a significant correlation coefficient. However, it has been shown that higher values of porosity are characteristic of younger stratigraphic groups (Cracow Sandstone Series *CSL* and Silstone Series *SO, SZ*). A small number of coal samples collected from Poreba beds (seam 615) resulted from the small scale of mining works in these beds.



CSL –	*Cracow Sandstone Series (Laziskie Beds)*
SO –	*Siltstone Series (Orzeskie Beds)*
SZ –	*Siltstone Series (Zaleskie Beds)*
USSR –	*Upper Silesian Sandstone Series (Rudzkie Beds)*
USSS –	*Upper Silesian Sandstone Series (Siodlowe Beds)*
PP –	*Paralic Series (Porebskie Beds)*
PJ –	*Paralic Series (Jaklowieckie Beds)*

Fig. 7. Relations between coal porosity and compressive strength

Rys. 7. Zależność porowatości węgli od wytrzymałości na ściskanie

TABLE 3

Effective porosity of Upper Silesian coals

TABELA 3

Porowatość efektywna węgli górnośląskich

Stratigraphic	Porosity [%]
Cracow Sandstone Series, Laziskie Beds	4,75–10,54
Siltstone Series, Orzeskie Beds	4,22–6,67
Siltstone Series, Zaleskie Beds	1,85–5,91
Upper Silesian Sandstone Series, Rudzkie Beds	1,29–6,37
Upper Silesian Sandstone Series, Siodlowe Beds	1,29–3,99
Paralic Series, Porebskie Beds	1,40
Paralic Series, Jaklowieckie Beds	0,96–2,38

Examining the influence of deposition depth of investigated coals on the values of their porosity, it has been found that with the increase in depth, porosity generally decreases. Shifting of the upper and lower limits of variability intervals of porosity toward lower values with the increase in coal age, from the Laziska beds to the Jaklowice beds, was observed (Table 3, Fig. 8).

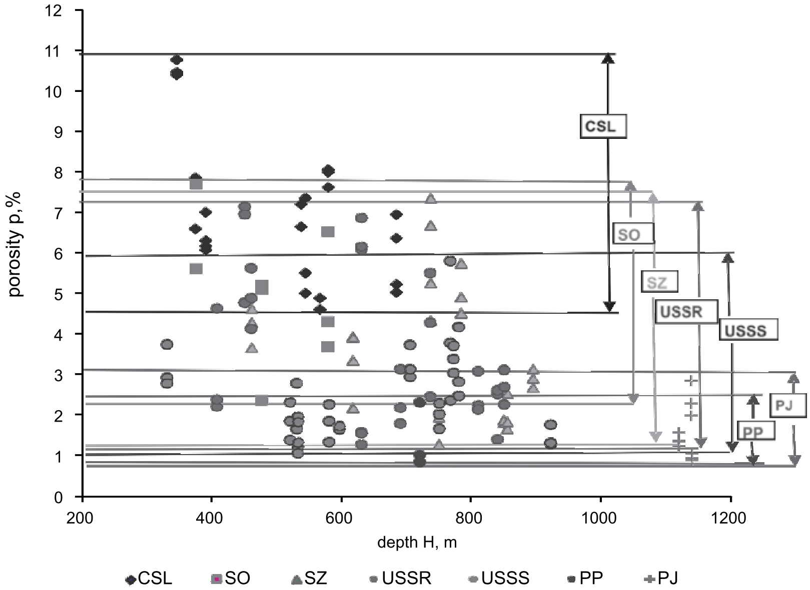


Fig. 8. Relation between coal porosity and deposition depth

Rys. 8. Zależność porowatości węgli od głębokości zalegania

2. Changes of compression strength of hard coal in the process of carbonification

Hard coal demonstrates heterogeneous petrographic structure. Heterogeneity of petrographic structure exerts an influence on coal strength. Changes in the strength of coals vary with the degree of their coalification, whereas results from changes in coal material from the peat stage to shungite. The carbonification degree increases with the depth of a seam's bedding. Temperature and pressure increase simultaneously with an increase in depth. In the USCB, in general, the metamorphism stage of hard coals increases with depth in an east to west direction (Jureczka, Kotas 1995).

Figure 9 presents variations in the coalification of bright coal forming seams from the Libiaz beds through Laziska, Orzesze to Ruda beds in the USCB with depth of occurrence in the basin ($C = 0.0407H + 45.951$; $R^2 = 0.7866$).

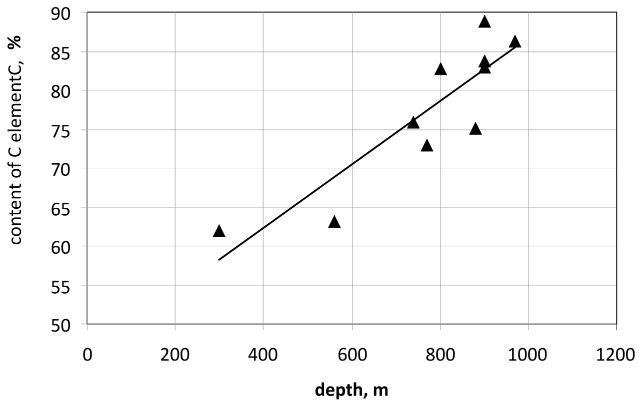


Fig. 9. Relation between content of element C of bright coal of seams of group from 100 to 400 and deposition depth (Bukowska 2012)

Rys. 9. Zależność zawartości pierwiastka C węgli błyszczących pokładów grupy od 100 do 400 od głębokości zalegania (Bukowska 2012)

The strength of coal depends on the properties of particular components forming it. The elementary components of coal are macerals. Groups of macerals differ as far as physical, chemical, and technological properties are concerned. Macerals form microlitotypes, i.e. intergrowths in the form of strips with a thickness of at least 50 μm. Higher compression strength is attributed to some microlitotypes than to others.

The most resistant microlitotypes of hard coal are considered to be durain, clarodurain, and carbominerite. Content of these components in bright coal and semi-bright coal decreases with depth (Fig. 10).

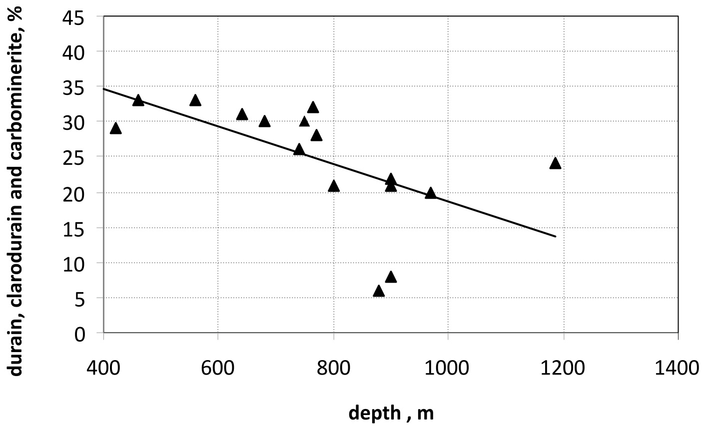


Fig. 10. Relation between content of the most resistant microlitotypes of hard coal in the USCB and depth (Bukowska 2012)

Rys. 10. Zależność zawartości najbardziej wytrzymałych mikrolitotypów węgla kamiennego w GZW od głębokości (Bukowska 2012)

The consequence of decreasing the fraction of the hardest microlitotypes in bright coals and semi-bright coals with depth is a reduction in uniaxial compressive strength (UCS = 0.767x – 3.1573; R^2 = 0.6431) (Fig. 11).

For bright coal, it was possible to determine the relationship between uniaxial compressive strength (UCS) and the deposition depth of the seam (Fig. 12), below 600 m depth (UCS = –0.0575D + 59.856; R^2 = 0.732), that is, for the depth of currently conducted exploitation in the USCB.

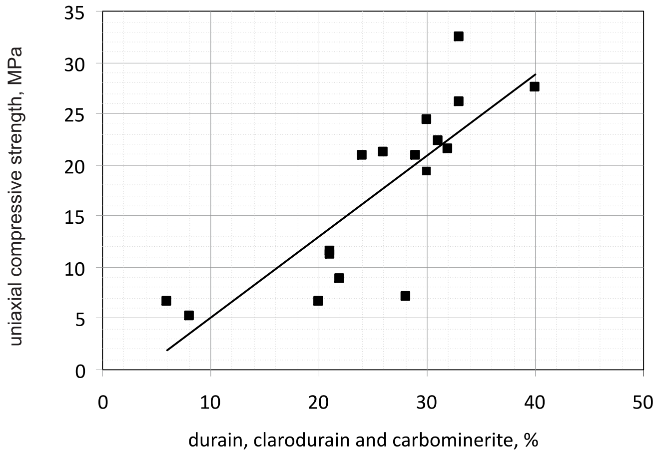


Fig. 11. Relation between compressive strength and fraction of the most resistant microlitotypes of hard coal in the USCB (Bukowska 2012)

Rys. 11. Zależność wytrzymałości na ściskanie od udziału najbardziej wytrzymałych mikrolitotypów węgla kamiennego w GZW (Bukowska 2012)

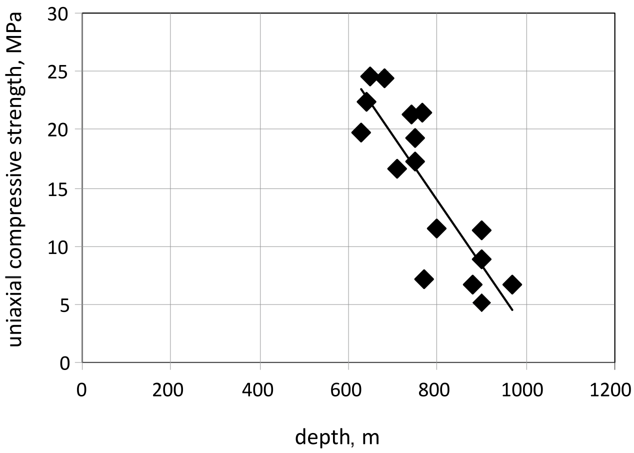


Fig. 12. Relation between compressive strength of bright coal and the depth of current exploitation in the USCB (Bukowska 2012)

Rys. 12. Zależność wytrzymałości na ściskanie węgla błyszczącego od głębokości aktualnej eksploatacji w GZW (Bukowska 2012)

High heterogeneity of semi-bright coals as well as semi-bright coals with inserts of dull coal did not allow for the determination of significant functional dependence. What could be observed was only a trend in strength variation with depth (Fig. 13, 14).

Many years of research on coals conducted by the Central Mining Institute (GIG) have indicated that in the area of the USCB, the frequency of occurrence of the coals' compressive

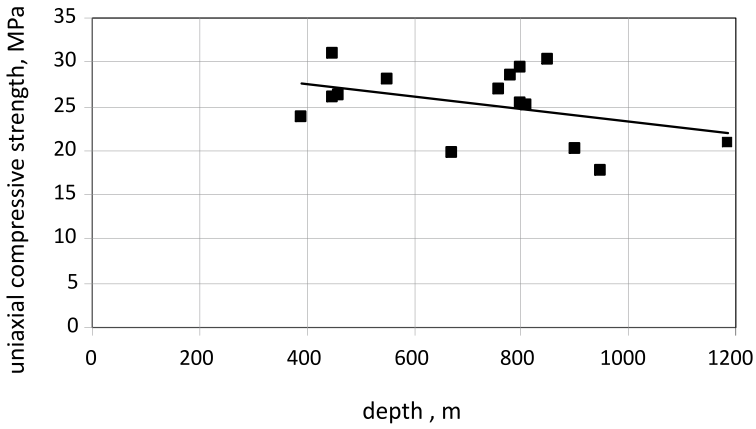


Fig. 13. Relation between compressive strength of semi-bright coal and deposition depth in the USCB (Bukowska 2012)

Rys. 13. Zależność wytrzymałości na ściskanie półbłyszczącego węgla od głębokości zalegania w GZW (Bukowska 2012)

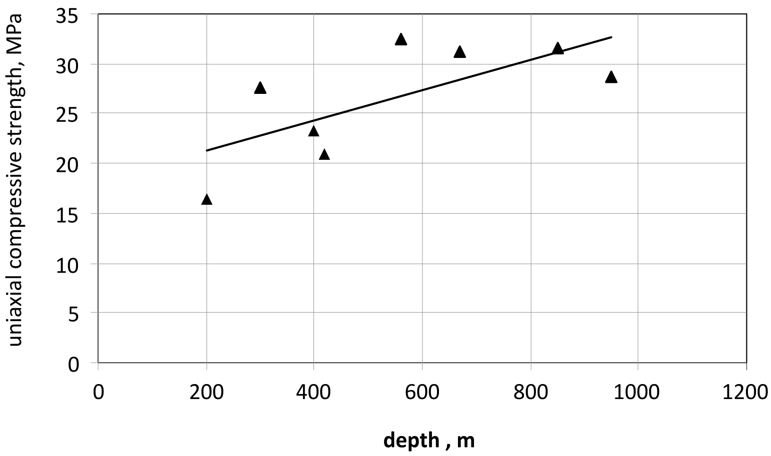


Fig. 14. Relation between compressive strength of semi-bright coal with interbedding of dull coal and deposition depth in the USCB (Bukowska 2012)

Rys. 14. Zależność wytrzymałości na ściskanie półbłyszczącego węgla z przewarstwieniami matowego od głębokości zalegania w GZW (Bukowska 2012) strength in particular intervals is clearly differentiated. From Figure 15, it is evident that coals with average compressive strength from the value range of 10–30 MPa comprise over 75% of all coals from the examined lithostratigraphic groups in the area of the USCB. On the other hand, no regular changes in average uniaxial compressive strength, with the increase in the age of subsequent stratigraphic groups (Fig. 16), are observed.

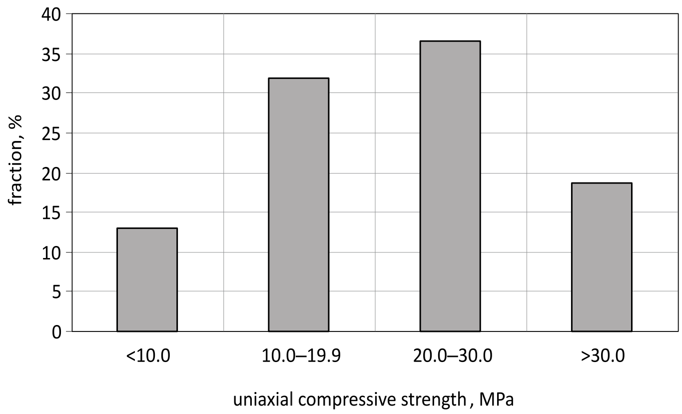


Fig. 15. Fraction of coals in established intervals of average compressive strength in the area of the USCB (Bukowska 2012)

Rys. 15. Udział węgli o średniej wytrzymałości na ściskanie w przyjętych przedziałach zmienności w obszarze GZW (Bukowska 2012)

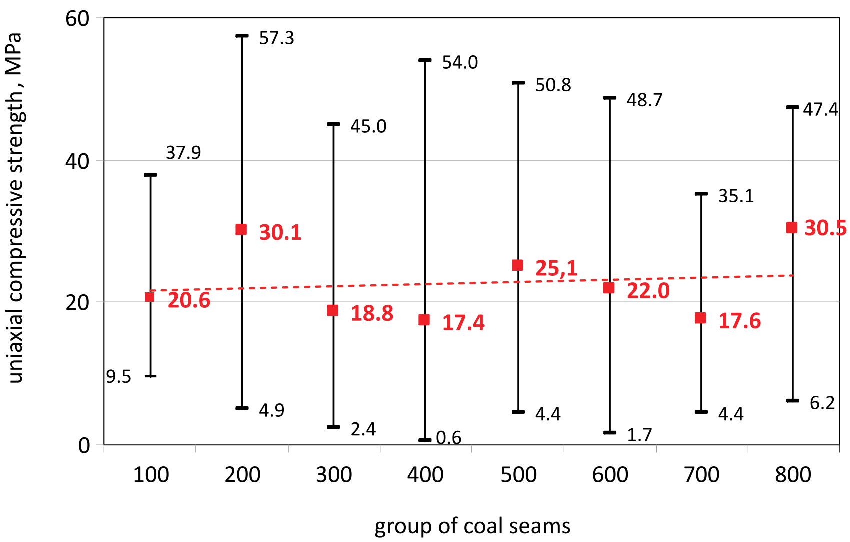


Fig. 16. Average compressive strength of coals and interval of their variability in stratigraphic groups in the USCB (Bukowska 2012)

Rys. 16. Średnia wytrzymałość na ściskanie węgli i przedział jej zmienności w grupach stratygraficznych w GZW (Bukowska 2012)

In connection with the lack of regularity of coal strength variation, the testing of strength and coal porosity are currently conducted in Polish coal mines. Its outcomes are utilized in designing exploitation and for the assessment of natural hazards. They also form a basis for establishing safety pillars (Bukowski 2010) and safety zones (Bukowski 2009), especially in mines conducting exploitation in the vicinity of liquidated or flooded mines.

Summary

Investigations into effective porosity and uniaxial compressive strength were conducted on hard coals from the USCB. Coals came from various stratigraphic cells of productive Carbon: the Cracow Sandstone Series, the Mudstone Series, Upper Silesian Sandstone Series, as well as the Paralic Series. Coals were deposited (occurred) at a depth of 350–1200 m. Coals from 35 seams in 14 mines were examined.

Effective porosity and uniaxial compressive strength vary with respect to age and depth. It has been shown that:

- Examined coals are characterized by effective porosity (open) within the range from 0.96 to 10.54%.
- From a chronostratigraphic viewpoint, shifting has been observed of the upper and lower limits of variability intervals of porosity towards higher values for the youngest coals. Higher values of porosity are characteristic for coals from younger stratigraphic groups (the Cracow Sandstone Series and the Mudstone Series).
- With the increase in depth, in general, there was a decrease in porosity.
- Uniaxial compressive strength of investigated coals ranged from 8.1 to 51.5 MPa. Most frequently, it falls within the range of 10–30 MPa.
- Heterogeneity of the petrographic structure of coals influences their strength. A decrease in the fraction of the hardest microlitotypes (durain, clarodurain, and carbominerite) with depth results in a decrease in compression strength. For bright coal and semi-bright coal, an abrupt drop in compression strength with deposition depth of coal was observed.
- With the increase in compression strength, the value of porosity in particular stratigraphic groups generally decreases. However, no regular changes in mean, uniaxial compressive strength, with the increase in the age of subsequent stratigraphic groups, were observed.
- The lack of regularity in the compressive strength of coal with its age and changes connected with its mineral structure indicate the need for the strength parameters of coal to be investigated to meet the needs of current mining activities. These investigations are of high importance for the assessment of conditions and means of exploitation, assessment of natural hazards, and to determine safety parameters, e.g. safety pillars.

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CHRONOSTRATYGRAFICZNA I GŁĘBOKOŚCIOWA ZMIENNOŚĆ POROWATOŚCI I WYTRZYMAŁOŚCI WĘGLI W GÓRNOŚLĄSKIM ZAGŁĘBIU WĘGLOWYM

S ł o w a k l u c z o w e

Porowatość, wytrzymałość, węgiel, GZW

S t r e s z c z e n i e

W artykule przedstawiono wartości porowatości i wytrzymałości na ściskanie węgli kamiennych z obszaru Górnośląskiego Zagłębia Węglowego. Zmiana stopnia uwęglenia, który wynika z przemian materii węglowej w procesie uwęglenia, jest źródłem wielu zmian w strukturze węgla. Zmiany te wpływają na wartość parametrów fizycznych, w tym na wartość porowatości i wytrzymałości. Porowatość i wytrzymałość na ściskanie zmieniają się ze stopniem uwęglenia, który wynika z głębokości zalegania. Przedstawione w artykule wartości porowatości efektywnej węgli i ich wytrzymałość zostały opracowane z uwzględnieniem chronologii wiekowej pokładów węgla i głębokości ich występowania. Przebadano węgle krakowskiej serii piaskowcowej, serii mułowcowej, górnośląskiej serii piaskowcowej i serii paralicznej, z głębokości od około 350 m do około 1200 m. Autorzy wykazali, że porowatość efektywna węgli górnośląskich zmienia się dla poszczególnych grup stratygraficznych i przyjmuje wartości od kilku do kilkunastu procent a wytrzymałość na ściskanie od kilkunastu do kilkudziesięciu megapaskali. Zaobserwowano, w ujęciu chronostratygraficznym, przesuwanie się górnej i dolnej granicy przedziałów zmienności porowatości w kierunku wyższych wartości dla węgli młodszych. Ze wzrostem wytrzymałości na ściskanie wartość porowatości w poszczególnych grupach stratygraficznych generalnie maleje. Nie zaobserwowano natomiast regularnych zmian średniej wytrzymałości na jednoosiowe ściskanie ze wzrostem wieku kolejnych grup stratygraficznych. Dla węgla błyszczącego i półbłyszczącego wykazano natomiast wyraźny spadek wytrzymałości na ściskanie z głębokością zalegania pokładów.

CHRONOSTRATIGRAPHIC AND DEPTH VARIABILITY OF POROSITY AND STRENGTH OF HARD COALS IN THE UPPER SILESIAN BASIN

Key words

Porosity, strength, coal, the USCB

Abstract

This article presents values of porosity and compression strength of hard coals from the area of the Upper Silesian Coal Basin. The change of the stage of carbonification, which results from conversion of coal substance in the process of coalification, is a source of many changes in the structure of coal. These changes exert influence on values of physical parameters, including the values of porosity and strength. Porosity and compression strength change with the degree of carbonification, a result of the depth of deposition. This study determined the values of effective porosity of coals and their strength considering the age chronology of coal seams and the depth of their occurrence. It examined coals of the Cracow Sandstone Series, the Mudstone Series, the Upper Silesian Sandstone Series, and the Paralic Series from depths ranging from about 350 m to 1200 m. The authors have shown that effective porosity of the Upper Silesian coals changes for particular stratigraphic groups and assumes values from a few to a dozen or so per cent, while compression strength from several to several dozen megapascals. It has been observed, from a chronostratigraphic perspective, that there is a shifting of the upper and lower limits of intervals of porosity variations towards higher values for younger coals. With the increase in compression strength, value of porosity in particular stratigraphic groups generally decreases. However, no regular changes were observed in mean, uniaxial compressive strength with the increase in the age of subsequent stratigraphic groups. On the other hand, for bright coal and semi-bright coal, a visible decrease in compression strength with the depth of deposition of strata was observed.