Mat. Symp. str. 16 – 30

Mirosława BUKOWSKA, Urszula SANETRA, Mariusz WADAS
Central Mining Institute, Katowice

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

Key words

Porosity, strength, coal, the USCB

Abstract

In the article, values of porosity and compression strength of hard coals from the area of the Upper Silesian Coal Basin are presented. 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 value of porosity and strength. Porosity and compression strength change with the degree of carbonification which is a result of the depth of deposition. Presented in the article, values of effective porosity of coals and their strength have been determined considering age chronology of coal seams and depth of their occurrence. Coals of the Cracow Sandstone Series, the Mudstone Series, the Upper Silesian Sandstone Series and the Paralic Series, from depth ranging from about 350 m to about 1200 m, were examined. 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 chronostratigraphic perspective, there is a shifting of the upper and lower limit of intervals of porosity variations towards higher values for younger coals. With the increase of compression strength, value of porosity in particular stratigraphic groups generally decreases. However, no regular changes were observed of mean uniaxial compressive strength with the increase of age of subsequent stratigraphic groups. On the other hand, for bright coal and semi-bright coal, visible decrease of compression strength with the depth of deposition of strata was observed.

1. Introduction

Hard coal is sedimentary rock of organic origin. It was formed as a result of accumulation of plant material in suitable environmental conditions. Organic matter was subject to long-term processes, initially biochemical metamorphosis, and later geochemical one (Gabzdyl 1989) (Fig. 1.1). Developing carbonisation process leads to the increase of chemical element C content. Simultaneously decreases the fraction of oxygen, hydrogen and volatile elements in coal generating organic matter.

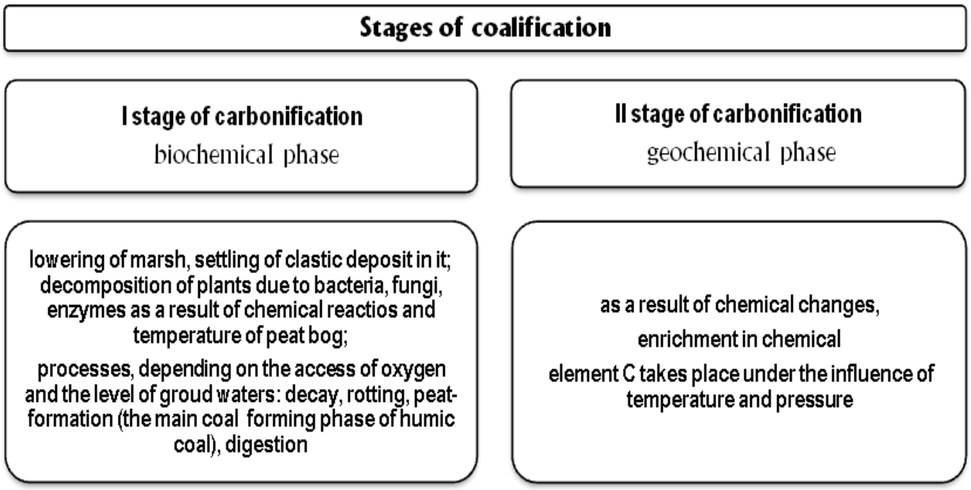


Fig. 1.1. Stages of coalification of coal generating organic matter

The regularity of coalification with the increase of the value of pressure and temperature in earth interior is known. Progressive carbonization process is responsible for formation of series of types of coal (Fig. 1.2).

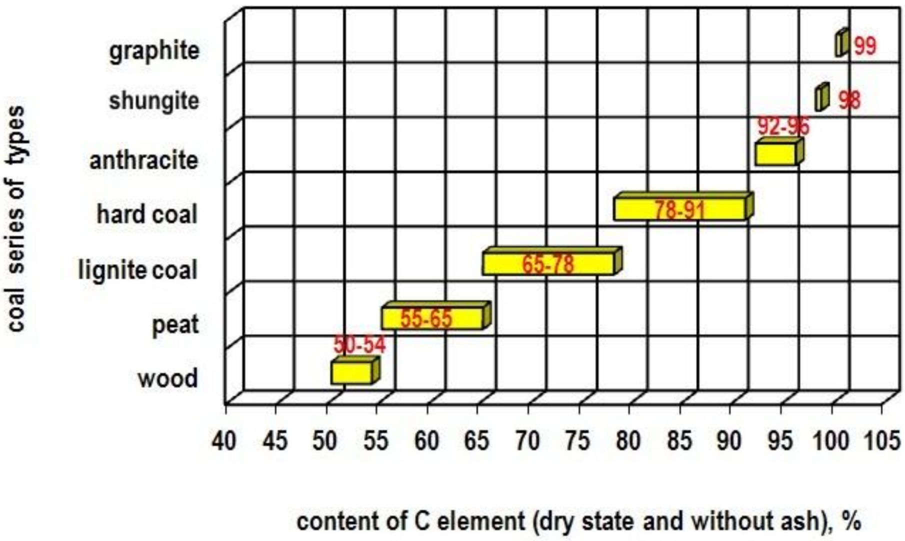


Fig. 1.2. Content of chemical element C in series of types of coal

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

Results of testing porosity and compression strength of hard coals of the USCB, which are recognized as the group of physical parameters, are presented in the article. 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. It refers to lithostratigraphy and tectonics. Complex structure of the basin causes that order of occurrence in time of coal seams does not mean increase of the depth of their occurrence. Taking into account complete lithostratigraphic profile of the USCB, in general, numbering of seams increases with depth. However, to none of the groups of seams one can assign constant range of deposition depth (Bukowska 2012). It is formed differently in various parts of the USCB and mining areas of mines. Taking the above mentioned into account, the Authors of the article presented variability of porosity and strength of the Upper Silesian coals from the aspect of age and depth.

2. Effective porosity of hard coals in the USCB

Important physical property of hard coals, on which depend other physical properties, is density (Bukowska et al. 2000; Krzesińska, Pilawa, Pusz 2004; Bukowska 2012). Porosity is directly connected with density and determines content of empty spaces in rock. These spaces are called pores or crevices. Pores in rocks are of different size (Tab. 2.1). With the size of connected pores is involved a possibility of gases and fluids flow in rock medium (Fig. 2.1).

Table 2.1. Classification of pores relative to size (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 gases 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 gases particles, movement of fluid and slow laminar flow of fluid and gases
macropores	10^{-4} - 10^{-1}	Possible laminar and turbulent flow
megapores	$>10^{-1}$	Free flow of fluid and gases

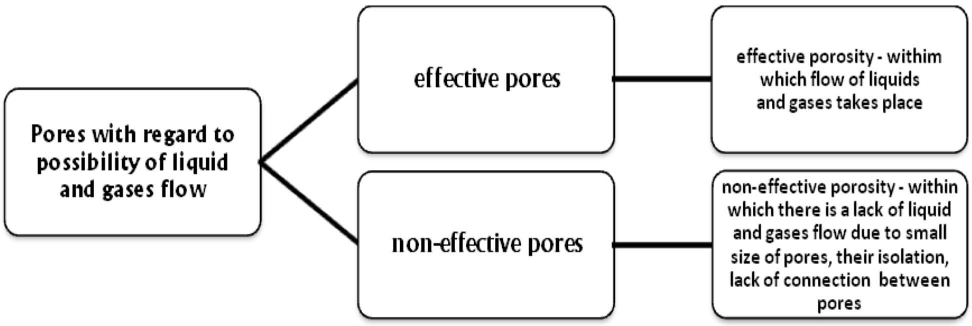


Fig. 2.1. Division of pores in rock with regard to possibility of fluids and gases flow

Coal demonstrates porous structure. It is marked by considerable heterogeneity. Pores differ in shape and size. Structure of coal is subject to changes with the increase of coalification degree. In 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, volume of macropores and mezopores is small in comparison with total volume of pores (Mahajan 1991; 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 of the reference books describe different models of 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). Model of so called biporous structure of coal and some factors which influence it, are presented in Fig. 2.2 (vide Orzechowska-Zięba, Nodzeński 2008). Strugała (2001) indicated that there is relationship between volume of pores of radius below 7.5 nm and fraction and structure of organic matter of coal. In case of larger pores, he demonstrated that there is a relation between porosity and fraction of organic matter and mineral impurities in coal.

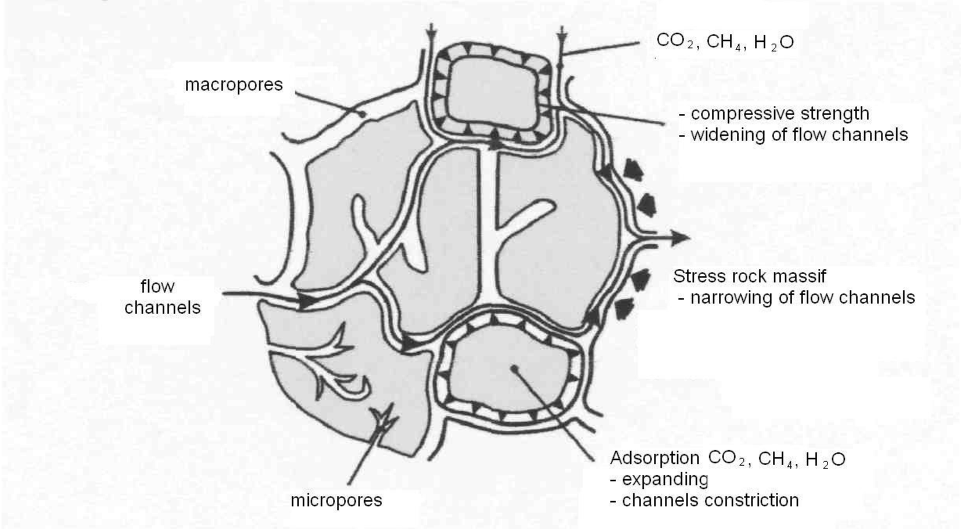


Fig. 2.2. Model of porous structure of coal and some factors which influence it (Seewald, Klein 1985)

Porosity of hard coals was the subject of many researches which have shown that it varies in the range from a few to several dozen per cent (Fig. 2.3). 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 range from 3.65 to 16.92%.

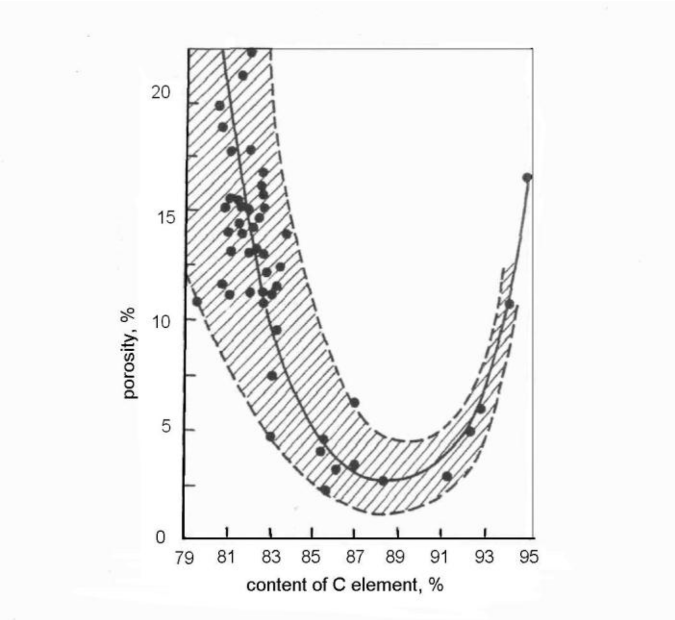


Fig. 2.3. Changes of porosity of hard coals versus metamorphism stage (Kawęcka 1988)

Moreover, in the Central Mining Institute (Polish acronym: GIG), investigations of porosity of the USCB coals of various degree of coalification were also carried out (Bukowska 2012). It was shown that open porosity of hard coals is shaped on the 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 display minimum at the value of about 75% content of chemical element C (Fig. 2.4).

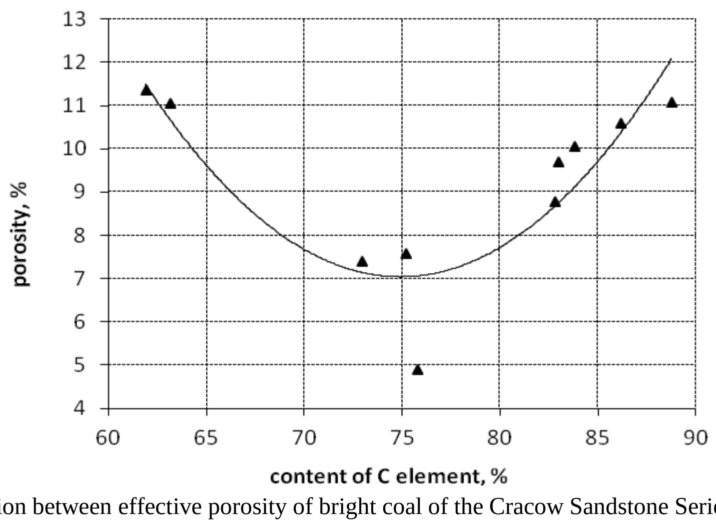


Fig. 2.4. Relation between effective porosity of bright coal of the Cracow Sandstone Series as well as the Mudstone Series in the USCB and carbonification degree (Bukowska 2012)

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 depth range of about 350 m do 1200 m (Tab. 2.2).

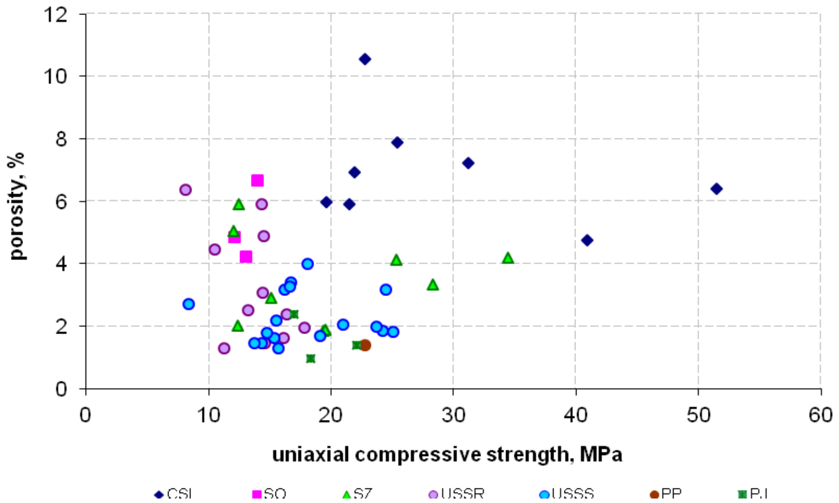
Table 2.2. List of examined coals of the Upper Carbon formation the USCB according to stratigraphic cells

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, Makoszowy Mine, 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

Investigations of porosity were conducted in compliance with PN-EN 1936 (2010) standard *"Natural stone test methods: determination of real density and apparent density, and of total and open porosity".* Measurements were performed on samples in a form of nodules cut out of parent material. In accordance with the standard, samples desiccated to constant mass were placed in vacuum vessel and subject to activity of subatmospheric pressure in order to remove the air included in 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 sample in water was determined as well as the mass of a saturated sample. Open porosity (effective) the was calculated from the relation between volume of open pores and volume of tested sample.

On the basis of 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 constitute samples of coal of strength within 10 – 30 MPa.

On the basis of research results, it has been stated that with the increase of compression strength, values of porosity in respective stratigraphic groups generally show a downward tendency. At this stage of the research, for none of the stratigraphic groups, functional dependencies cannot be given between porosity and compressive strength of 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*). Small number of coal samples collected from Poreba beds (seam 615) results from 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. 2.6. Relations between coal porosity and compressive strength

Investigating the influence of deposition depth of investigated coals on values of their porosity it has been found that with the increase of depth porosity generally decreases. Shifting of the upper and lower limits of variability intervals of porosity towards lower values with the increase of coal age, from Laziska beds to Jaklowice beds, was observed (Fig. 2.5, Tab. 2.3).

Table 2.3. Effective porosity of Upper Silesian coals

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

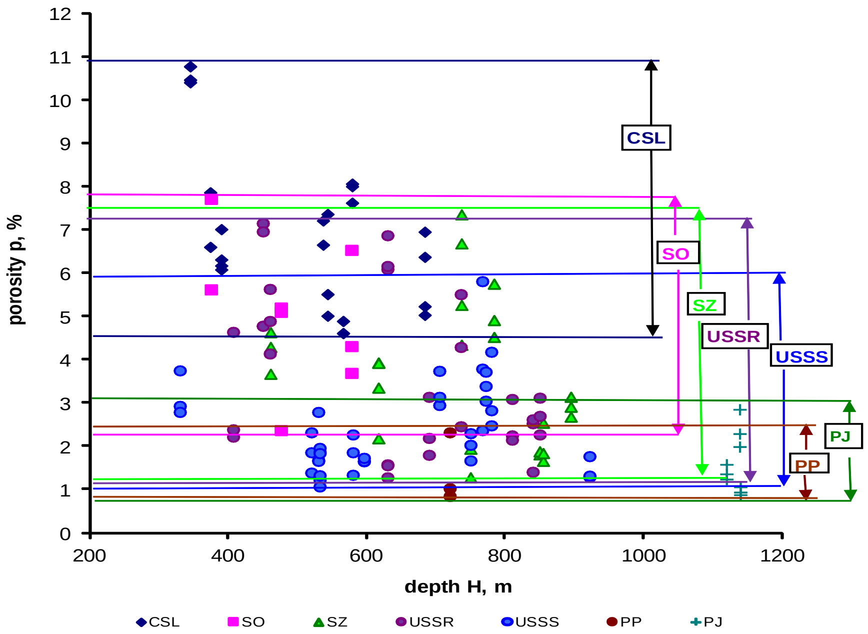


Fig. 2.5. Relation between coal porosity and deposition depth

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

Hard coal demonstrates heterogeneous petrographic structure. Heterogeneity of petrographic structure exerts influence on coal strength. Changes of strength of coals vary with the degree of their coalification, whereas this one results from changes of coal material from peat stage to shungite. Carbonification degree increases with depth of seams bedding. Simultaneously with the increase of depth, increases temperature and pressure. In the USCB, in general, metamorphism stage of hard coals increases with depth in the direction from the East to the West (Jureczka, Kotas 1995).

Figure 3.1 presents variations of coalification of bright coal forming seams from Libiaz beds through Laziska, Orzesze to Ruda beds in the USCB with depth of occurrence in basin (C = 0,0407H + 45,951; R^2 = 0,7866).

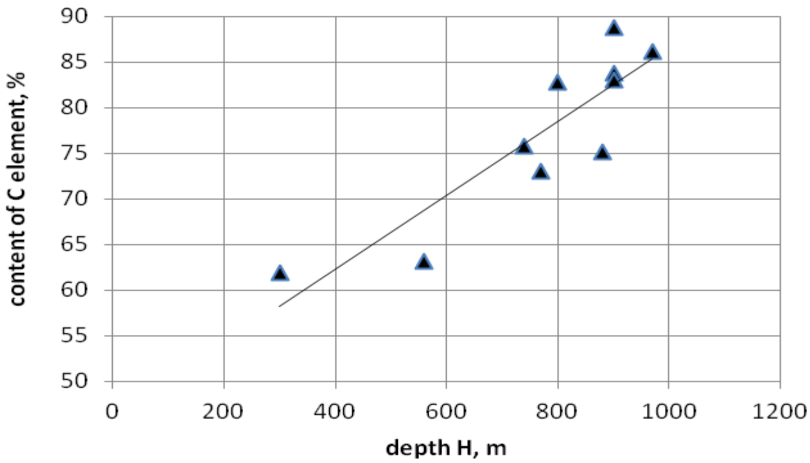


Fig. 3.1. Relation between content of element C of bright coal of seams of group from 100 to 400 and deposition depth (Bukowska 2012)

Strength of coal depends on properties of particular components forming it. 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 form of strips of thickness of at least 50 μm. Higher compression strength is attributed to some of the microlitotypes than to the remaining ones.

For the most resistant microlitotypes of hard coal are considered durain, clarodurain and carbominerite. Content of these components in bright coal and semi-bright coal decreases with depth (Fig. 3.2).

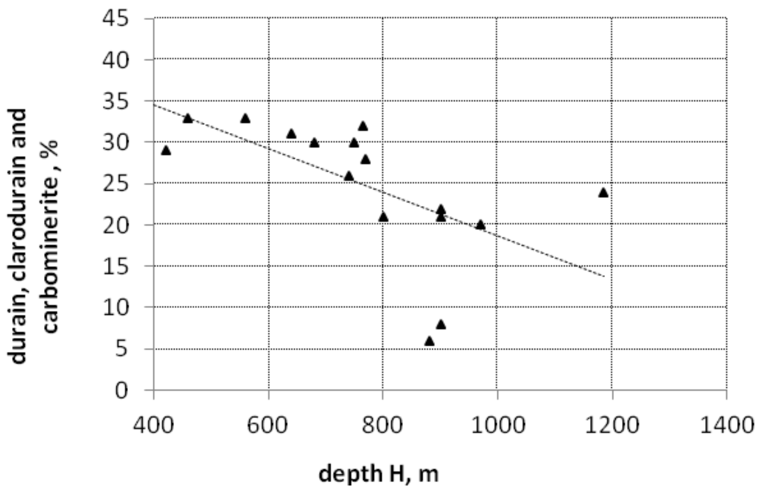


Fig. 3.2. Relation between content of the most resistant microlitotypes of hard coal in the USCB and depth (Bukowska 2012)

The consequence of decreasing the fraction of the hardest microlitotypes in bright coals and semi-bright coals with depth is reduction in uniaxial compressive strength (Fig. 3.3).

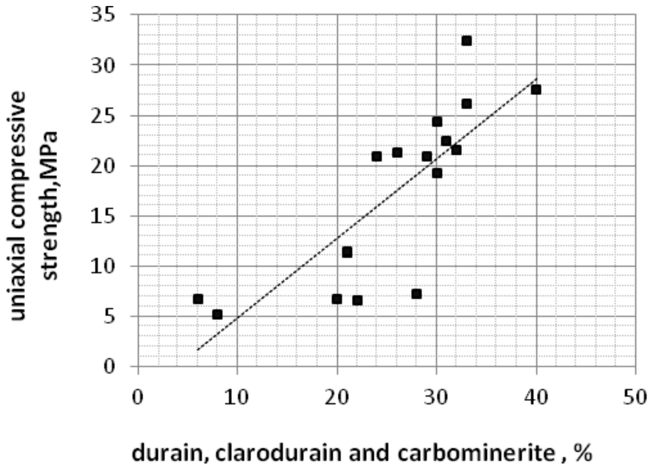


Fig. 3.4. Relation between compressive strength and fraction of the most resistant microlitotypes of hard coal in the USCB (Bukowska 2012)

For bright coal it was possible to determine the relationship between uniaxial compressive strength (*UCS*) and deposition depth of seam (Fig. 3.5), below 600 m depth (UCS = -0,0575H + 59,856; R^2 = 0,732), that is for depth of currently conducted exploitation in the USCB.

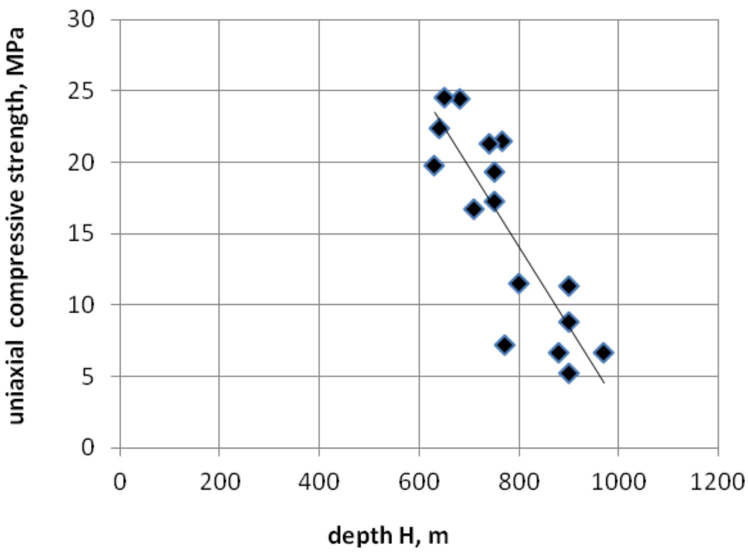


Fig. 3.5. Relation between compressive strength of bright coal and the depth of current exploitation in the USCB (Bukowska 2012)

High heterogeneity of semi-bright coals as well as semi-bright coals with inserts of dull coal did not allow to determine significant functional dependence. What could be observed was only a trend of strength variation with depth (Fig. 3.6, 3.7).

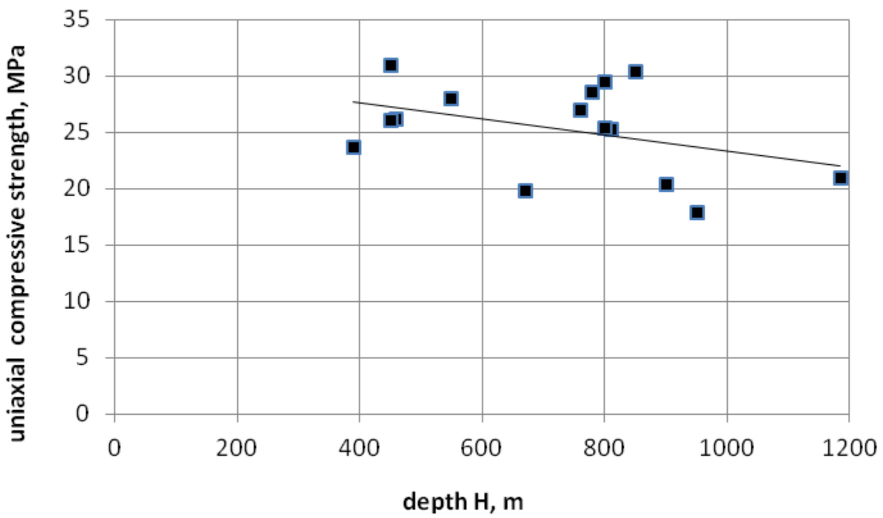


Fig. 3.6. Relation between compressive strength of semi-bright coal and deposition depth in the USCB (Bukowska 2012)

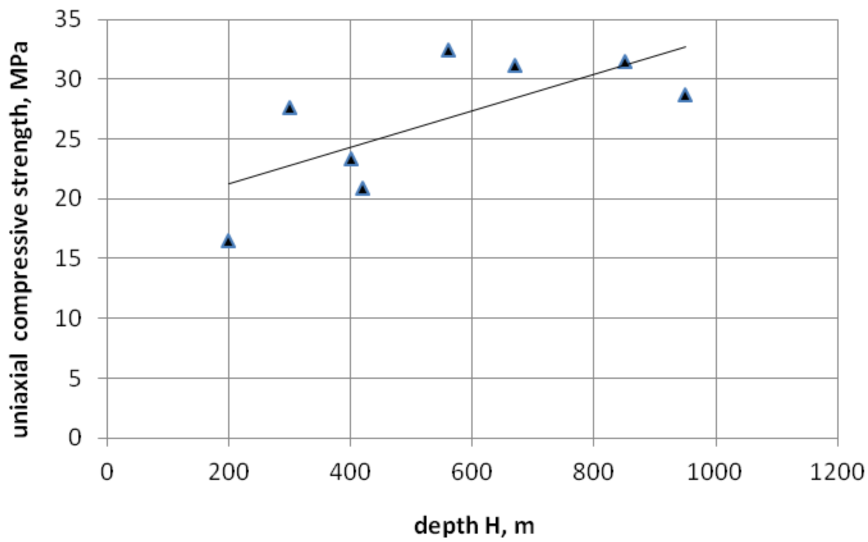


Fig. 3.7. Relation between compressive strength of semi-bright coal with interbedding of dull coal and deposition depth in the USCB (Bukowska 2012)

Many years' research of coals conducted in the Central Mining Institute (GIG) have indicated that in the area of the USCB, frequency of occurrence of coals compressive strength in particular intervals is clearly differentiated. From Figure 3.8, it is visible that coals with average compressive strength from 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 of average uniaxial compressive strength, with the increase of the age of subsequent stratigraphic groups (Fig. 3.9), are observed.

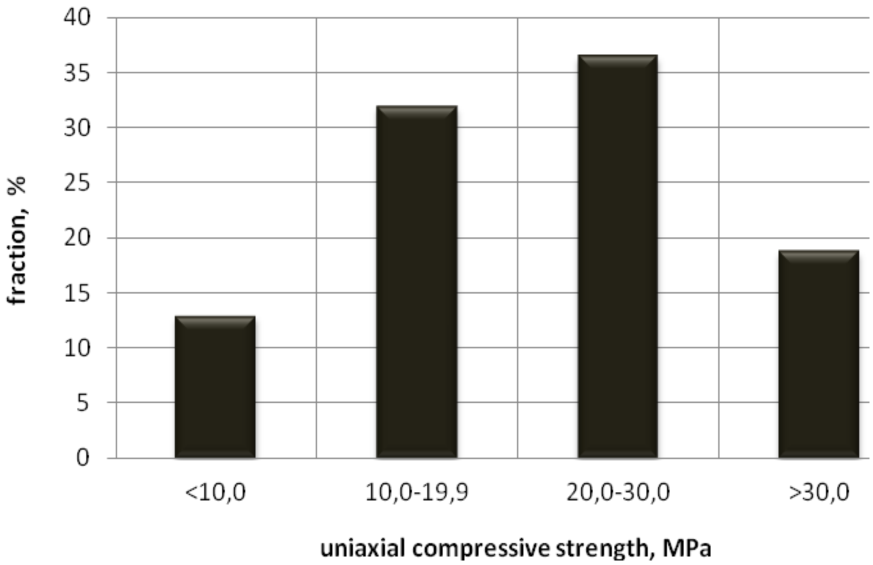


Fig. 3.8. Fraction of coals in established intervals of average compressive strength in the area of the USCB (Bukowska 2012)

In connection with lack of regularity of coal strength variation, 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.

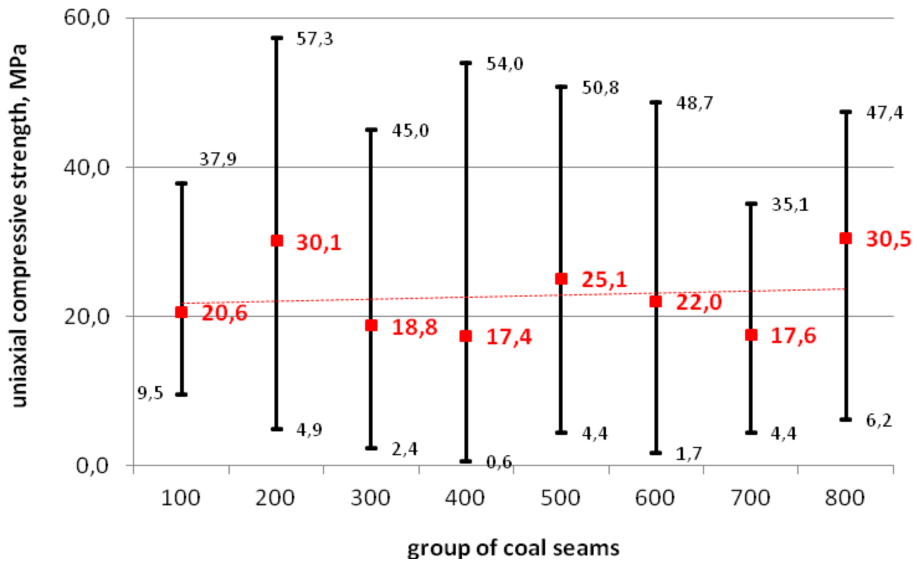


Fig. 3.9. Average compressive strength of coals and interval of its variability in stratigraphic groups in the USCB (Bukowska 2012)

4. Summary

Investigations of effective porosity and uniaxial compressive strength were conducted on hard coals of 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 the depth of 350 - 1200 m. Coals from 35 seams in 14 mines were examined.

In the article, variability of effective porosity and uniaxial compressive strength with respect to age and depth are presented. It has been shown that:

- Examined coals are characterized by effective porosity (open) within the range from 0.96 to 10.54%.
- It has been observed, in chronostratigraphic view, shifting the upper and lower limit 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 of depth, in general, decrease of porosity was found.
- 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 petrographic structure of coals influences their strength. Fall of fraction of the hardest microlitotypes (durain, clarodurain and carbominerite) with depth results in decrease of compression strength. For bright coal and semi-bright coal, an abrupt drop of compression strength with deposition depth of coal was observed.

- With the increase of compression strength the value of porosity in particular stratigraphic groups generally decreases. However, no regular changes of mean uniaxial compressive strength, with the increase of the age of subsequent stratigraphic groups, were observed.
- Lack of regularity of compressive strength of coal with its age and changes connected with its mineral structure cause that strength parameters of coal should be investigated for the needs of conducting current mining activities. These investigations are of high importance for the assessment of conditions and ways of exploitation, assessment of natural hazards and to determine parameters of protection, e.g. safety pillars.

Research and analysis of porosity of coals were conducted within the framework of realized by GIG and Kompania Weglowa S.A. research project LOWCARB - Low carbon mine site energy initiatives (Contract no. RFCR-CT-2010-00004) – partially funded by the Research Fund for Coal and Steel as well as Ministry of Science and Higher Education.

REFERENCES

[1] Bukowska M., Gawyś J., Sanetra U., Szedel D., Wadas M. 2000: Parameters of rocky raw materials and their usefulness in construction industry [In Polish: Parametry fizyczne surowców skalnych a ich przydatność w budownictwie i drogownictwie]. Gospodarka Surowcami Mineralnymi, t.16, z. 2

[2] Bukowska M. 2012: Susceptibility of Rock Mass to Rockburst – Geological and Geomechanical Methods of Testing [In Polish: Skłonność górotworu do tąpań – geologiczne i geomechaniczne metody badań] Wydawnictwo GIG. Katowice.

[3] Bukowski P. 2009: Determining of water hazard zones for mining exploitation planned in the vicinity of reservoirs in abandoned mines. Mineral Resources Management. Vol. 25, No. 3, 203-215. Cracow.

[4] Bukowski P. 2010: Determining of safety pillars in the vicinity of water reservoirs in mine workings within abandoned mines in the Upper Silesian Coal Basin (USCB). Journal of Mining Science. Vol. 46, No. 3, 298-310.

[5] Ceglarska-Stefańska G., Stachurski J., Vogt E. 1995: Porosity of the Polish Hard Coals, Archives of Mining Sciences, Volume 40, Issue 3

[6] Chodyniecka L., Gabzdyl W., Kapuściński T. 1993: Mineralogy and Petrography for Miners. [In Polish: Mineralogia i petrografia dla górników]

[7] Chudzik W., Nodzeński A. 1993: Low-temperature Adsorption of Argon on Hard Coals. [In Polish: Niskotemperaturowa adsorpcja argonu na węglach kamiennych] Mat. Zjazdu PTChem. i SITP Chem., Toruń, S-4 P-29.

[8] Czapliński A. (ed.) 1994: Hard Coal. [In Polish: Węgiel Kamienny] Wydawnictwo AGH, Kraków.

[9] Gabzdyl W. 1989: Geology of Coal [In Polish: Geologia węgla] Skrypt Pol. Śl. no.1427/2.

[10] Jasieńko S. (red.) 1995: Chemistry and Physics of Coal [In Polish: Chemia i fizyka węgla] Oficyna Wydawnicza Politechniki Wrocławskiej Wrocław, pp. 221–261.

[11] Jureczka J., Kotas A. 1995: Tectonogenesis of the Upper Silesian Coal Basin [In Polish: Tektonogeneza Górnośląskiego Zagłębia Węglowego] In: The Carboniferous System in Poland. Zdanowski A., Żakowa H. (ed.). Prace PIG Vol. CXLVIII, pp. 168–171.

[12] Kawęcka J. 1988: Porous Structure of Hard Coal [In Polish: Struktura porowata węgli kamiennych] Zeszyty Naukowe AGH no. 1212, Chemia, no. 8, pp. 69-88.

[13] Krevelen D. W., Schuyer J. 1959: Coal. Chemistry of Coal and its Structure [In Polish: Węgiel. Chemia węgla i jego struktura] PWN. Warszawa.

[14] Krevelen D, W. 1961: COAL. Typology – Chemistry – Physics – Construction. Elsevier Publishing Comany.

[15] Krzesińska M., Pilawa B., Pusz S. 2004: Physical Structure of Hard Coals in the Light of Spectroscopy EPR, Ultrasound and Optic Testing. [In Polish: Struktura fizyczna węgli kamiennych w świetle badań spektroskopii EPR, ultradźwiękowej i optycznej] Karbo 2004 no. 2, pp. 64-67.

[16] Lasoń M. (ed.) 1988: Sorption of Gases and Vapours versus Properties of Polish Hard Coals as Dispersion Systems. [In Polish: Sorpcja gazów i par a własności polskich węgli kamiennych jako układów dyspersyjnych] Part I, Zeszyty Naukowe AGH, Chemia, no. 8. Kraków.

[17] Mahajan O.P. 1991: CO_2 Surface Area of Coal: the 25 – Year Paradox. Carbon 29, 735.
[18] Ndaji F.H., Butterfild I.M., Thomas K.M., 1997: Changes in the macromolecular structure of coals with pyrolysis temperature. Fuel, 76, 169.
[19] Nelson J.R. 1983: Determination of molecular wight between crosslinks of coals from solvent – swelling studies. Fuel 62, 112.
[20] Orzechowska-Zięba A., Nodzeński A. 2008: Sorption Capacity of Hard Coal against Hydrocarbons C_6–$C_{8.}$ [In Polish: Chłonność sorpcyjna węgla kamiennego względem węglowodorów C_6–C_8. Gospodarka Surowcami Mineralnymi, Volume 24, Number 3/3.
[21] Ryncarz T. 1993: An Outline of Rock Mass Physics. [In Polish: Zarys fizyki górotworu] Śląskie Wydawnictwo Techniczne. Katowice.
[22] Seewald H., Klein I. 1985: Methansorption an Stainkohle und Kennzeichnung der Porenstrukture. Gluckauf – Forschungshefte, 47, 149.
[23] Strugała A. 2001: Porosity of Bituminous Coals. [In Polish: Porowatość węgli bitumicznych] Gospodarka Surowcami Mineralnymi, Vol. 17, No. 2, pp. 5-17.
[24] Walker P.L., Verma S.K., Rivera-Ultrilla J., Davis A. 1988: Densities, Porosities and Surface Areas of Coal Maurals as Measured by their Interaction With Gases. Vapours and Liquids, Fuel, 67, 1615.
[25] Żyła M. (ed.) 2000: Hard Coal-Methane System from the Aspect of Desorption and Methane Recovery from Mine Gases. [In Polish: Układ węgiel kamienny-metan w aspekcie desorpcji i odzyskiwania metanu z gazów kopalnianych] Uczelniane Wydawnictwa Naukowo-Dydaktyczne AGH, Kraków.

Przekazano: 11 marca 2012 r.