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POST-CRITICAL MECHANICAL PROPERTIES OF SEDIMENTARY ROCKS IN THE UPPER SILESIAN COAL BASIN (POLAND)

MECHANICZNE WŁAŚCIWOŚCI POKRYTYCZNE SKAŁ OSADOWYCH W GÓRNOŚLĄSKIM ZAGŁĘBIU WĘGLOWYM (POLSKA)

In this paper, we present the results of a study of the Upper Carboniferous sedimentary rocks of the Upper Silesian Coal Basin (USCB) in Poland. We examined the hard coals, which belong to various stratigraphic units of Upper Carboniferous coal-bearing strata, and waste rocks, i.e., sandstones, mudstones, claystones. We present the results of tests of their post-critical mechanical properties. These results are from tests of the post-critical modulus, residual stress and residual deformation from experiments using a servo-controlled testing machine (MTS) with uniaxial compression and conventional triaxial compression. We applied confining pressures of up to 50 MPa at a strain rate of 10^{-5} – 10^{-1} s^{-1} (0.003-6.0 mm/sec). The confining pressure applied in the triaxial compression tests reflected the conditions of current and future mining activities in the USCB at depths exceeding 1.300 metres. The strain rate applied in the tests reflected the values observed in the rockmass surrounding the mine workings and the rate of certain geodynamic phenomena occurring in the Carboniferous rockmass in the USCB, e.g., rock bursts. We present the values of the sub-critical modulus of coals and waste rocks, the functional relationships between the post-critical modulus and uniaxial compression strength, which are described using an exponential function of high correlation coefficients of the given rocks, and an exponential relationship between the post-critical modulus and the longitudinal elasticity modulus (Young's modulus). Based on the results of tests of the post-critical properties of the Carboniferous rocks under triaxial compression and at various strain rates, we devised the functional relationships between the properties of the rocks and the confining pressure. The dependence of the post-critical modulus of the sandstones and claystones on the confining pressure is described using a polynomial function of degree 2, and that of the coals is described using an exponential function. The relationship between the residual stress and residual deformation in the rocks and the confining pressure was described using a linear function. The obtained results of tests have a practical application in forecasting behaviour of rocks located deep, and designing safe exploitation of mineral deposits. Confining pressures of up to 50 MPa used in the conventional triaxial compression tests allowed us to predict the behaviour of the rock mass at large depths. These data provide general knowledge of the tendencies in behaviour of rocks at substantial depths and the ability to design safe methods of mining deposits of various raw materials, including energy sources. These deposits are mined from increasingly great depths as the reserves are gradually exhausted and collieries of the largest European coal basins are continuously reconfigured.

Keywords: post-critical properties of rocks, post-critical modulus, residual deformation, residual stress, Upper Silesian Coal Basin

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Właściwości skał uzyskane z pokrytycznej krzywej naprężeniowo-odkształceniowej opisują pokrytyczne parametry mechaniczne: moduł pokrytyczny, wytrzymałość resztkowa i odkształcenie resztkowe. We współczesnej geomechanice górniczej, znajomość wartości pokrytycznych parametrów mechanicznych skał jest nie do przecenienia. Wartości tych parametrów są, bowiem wykorzystywane do rozwiązywania zadań związanych z projektowaniem i prowadzeniem podziemnej eksploatacji górniczej. Przykładem ich zastosowania jest ocena dynamiki destrukcji skał i górotworu i ocena wystąpienia zagrożeń naturalnych w górotworze spowodowanych prowadzeniem podziemnej eksploatacji górniczej. Dotyczy to głównie zagrożeń geomechanicznych i wodnych, zwłaszcza w kopalniach prowadzących eksploatację w pobliżu zbiorników wodnych utworzonych w zrobach zlikwidowanych kopalń. Ponadto, wartości tych parametrów służą do interpretacji warunków w obrębie źródeł zagrożenia wodnego oraz stanowią podstawę do wyznaczania filarów bezpieczeństwa i stref bezpieczeństwa i mają szerokie zastosowanie w wyznaczaniu zasięgu stref zniszczenia wokół wyrobisk podziemnych i wymiarowania filarów technologicznych w filarowo-komorowym systemie eksploatacji.

W artykule przestawiono wyniki badań właściwości pokrytycznych węgli kamiennych należących do różnych ogniw stratygraficznych serii węglonośnej górnego karbonu w Górnośląskim Zagłębiu Węglowym i skał płonnych – piaskowców i mułowców oraz iłowców. Wyniki badań modułu pokrytycznego, naprężenia resztkowego i odkształcenia resztkowego uzyskano z eksperymentów przeprowadzonych w serwosterowanej maszynie wytrzymałościowej MTS-810. Badania przeprowadzano w jednoosiowym ściskaniu na próbkach w kształcie sześcianu i boku podstawy 50 mm i w osiowosymetrycznym stanie naprężenia, gdy spełniony jest warunek naprężeniowy $\sigma_1 > 0$, $\sigma_2 = \sigma_3 = p$ na próbkach w kształcie walca o średnicy 30 mm i o smukłości 2. Stosowano ciśnienia okólne do wartości 50 MPa. Stosowane w badaniach trójosiowego ściskania ciśnienia okólne były odpowiednie dla warunków prowadzonej i przyszłej eksploatacji w GZW na głębokościach przekraczających 1300 m. Próbki były ściskane w kierunku prostopadłym do uwarstwienia. Sterowanie maszyną wytrzymałościową odbywało się za pomocą prędkości odkształcenia podłużnego mierzonego w systemie pomiarowym prasy przemieszczeniem tłoka. Eksperymenty przeprowadzano z prędkością odkształcenia rzędu 10^{-5} – 10^{-1} s^{-1}, co po uwzględnieniu wysokości próbek odpowiada prędkościom przemieszczenia tłoka (0,003-6,0 mm/s). Prędkości odkształcenia stosowane w badaniach odpowiadały prędkości odkształcania się skał w otoczeniu wyrobisk eksploatacyjnych i prędkości niektórych zjawisk geodynamicznych, które zachodzą w górotworze karbońskim w GZW, na przykład tąpnięć.

Na podstawie badań skał w warunkach jednoosiowego ściskania podano wartości modułu pokrytycznego węgli i skał płonnych w poszczególnych grupach stratygraficznych górnego karbonu w Górnośląskim Zagłębiu Węglowym. Wartości modułu pokrytycznego zmieniają się w szerokim zakresie (Tab. 1, 2).

Sformułowano równania matematyczne zależności geomechanicznych parametrów pokrytycznych od wytrzymałości na jednoosiowe ściskanie i od ciśnienia okólnego. Kluczowymi składnikami opracowanych równań był moduł pokrytyczny, naprężenie resztkowe i odkształcenie resztkowe. Wyniki badań są zróżnicowane w zależności od typu skały, ciśnienia okólnego i prędkości odkształcenia.

Zależności funkcyjne modułu pokrytycznego od wytrzymałości na jednoosiowe ściskanie opisano funkcją potęgową o wysokich współczynnikach korelacji dla poszczególnych skał (Tab. 3). Wykazano, że węgle kamienne w GZW w porównaniu ze skałami płonnymi osiągają większe wartości modułu pokrytycznego przy mniejszych wartościach wytrzymałości na jednoosiowe ściskanie. Po przekroczeniu wytrzymałości na jednoosiowe ściskanie dynamika rozpadu węgli jest większa niż dynamika rozpadu skał płonnych.

Na podstawie wyników badań skał karbońskich podano zależność potęgową między modułem pokrytycznym a modułem Younga (Tab. 4).

W warunkach osiowo-symetrycznego stanu naprężenia, gdy spełniony jest warunek $\sigma_1 > \sigma_2 = \sigma_3$, wzrost wartości ciśnienia okólnego powoduje przejście skały ze stanu kruchego w stan ciągliwy przy wysokich ciśnieniach okólnych. W części pokrytycznej krzywej naprężeniowo-odkształceniowej zmniejsza się wartość spadku naprężenia, co oznacza, że ze wzrostem ciśnienia okólnego wzrasta wartość naprężenia resztkowego a krzywa pokrytyczna jest łagodniej nachylona w stosunku do osi poziomej. Skutkuje to mniejszymi wartościami modułu pokrytycznego, który obrazuje dynamikę niszczenia skały w obszarze pozniszczeniowym.

Badania właściwości pokrytycznych skał karbońskich w trójosiowym ściskaniu wykonano w warunkach wzrastających ciśnień okólnych do 50 MPa, przy różnych wartościach prędkości odkształcenia. Wykazano liczne zmiany wartości parametrów pokrytycznych wynikające ze stosowanych wartości ciśnienia okólnego.

Moduł pokrytyczny maleje ze wzrostem ciśnienia okólnego dla piaskowca i węgla zgodnie z funkcją wielomianu drugiego stopnia lub wykładniczą (Tab. 5, Rys. 7, 8). Dla iłowca nie stwierdzono zależności

pomiędzy modułem osłabienia a ciśnieniem okólnym 0-50 MPa w zakresie prędkości odkształcenia $10^{-4} - 10^{-1}$ s^{-1}. Wykazano również, że moduł pokrytyczny węgla w warunkach wzrastających ciśnień okólnych jest mniejszy niż dla skał płonnych. Badania wpływu prędkości odkształcenia na wartości modułu pokrytycznego skał karbońskich nie wykazały regularnych jego zmian wraz z prędkością odkształcenia.

Zależność naprężenia resztkowego i odkształcenia resztkowego od ciśnień okólnych (0-50 MPa) w zakresie prędkości odkształcenia $10^{-5} \div 10^{-1}$ s^{-1} dla badanych skał osadowych karbonu GZW opisano funkcją liniową (Tab. 6, Rys. 9; Tab. 7. Rys. 10). Dla wyższych ciśnień okólnych różnice między wartościami naprężenia resztkowego i odkształcenia resztkowego dla poszczególnych skał są coraz większe. Piaskowce wykazują największe wartości naprężenia resztkowego w miarę wzrostu ciśnienia okólnego a węgle wartości najmniejsze. Z przebiegu krzywych widać również, że skały płonne charakteryzują się mniejszymi wartościami odkształcenia resztkowego w porównaniu z węglem kamiennym. Spośród parametrów geomechanicznych największe zmiany wartości ze wzrostem ciśnienia okólnego wykazuje naprężenie resztkowe, które odzwierciedla nośność pokrytyczną górotworu w rejonach eksploatacji (np. nośne strefy spękanych filarów węglowych). Dla piaskowca, iłowca i węgla zależność naprężenie resztkowe – ciśnienie okólne 0-50 MPa, odpowiadające warunkom eksploatacji w GZW, ma przebieg prostoliniowy.

Analiza wpływu prędkości odkształcenia i ciśnienia okólnego na wartości parametrów poznisz-czeniowych skał karbońskich GZW wykazała, że ciśnienie okólne w zakresie 0-50 MPa ma większy wpływ na wartość parametrów pozniszczeniowych niż prędkość odkształcenia w zakresie $10^{-5} - 10^{-1}$ s^{-1} (0,003-6,0 mm/sec).

Stosowane w eksperymentach trójosiowego konwencjonalnego ściskania ciśnienia okólne do 50 MPa dają podstawę prognozowania zachowania się górotworu na dużych głębokościach. Daje to ogólną wiedzę o tendencjach zachowania się skał na dużych głębokościach i możliwościach wnioskowania dla celów projektowania bezpiecznej eksploatacji złóż różnych surowców, w tym również surowców energetycznych, których eksploatacja schodzi na coraz to większe głębokości w związku ze stopniowym wyczerpywaniem się złóż bilansowych i postępującą restrukturyzacją kopalń w największych zagłębiach europejskich.

Słowa kluczowe: właściwości pokrytyczne skał, moduł pokrytyczny, odkształcenie resztkowe, naprężenie resztkowe, Górnośląskie Zagłębie Węglowe

1. Introduction

It was possible to examine the post-critical behaviour of rocks using servo-controlled testing machines in the tests of mechanical properties of rocks. During the process of compressing rock samples (uniaxial load, conventional triaxial compression, true triaxial compression), we may obtain a destruction curve for the entire range of its loading when the stiffness of the testing machine is greater than the stiffness of the tested rock sample, and when the machine is servo-controlled, the system provides an appropriately high reaction rate for the removal of the load during the process of destroying a sample. This arrangement lowers the requirements concerning stiffness of the frame loading the testing machine (Cain, 1996). The works of Cook (1965), Bieniawski (1970) and Wawersik and Fairhurst (1970) are pioneering studies in this area. The rock properties obtained from post-critical stress-strain curves describe the post-critical mechanical parameters: post-critical modulus, residual strength, and residual deformation.

The post-critical mechanical parameters are used to solve problems of mining geomechanics. These parameters may be used directly to assess natural hazards, such as the dynamics of rocks and rockmass deformation, which is indispensable for describing such methan hazards (Krause & Łukowicz, 2012; Dziurzyński & Krause, 2012; Koptoń & Wierzchowski, 2014) and geomechanical hazards as sejsmic hazard (Butra et al., 2001; Mutke et al., 2009; Marcak & Mutke, 2013), and rockbursts (Kabiesz 2010), cave-ins, and gas and rock outbursts. They also play an important role in forecasting rockburst hazards in the mined areas by using them to evaluate the susceptibility of the rockmass to rockbursts (Bukowska 2006, 2012). The post-critical mechanical parameters of rocks are also used in forecasting other natural hazards associated with mining activities, e.g., water hazards (Bukowski, 2009, 2015; Bukowski & Augustyniak 2013), especially in collieries in the vicinity of water reservoirs formed in goafs of abandoned collieries (Bukowski, 2010). The parameters are used for interpreting conditions near the source of the water hazard and are the basis for designing support pillars and protective zones. They are widely used in determining the range of a failure zone around workings of various cross-sectional shapes and the sizes of pillars in the room-and-pillar mining method.

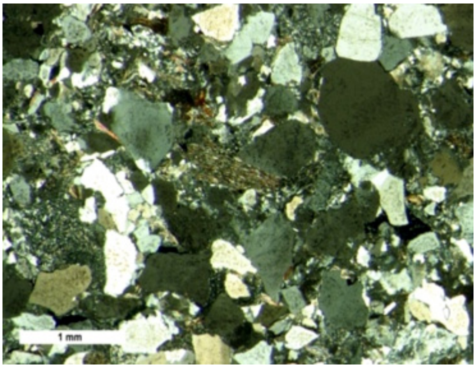
Moreover, disadvantageous geotechnical conditions in the rock mass require the development and application of innovative techniques of coal mining (Kabiesz et al., 2008; Drzewiecki & Kabiesz, 2008). Considering the above-mentioned data we conducted tests of geomechanical properties of Carboniferous rocks of different various load conditions, in the full range of their deformation. The fact that, as a result of mining activity, the rock mass is destroyed was also taken into consideration. Around underground workings there is a destruction zone of the rock mass and that is why it is necessary to forecast deformation of the rock mass and stability of underground workings (Prusek, 2010; Prusek & Jędrzejec, 2008; Majcherczyk et al., 2006) and determine the complete stress tensor (Makówka, 2014; Makówka & Drzewiecki, 2011). Nowadays, to do this in numerical calculations, also full stress-strain characteristics of rocks is considered.

2. Upper Carboniferous rocks in the Upper Silesian Coal Basin

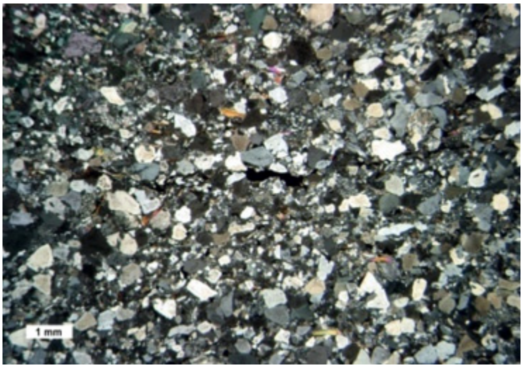
The Upper Silesian Coal Basin (USCB) is one of several Upper Carboniferous basins. These coal basins are found in western North America, Europe, North Africa, and western Asia. The formation of the Upper Silesian Coal Basin is associated with the Variscan orogeny. It initially was a premontane basin that later transformed into an intramontane basin. The coal-bearing unit of the Upper Carboniferous Upper Silesian Coal Basin is composed of clastic and clayey sedimentary rocks, organogenic rocks and subordinate chemical rocks. Sedimentation of coal-bearing deposits of the Upper Carboniferous of the USCB is characterised by its distinctive sequence of rock types and bedding types. Sedimentary cyclothems in various parts of the basin generally have thicknesses ranging between a few and a few dozen meters. The cyclothems contain primarily sandstones of various grain sizes, mudstones, claystones and coals. Molasse formations are found together with rocks of chemical and organic origin (siderites, clay siderites, coal shales and refractory shales).

This paper presents the results of investigation of these sandstones, mudstones, claystones and coals. The characteristics of the rocks are presented below.

Sandstones of the Upper Carboniferous of the USCB are medium-grained clastic rocks, typically arenite. Based on their grain sizes, they are divided into coarse-grained (grain diameter of 2-1 mm), medium-grained (grain diameter of 1-0.5 mm) and fine-grained (grain diameter of 0.5-0.1 mm) sandstones. The most common components of the sandstones are quartz and other mineral forms of silica (opal, chalcedony), feldspars, i.e., primarily sodium/potassium (orthoclase) and subordinate plagioclase (often highly altered to sericite or kaolinite), clay minerals (kaolinite, mica) and carbonates. The micas are minor components: the biotite is often highly altered and the muscovite is mechanically weathered. The rudzkie and orzeskie beds contain heavy and subsidiary minerals: zirconium, tourmaline, and apatite. In marginal beds and saddle beds, biotite dominates the subsidiary minerals. A group of clay minerals (hydromica, kaolinite, chlorite, minerals of mixed structure, i.e., illite/montmorillonite) dominates the minerals forming the binder, whereas carbonate minerals (dolomite, siderite, calcite) and silica are rarer. The dominant sandstones in the USCB are fine-grained (Fig. 1) and grey, medium-grained sandstones. These are characterised by chaotic or oriented textures. Quartz sandstones dominate in the saddle beds and rudzkie beds. Polymict sandstones dominate the upper part of the Upper Silesian sandstone series, mudstone series and Cracow sandstone series. The sandstones of marginal beds (porębskie, jaklowieckie, gruszowskie and pietrzkowickie beds) are primarily greywacke or polymict sandstones interbedded with rare local thin quartz sandstones.



Rigid framework of grains (transmitted light)



Lamina with organic matter (transmitted light)

Fig. 1. Photomicrographs (transmitted light) of a sample of fine-grained quartz sandstone, medium sorted, of porous and contact clay cementation

The proportion of sandstones in the USCB varies (Fig. 2) both vertically and horizontally along the bedding. Among the molasse formations, which form the main core of the coal-bearing deposits in the USCB, the proportion of sandstones in the Upper Silesian sandstone series exceeds 50%, and they dominate the Cracow sandstone series, where their proportion in the łaziskie beds exceeds 95%. Thick layers of sandstones that are coarse-grained, medium-grained and fine-grained and coal deposits, claystones and mudstones are the basic components of the saddle beds and lower part of the rudzkie beds. In the rudzkie beds in the northern part of the basin, the proportion of fine clastic sediments is greater, especially in the upper part, where the thick layers of sandstones are interbedded with clay/mud containing coal deposits. The sandstones form layers of various thicknesses.

Mudstones are fine-grained clastic rocks intermediate between sandstones and claystones, in which the proportion of grains smaller than 30 mm exceeds 75%. Their primary components are grains of quartz, feldspars, fine-grained rock clasts, micas and carbonates. The clay mineral component is subordinate. Bedding of the mudstones is primarily parallel, in the form of layers of dusty and sandy material highlighted by the presence of mica on the diagonal or wavy cleavage planes. The mudstones play the primary role in the mudstone series, where their proportion reaches 40% (Fig. 2). The proportion of mudstones is also significant in the paralic series and marginal beds, where they accounts for 38%. Compared to the sandstones, the mudstones are present in thin layers, although their compressional strength is often higher than that of the Carboniferous sandstones and exceeds 100 MPa.

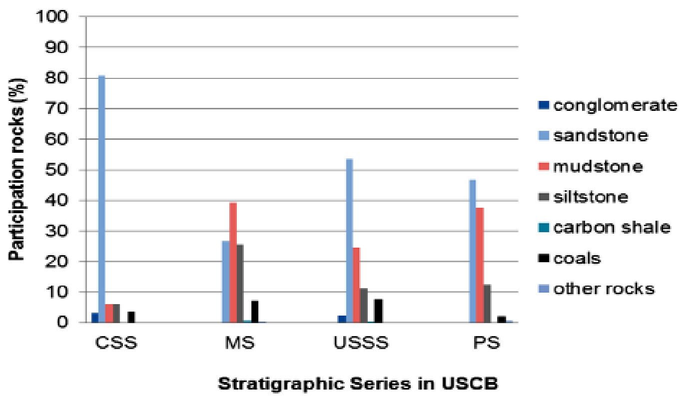


Fig. 2. Proportion of rocks in stratigraphic series of Upper Carboniferous USCB:
CSS – Cracow Sandstone Series; MS – Mudstone Series; USSS – Upper Silesian Sandstone Series;
PS – Paralic Series

The claystones (Fig. 3) contain over 50% grains smaller than 0.002 mm. Clay minerals dominate their mineral composition. The claystones display indistinct lamination, which is primarily parallel. They contain abundant plant detritus. The claystones that feature easily separated flat beds, usually parallel to the bedding, are typically clay shales (clayey admixtures) or sandy shales (sandy admixtures). The largest proportion of claystones is observed in the samples from boreholes in the mudstone series, where they account for approximately 26% of the rock. In the area of the USCB, the claystones are of various types: those with plant detritus, of various sand admixtures, with local concentrations of clay siderites or bedded with claystones or sandstones. Generally, the claystones display the lowest values of geomechanical parameters, whereas locally stronger rock (e.g., claystone with sand, claystone with clay siderite) may result in a considerable increase in the parameters.

Hard coal is a caustobiolith created via accumulating plant matter under appropriate environmental and climate conditions. Thus, hard coal belongs to the group of rocks of organic origin.

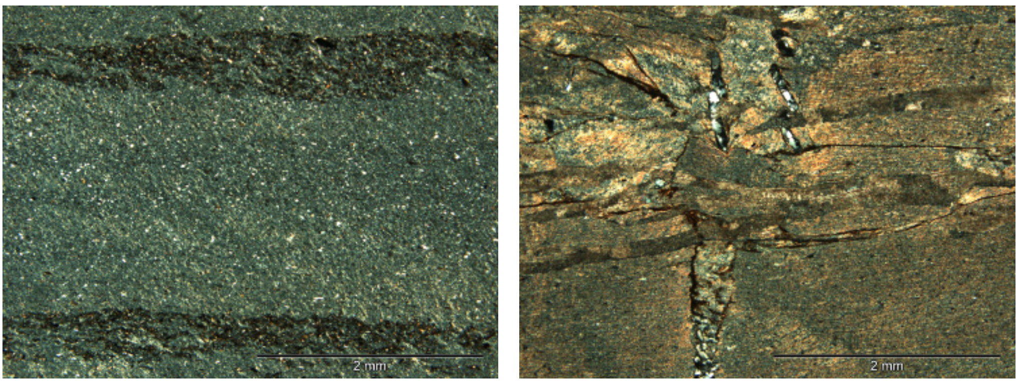


Fig. 3. Photomicrographs of claystone; transmitted light, polarised, with one nicol prism

The organic matter underwent a lengthy series of processes, initially of biogenic transformation (open peat bog) and then of geochemical transformation. The primary components of coals are carbon, hydrogen, oxygen, sulphur and nitrogen. Coal contains additional mineral substances (e.g., silicates, sulphides, Figs. 4, 5) and rare elements (e.g., arsenic, gallium). The colour of coal reflects its petrographic composition and rank. Depending on the petrographic composition, the colour changes from pitch black through black and grey-black to grey. With the increase in the rank of coal, the colour changes from dark brown, through black, and grey-black to steel-grey. Coal deposits in the USCB are primarily found together with sandstones, mudstones, claystones and in lesser amounts with conglomerates, sedimentary clastic and phytogenic rocks, which are classified as the lower paralic series and have characteristic regular structure; and in the upper land series of the Variscan – Upper Carboniferous molasse.

The research presented in this paper refers to the sandstones, mudstone, claystones and coals. Coal is an organic rock, and its petrographic composition varies greatly, which significantly influences its properties, including its geomechanical properties.

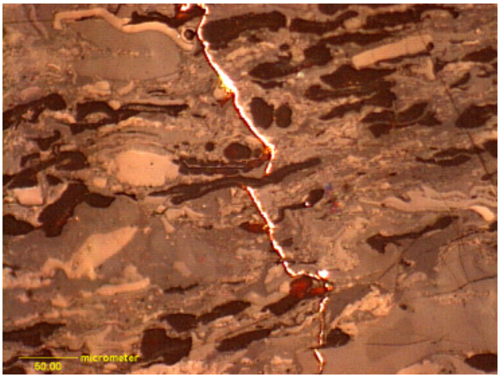


Fig. 4. Duroclarite composed of z inertinite (lightest colour), liptinite (darkest colour) and basic vitrinite mass with veinlets of pyrite

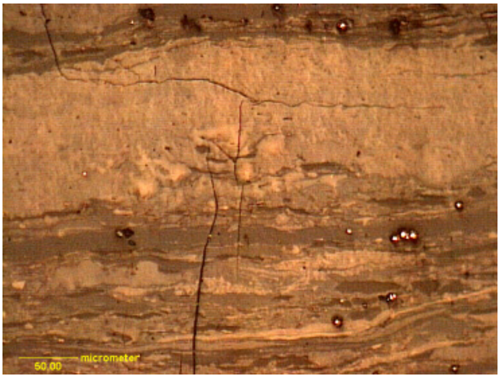


Fig. 5. Inertinite (light fragment at the top of the photo) and clarodurite (bottom of the photo) with single crystals of pyrite and cracks

3. Methods of research into post-critical properties of rocks

The Carboniferous rockmass in the USCB is not homogenous. It is anisotropic, discontinuous and of nonlinear deformation. These qualities result in significant variations in rock properties along the bedding (horizontally) and with the depth (vertically). Significant variations in the values of the parameters make it necessary to use an average value of a given parameter, which consists of several values obtained during tests.

The results of research into the mechanical properties of the sandstones, mudstone, claystones and coals presented in this paper were obtained from tests conducted using a stiff testing machine, the MTS-810. The tests included uniaxial compression test of 50×50×50 mm cubic samples (in an axially symmetric stress-strain state ($\sigma_1 > 0$, $\sigma_2 = \sigma_3 = 0$), meeting the conditions $\sigma_1 > 0$ and

$\sigma_2 = \sigma_3 = p$ on toroid samples of 30 mm diameter and a slenderness ratio of 2. The samples were compressed perpendicular to bedding. Control of the stiff testing machine was performed via the longitudinal strain rate measured in the system of the press with the stroke of the piston. The tests were conducted at strain rates of $10^{-5} – 10^{-1}$ s^{-1} (0,003-6,0 mm/s).

In tests of conventional triaxial compression, we used a pressure chamber with a maximum confining pressure of 70 MPa. An integral element of the equipment for testing rocks in a pressure chamber is a pump that the side pressure to be maintained at a given, steady level. The confining pressure in the chamber for triaxial tests was produced using oil. Using a liquid medium requires the rock samples to be sealed against potential permeation of liquid into pores and micro-cracks. To do so, before the test, the samples were sealed with latex covers and covered with heat shrink wrap tightly covering the entire surface of the rock sample. The tests were conducted in accordance with the procedures of conventional single-stage triaxial testing by Kovari et al. (1983). The laboratory testing of the rocks was conducted in accordance with ISRM recommendations (Ulusay & Hudson (ed.), 2007) and our own procedures based on experience, collected over many years, in interpreting the strength data obtained using a serco-controled testing machine.

4. Results of research into post-critical mechanical properties of Carboniferous rocks in USCB

Based on the post-failure stress-strain characteristics obtained during the uniaxial compression tests and triaxial compression tests in the stiff testing machine, we determined the post-critical modulus, residual strength and residual deformation (Fig. 6). The method of determining these parameters has not yet been firmly established. In research centres around the world and in Poland, these parameters are determined at various loads and using various methods of control of the stiff testing machine.

One way to determine the post-critical modulus is to determine the tangent of the angle of the linear approximation of a stress-strain curve in its falling portion (Fig. 6) or to calculate its value using the equation

$$M = \frac{\Delta\sigma}{\Delta\varepsilon} \tag{1}$$

where

$\Delta\sigma$ — is the decrease in strain in the falling portion of the stress-strain curve, and

$\Delta\varepsilon$ — is the increase in deformation in the falling portion of the stress-strain curve.

The residual deformation corresponds to the residual stress (Figure 6) and is determined using the dependence

$$\varepsilon_r = \frac{\Delta h}{h} \cdot 1000 \tag{2}$$

where

h — is the height of the sample, in mm, before the test,

Δh — is the change in the height of the sample determined on the border of residual strength in the post-critical portion of the stress-strain curve of the compressed sample, mm.

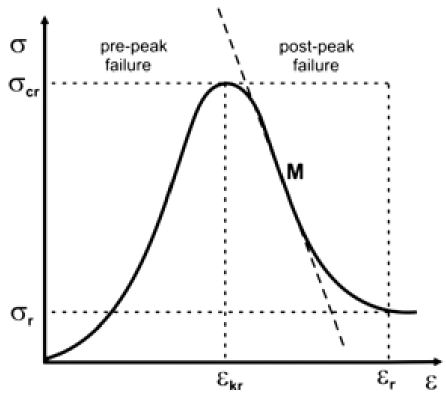


Fig. 6. Determining post-critical modulus *M*, residual stress (σ_r), and residual strain (ε_r) based on the shape of the stress-strain curve

In the post-critical portion of the stress-strain curve, the stress decreases until it reaches the residual value. The decrease in stress in the post-critical area corresponds to an increase in the residual deformation. The value of the residual stress reflects the value of residual deformation (Fig. 6).

4.1. Results of tests of post-critical modulus of Carboniferous rocks in a uniaxial compression test

The post-critical modulus of the rocks in the USCB, determined under uniaxial compression, varies greatly depending on the stratigraphic unit of the Upper Carboniferous series. The ranges of these parameters together with their average values and the size (n) of the data sets are presented in Table 1, and those for waste rocks are presented in Table 2.

TABLE 1

Post-critical modulus of coals in USCB

Stratigraphic series of Upper Carboniferous	**Stratigraphic coal group; number of sets**	**Average of post-critical modulus, GPa**	**Minimum of post-critical modulus, GPa**	**Maximum of post-critical modulus, GPa**
CSS	Libiąz Beds (n = 12)	14.395	13.400	15.390
CSS	Łaziskie Beds(n = 912)	14.200	1.360	41.209
MS	Orzeskie Beds (n = 592)	8.849	0.762	26.620
USSS	Ruda Beds (n = 1964)	7.509	0.230	43.900
USSS	Siodłowe Beds (n = 1922)	11.779	0.590	43.095
PS	Porębskie Beds (n = 55)	5.958	0.203	18.640
PS	Jaklowieckie Beds (n = 228)	8.683	0.412	37.728

TABLE 2

Post-critical modulus of waste rock in USCB

Rocks; number of sets	Average of post-critical modulus, GPa	Minimum of post-critical modulus, GPa	Maximum of post-critical modulus, GPa
conglomerates (n = 20)	15.170	4.500	24.820
coarse-grained sandstones (n = 76)	4.401	0.418	13.030
medium grit sandstone (n = 381)	21.196	1.275	76.430
fine-grained sandstones (n = 3817)	30.282	1.600	72.284
mudstones (n = 1084)	24.681	2.405	57.339
claystones (n = 2785)	14.872	0.873	54.391

The multiple-year study of the properties of the rocks in the USCB indicated a dependence of the post-critical modulus on the uniaxial compressive strength of rocks. The results of statistical analysis of data from the primary types of rocks of the Upper Carboniferous USCB are presented in Table 3. These figures contain graphs of the dependence, regression equations, correlation coefficients (r) and the size (n) of the data sets. The connection between the compressive strength and post-critical modulus displays the characteristics of an exponential relationship with correlation coefficients of 0.86 for the coals, 0.78 for the claystones, 0.69 for the mudstones and 0.88 for the sandstones. The functional relationships between the uniaxial compressive strength (UCS) and uniaxial post-critical modulus have a significance level of 0.001.

TABLE 3

Dependence of post-critical modulus and uniaxial compression stress of coals and waste rocks in USCB

Rocks; number of sets	Equation	Correlation Coefficient *r*
coals (n = 5685)	$M = 91.163\ \mathrm{UCS}^{1,4627}$	0.86
claystones (n = 2713)	$M = 43.543\ \mathrm{UCS}^{1,5274}$	0.78
mudstones (n = 1075)	$M = 376.0\ \mathrm{UCS}^{0,990}$	0.69
sandstones (n = 1425)	$M = 91.568\ \mathrm{UCS}^{1,3267}$	0.88

We conclude that the hard coals in the USCB have higher values of the post-critical modulus at lower values of compressive strength compared to the waste rocks. These uniaxial compression strengths indicate that the dynamics of failure of the coals are greater than that of the waste rocks.

We demonstrated a dependence between the pre-critical and post-critical mechanical properties of the Upper Carboniferous rocks in the USCB. There is a distinct relationship between the post-critical modulus and longitudinal elasticity modulus (Young's modulus), and this relationship is an exponential one (Table 4).

TABLE 4

Dependence of post-critical modulus and longitudinal elasticity modulus of coals and waste rocks in USCB

Rocks; number of sets	Equation	Correlation Coefficient *r*
coals (n = 4180)	$M = 0.0321\ \mathrm{E}^{1,51}$	0.82
waste rocks (n = 4575)	$M = 0.0322\ \mathrm{E}^{1,66}$	0.82

4.2. Results of tests of post-critical properties of Carboniferous rocks under triaxial compression at various strain rates

In an axially symmetric stress-strain state, when the compression condition $\sigma_1 > \sigma_2 = \sigma_3$ is met, an increase in the confining pressure results in the transition of rocks from brittle fracture to ductile flow at high confining pressures. In the post-critical part of the stress-strain curve, the strain decreases. In other words, with the increase in the confining pressure, the residual stress increases and the post-critical curve makes a smaller angle with the horizontal axis. This nature of the post-critical curve results in lower values of the post-critical modulus, which reflects the dynamics of rock deformation in the post-failure area. At low values of confining pressure in highly brittle rocks, e.g., crystalline, certain researchers have observed, with increases in the confining pressure, only a slight decrease in the post-failure modulus (Arzua, Alejano 2013). In the post-critical part of the stress-strain curve, the stress decreases. In other words, with the increase in confining pressure, the residual stress increases and the post-critical curve has a lower gradient. This gradient results in lower values of the post-critical modulus, which reflects the dynamics of the rock deformation in the post-failure area and higher values of residual strain. In the case of fine-grained sandstones and claystones in the USCB, the dependence of the post-critical modulus on confining pressures between 0 and 50 MPa is best described using a polynomial function of degree 2 (Table 5). For claystones tested using a strain rate of $10^{-4} – 10^{-1}$ s^{-1} (0,006 – 6,0 mm/s), there were no significant functional relationships. This finding most likely was caused by diversity among the tested claystones and the difficulties in preparing a sufficient number of samples for the tests. In the case of coals in the USCB, the dependence of the post-critical modulus on confining pressures between 0 and 50 MPa is best described using an exponential function of high correlation coefficients (Table 5).

TABLE 5

Dependence of post-critical modulus on confining pressures of 0-50 MPa
and various strain rates (Bukowska 2005)

Rock	Strain Rate (σ^{-1})	Equation	Correlation Coefficient *r*
sandstone	$5 \cdot 10^{-5}$	$M = 0.01p^2 – 0.92p + 162.15$	0.98
	10^{-4}	$M = 0.07p^2 – 4.97p + 192.86$	0.93
	10^{-3}	$M = 0.04p^2 – 2.78p + 143.03$	0.92
	10^{-2}	$M = 0.05p^2 – 2.44p + 146.56$	0.66
	10^{-1}	$M = 0.002p^2 – 0.68p + 108.58$	0.95
claystone	$5 \cdot 10^{-5}$	$M = 0.01p^2 – 1.22p + 97.11$	0.91
coal (Fig. 7)	$5 \cdot 10^{-5}$	$M = 28.64e^{-0.05p}$	0.85
	10^{-4}	$M = 20.96e^{-0.04p}$	0.82
	10^{-3}	$M = 37.48e^{-0.07p}$	0.92
	10^{-2}	$M = 28.04e^{-0.06p}$	0.86
	10^{-1}	$M = 24.43e^{-0.03p}$	0.99

Figure 8 shows variations in the post-critical modulus of the Carboniferous rocks at strain rates of 10^{-5} s^{-1}. The curves of the values of the post-critical modulus with increasing confining pressure show that the post-critical modulus of the coal is much lower than that of the waste rocks, despite the fact that the trends in their changes are similar.

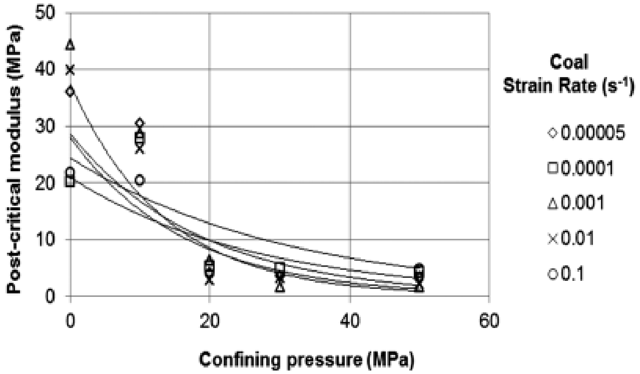


Fig. 7. Dependence of post-critical modulus of coal in USCB on pressure and strain rate

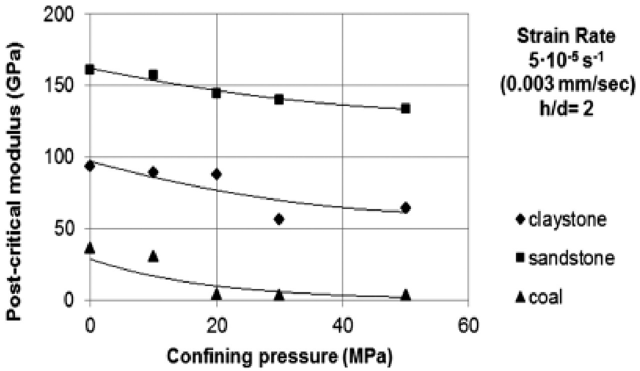


Fig. 8. Dependence of post-critical modulus of sedimentary rocks of USCB on confining pressure

Changes in the residual stress with confining pressure in sandstones, claystones and USCB coals is best approximated using a linear relationship of high correlation coefficients (Table 6). Figure 9 shows curves of changes in the residual stress with at confining pressures of up to 50 MPa. The curves show that, in the case of uniaxial compression ($\sigma_2 = \sigma_3 = 0$), the values of residual stresses in the three types of rocks are similar. With the increase in confining pressure, there are distinct differences in the values of residual stress for the tested rocks. Sandstones display the highest values of residual stress with the increase in confining pressure, and coals display the lowest values.

Increases in the confining pressure result in changes in the residual deformation of the rocks. The dependence of the tested rocks is described using a linear function, for which we obtained high correlation coefficients (Table 7). We also confirmed a pattern: the increases in certain parameters resulting from the increase in confining pressure is larger for the rocks of lower uniaxial compression strength. Figure 10 presents the dependences of the residual deformation on the confining pressure for coal and the surrounding rocks (Carboniferous sandstone and claystone).

The curves show clear differences in the values of residual deformation for coals and waste rocks at confining pressures above zero. The curves also show that waste rocks have lower values of residual deformation than does hard coal. This trend is characteristic of all of the strain rates within the range of $10^{-5} – 10^{-1}$ s^{-1}.

TABLE 6

Dependence of residual stress on confining pressure in the range of 0-50 MPa at various strain rates

Rock	Strain Rate (s^{-1})	Equation	Correlation Coefficient *r*
sandstone (Bukowska 2005)	$5{\cdot}10^{-5}$	$\sigma_r = 4.56p + 13.81$	0.99
	10^{-4}	$\sigma_r = 4.21p + 25.78$	0.98
	10^{-3}	$\sigma_r = 4.69p + 21.48$	0.99
	10^{-2}	$\sigma_r = 3.49p + 51.96$	0.99
	10^{-1}	$\sigma_r = 4.10p + 24.81$	0.97
claystone	$5{\cdot}10^{-5}$	$\sigma_r = 3.07p + 16.78$	0.99
	10^{-4}	$\sigma_r = 2.56p + 26.55$	0.97
	10^{-3}	$\sigma_r = 3.63p + 16.67$	0.99
	10^{-2}	$\sigma_r = 3.25p + 20.86$	0.97
	10^{-1}	$\sigma_r = 3.17p + 22{,}92$	0.96
coal	$5{\cdot}10^{-5}$	$\sigma_r = 3.21p + 4.63$	0.96
	10^{-4}	$\sigma_r = 2.01p + 14.88$	0.89
	10^{-3}	$\sigma_r = 2.28p + 10.99$	0.98
	10^{-2}	$\sigma_r = 2.83p + 17.38$	0.97
	10^{-1}	$\sigma_r = 2.89p + 24.95$	0.95

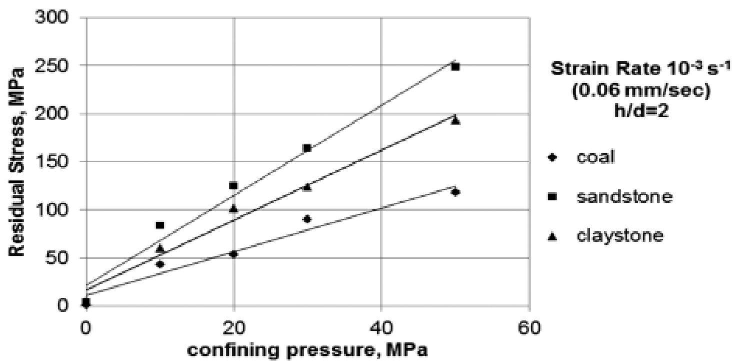


Fig. 9. Dependence of residual stress in sedimentary rocks of the USCB on the confining pressure

TABLE 7

Dependence of residual strain on confining pressures of 0-50 MPa for various strain rates

Rock	Strain Rate (s^{-1})	Equation	Correlation Coefficient *r*
sandstone	$5 \cdot 10^{-5}$	$\varepsilon_r = 0.424p+12.41$	0.90
	10^{-4}	$\varepsilon_r = 0.567p + 14.75$	0.89
	10^{-3}	$\varepsilon_r = 0.423p + 13.78$	0.92
	10^{-2}	$\varepsilon_r = 0.346p + 14.50$	0.88
	10^{-1}	$\varepsilon_r = 0.460p + 16.79$	0.94
claystone	$5 \cdot 10^{-5}$	$\varepsilon_r = 0.196p + 14.15$	0.81
	10^{-4}	$\varepsilon_r = 0.439p + 8.837$	0.96
	10^{-3}	$\varepsilon_r = 0.624p + 8{,}149$	0.95
	10^{-2}	$\varepsilon_r = 0.227p + 15.06$	0.66
	10^{-1}	$\varepsilon_r = 0.482p + 12.79$	0.99
coal	$5 \cdot 10^{-5}$	$\varepsilon_r = 0.928p + 18.80$	0.90
	10^{-4}	$\varepsilon_r = 0.716p + 17.01$	0.97
	10^{-3}	$\varepsilon_r = 0.878p + 28.48$	0.80
	10^{-2}	$\varepsilon_r = 1.191p + 20.31$	0.98
	10^{-1}	$\varepsilon_r = 0.979p + 25.21$	0.87

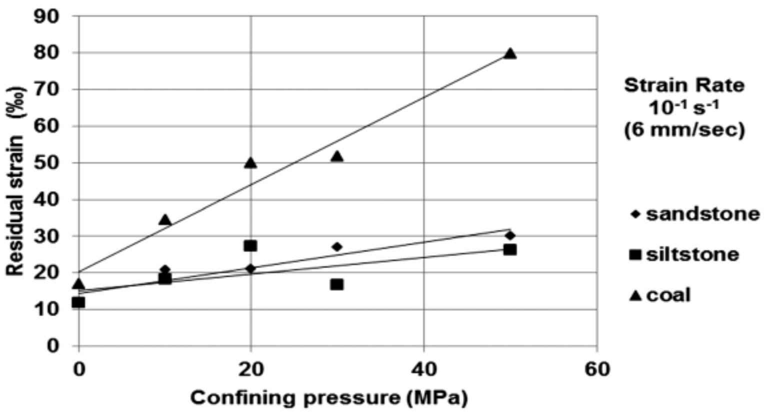


Fig. 10. Dependence of residual strain in sedimentary rocks of the USCB on confining pressure

Tests of the influence of confining pressure on the post-critical mechanical parameters of Carboniferous rocks were conducted by applying various strain rates in the range of $10^{-5} - 10^{-1}$ s^{-1} during the experiments.

Knowledge of the influence of the strain rate on the behaviour of rocks is used in solving many problems in mining geomechanics and geoengineering. The strain rates used in the experiments correspond with those of certain natural phenomena occurring in the rockmass and processes caused by mining activities. The rate of $10^{-5} - 10^{-3}$ s^{-1} is characteristic of deformation of rocks in the vicinity of underground workings. Many undesirable phenomena in the rockmass occur at various deformation rates. For example, rockbursts are dynamic, whereas the convergence of workings, i.e., slow closing of workings, is pseudostatic. Strain rates corresponding to the phenomena of rockbursts and rock outbursts fall within the range of $10^{-2} – 10^{2}$ s^{-1}. The influence of the strain rate on certain mechanical properties of rocks was described in foreign literature in the 1930s. Newer research dates to the 1960s and subsequent years (Peng, 1973; Paterson, 1978; Blanton, 1981; Okubo & Nishimatsu, 1985; Kwaśniewski, 1986; Lis & Kijewski, 1987; Bezat, 1987; Chong et al., 1989; Krzysztoń, 1990; Olsson, 1991; Lajtai et al., 1991; Li et al., 1999; Bukowska, 2000). These studies refer primarily to tests of the pre-critical parameters of rocks under uniaxial compression. Research into these post-critical parameters includes work by Bieniawski (1970), Peng (1973) and Bukowska (2000).

The research and analyses of Carboniferous rocks in the USCB indicate that the post-critical modulus of the sandstone at confining pressures of 0-50 MPa decreases by approximately 10 and 50%, whereas the modulus of the coal under confining pressures of 0-50 MPa decreases from 124% (for strain rate of 10^{-5} s^{-1}) to 78% (for strain rate of 10^{-1} s^{-1}) of the maximum value occurring at a confining pressure p = 0 MPa. What is characteristic of the coal under confining pressures of 10-20 MPa is a decrease in the post-critical modulus of approximately 80%. At the same time, we can observe variations in the post-critical modulus of the coal depending on the strain rate at lower confining pressures. The post-critical modulus at a given strain rate decreases with higher confining pressures (20-50 MPa). For claystone, we observed no dependence between the post-critical modulus and confining pressures of 0-50 MPa at strain rates of $10^{-4} – 10^{-1}$ s^{-1}. With increases in the confining pressure from p = 0 MPa to p = 50 MPa, the influence of the strain rate on the residual strain of the sandstone decreases, whereas the influence of the strain rate on residual stress of the coal increases.

5. Conclusions

The scope of the research was the post-failure parameters of Upper Carboniferous sedimentary rocks of the Upper Silesian Coal Basin in Poland. The tests were conducted in a stiff testing machine, or MTS. The testing machine was controlled by setting the total strain of a sample, which is expressed as the piston stroke.

Based on the tests of rocks under uniaxial compression, we obtained values of the sub-critical modulus of coals and waste rocks in particular stratigraphic groups of the Upper Carboniferous. We also determined the dependence of the post-critical modulus on the uniaxial compressive strength in sandstones, mudstones, claystones and coals. The dependences of the post-critical modulus on the uniaxial compressive strength were described using an exponential function of high correlation coefficients for the given rocks. We demonstrated that the coals of the USCB compared to the waste rocks display high values of the post-critical modulus at lower values of uniaxial compressive strength. After exceeding the uniaxial compressive strength, the dynamics of deformation of the coals are higher than the dynamics of deformation of the waste rocks. Based on the test results, we derived an exponential relationship between the post-critical modulus and longitudinal elasticity modulus (Young's modulus).

The tests of the post-critical properties of the Carboniferous rocks under triaxial compression were conducted under confining pressures up to 50 MPa at various strain rates. We observed variations in the post-critical parameters depending on the confining pressure.

- The post-critical modulus decreases with an increase in the confining pressure in sandstone and coal. This relationship may be described using a polynomial function of degree 2 or an exponential function. For claystone, there was no dependence between the softening modulus and confining pressures of 0-50 MPa at strain rates of $10^{-4} – 10^{-1}$ s^{-1}. We also found that the post-critical modulus of the coal under increasing confining pressure is lower than that of the waste rocks. Tests of the influence of the strain rate on the post-critical modulus of the Carboniferous rocks did not exhibit any pattern associated with variations in the strain rate.

- The dependence of the residual stress and residual deformation on the confining pressure (0-50 MPa) at strain rates of $10^{-5} – 10^{-1}$ s^{-1} (0,003-6,0 mm/sec) in Carboniferous rocks of the USCB was described using a linear function. At higher confining pressures, the differences between the residual stress and residual deformation increased in a given rock. The sandstones displayed the highest residual stress with increases in the confining pressure, and the coals displayed the lowest values. The curves show that the waste rocks are characterised by lower values of residual deformation compared to the hard coal. Among the geomechanical parameters, the residual stress exhibited the largest variation in values with increases in the confining pressure, which reflects the post-critical bearing capacity of the rockmass in the mined areas (e.g., support zones of cracked coal pillars). For sandstone, claystone and coal, the dependence of the residual stress on confining pressures of 0-50 MPa, which simulates mining conditions in the USCB, is a straight-linear relationship.
- Analysis of the influence of the strain rate and confining pressure on the post-failure parameters of Carboniferous rocks in the USCB indicated that confining pressures of 0-50 MPa have a larger influence on the post-failure parameters than do strain rates of $10^{-5} – 10^{-1}$ s^{-1} (0.003 – 6.0 mm/sec).

Confining pressures of up to 50 MPa used in the conventional triaxial compression tests allowed us to predict the behaviour of the rock mass at large depths. These data provide general knowledge of the tendencies in behaviour of rocks at substantial depths and the ability to design safe methods of mining deposits of various raw materials, including energy sources. These deposits are mined from increasingly great depths as the reserves are gradually exhausted and collieries of the largest European coal basins are continuously reconfigured.

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