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INVESTIGATION OF GEOMECHANICAL PROPERTIES OF CARBONIFEROUS ROCKS FOR EVALUATING THE POSSIBILITY OF ENERGETIC USE OF WATER AND METHANE FROM HARD COAL MINES

This study aimed to indicate the variability range of parameter values describing the geomechanical properties of Carboniferous rocks depending on the moisture content of the laboratory sample. We assumed that the moisture content in the tested rock samples corresponds to various water saturation states in the rock mass. The states could be caused by complete and long-term drainage, water inflow, or the position of the rock sample to the ventilation ducts or the water table in flooded mine workings. In line with this assumption, measurements were made on samples of accompanying rock using two water saturation states of rock pores – moisture of samples, i.e., air-dried and capillary saturation states. Laboratory surveys were also made for the state of moisture of the coals obtained in the process of immersion of the sample in water. The air-dried state of rocks as standard in geomechanical tests in laboratories was compared with the surroundings of mining excavations, mostly ventilated ones, located within a long-term preserved depression cone, especially in hydrogeological covered areas. We used the capillary saturation state to demonstrate significant changes in the values of basic geomechanical parameters under the influence of the water from the surface and higher aquifers, circulating in the rock mass near groundwater reservoirs. Capillary saturation was the closest to natural moisture in the rock mass drained from free water. The coefficient of changes in the geomechanical properties of rocks associated with the change in moisture content and the transition of rocks from the air-dried state to the capillary saturation state was determined. The parameter was suitable for simulating probable changes in the values of geomechanical parameters of rocks and approximating the laboratory moisture content to the conditions occurring in the rock mass. Linear relationships were also developed with very good or good, and sometimes satisfactory coefficient determinations.

Keywords: geomechanics; rock properties; earth and planetary science; geothermal water management; hazards; sustainable development

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1. Introduction

Before Poland's coal mining industry is shut down, the surroundings around mining excavations, mostly ventilated ones, will be compared to the air-dried state of rocks as the standard in geomechanical tests. The active mines scheduled for decommissioning as the last ones must operate with mines that were closed earlier or are currently being closed. A mine closure means decommissioning the drainage system and flooding its mine workings and surrounding rocks with a natural water inflow. Consequently, in closed mines, substantial water reservoirs are formed, and the water could be used as a carrier of thermal or mechanical energy. The above-water spaces of reservoirs created in mining excavations are reservoirs of mine gases, most often methane, which is pushed out by the water table towards the surface of the land.

Mine closures caused by limiting access to the previously exploited parts of deposits are associated with the closing of the drainage system or the imposition of a change or limit with respect to its scope. Ultimately, such activities are associated with a water level increase in mining excavations and their complete flooding. An increase in the water saturation of mine workings caused by changes to or shutting of the drainage system affects the water saturation conditions in the surrounding rocks. Each new hydrodynamic state associated with the mine workings of a closed mine inevitably changes the geomechanical properties of the rock environment, which is crucial for the coexistence of water reservoirs in goafs (treated as a potential source of water supply for geothermal systems) and for conducting underground mining operations in their vicinity. Changes in the geomechanical properties of rocks under the influence of water vary depending on the age of rocks, their type, physical properties, grain size (porosity and density), petrographic structure, and depth of deposition. Under certain mining conditions, these changes are essential for mining, public and general safety, mining exploitation and mine decommissioning as well as for facilitating rock mass drainage conditions.

The changes occurring in the Polish hard coal mining industry have become the main reason for investigating the geomechanical properties of Carboniferous rocks [1] and using their results to plan safe final mining operations and activities as a part of the mine closure process. The results of laboratory tests presented in the article refer to states similar to the moisture content in the rocks surrounding flooded mine workings. The air-dried state appropriately reflects the mines that have been operating within the depression cone for many years and the mine workings with a circulating ventilation system. The water saturation state (especially including capillary saturation of rocks in the vicinity of exploited coal seams and the state of moisture of the coals obtained in the process of immersion of the sample in water) corresponds to the conditions in the mine-working surroundings in the rock mass that's not drained fully. This is subjected to intensive water infiltration or is resaturated by the extensive water reservoirs created in flooded mines [2]. The capillary saturation state of rocks best reflects the natural average moisture content in the rock mass. Considering the possible future use of our results of these studies for practical purposes and safety assessments, several parameters, which we deem necessary, were selected and assessed. To assess free methane resources in goafs or the heat energy of mine water and analyse water hazards, including geomechanical threats, we measured the uniaxial compression strength, residual stress, Young's modulus, post-critical modulus, and critical strain. These parameters describe the geomechanical properties of rocks and their behaviour under the influence of water and are essential for determining the rock masses prone to bumps. The values of the geomechanical parameters are also important to assess the risk-safety conditions associated with the development of various protective structures and the assessment of the possibility of running mining operations near the reservoir zone in a closed mine. The examples are using it as a free-space resource for methane or a water resource for geothermal parameters and recovering its energy.

Many researchers study the effect of water on the mechanical parameter values of rocks. Most cases are related to studying the influence of water on the strength of rocks (uniaxial, triaxial and tensile strength) [3-13]. Some studies only focus on the influence of water on the uniaxial strength and Young's modulus [14-18]. Some also consider Poisson's ratio [19]. Many researchers focus on studying the effect of water on the mechanical parameter values of rocks and applying the results of laboratory tests to numerical modelling, e.g., [20-23].

However, these studies show the influence of water on mechanical parameter values determined only from the precritical part of the stress-strain curve. Our research determined the effect of water on geomechanical parameter values of selected detrital and organogenic rocks in the full range of sample deformation during the loading process, i.e., in the precritical and post-critical parts from which the post-critical modulus and residual stress were determined. The results of the influence of water on the post-critical parameter values are unknown from the literature.

2. Materials and methods

2.1. Evaluated rocks and verifying the parameters describing their properties

Laboratory tests determined the geomechanical properties of selected detrital sedimentary, clay rocks, and organogenic rocks of the Upper Carboniferous series in the Upper Silesian Coal Basin (*USCB*) in Poland. The tests were conducted in changing rock moisture conditions, approximating the influence of water saturation in the actual conditions related to mining activities and mine closures. The geomechanical properties of rocks for the full water saturation state were not studied because the processes of destabilis ing the rock mass equilibrium are limited by filling the voids with water and the observed small changes during the transition from capillary saturation to full saturation. Sandstones and mudstones represent the investigated detrital sedimentary rocks, and claystones represent the group of clay rocks. The organogenic rocks were hard coal.

The rocks were collected in mines of different geological conditions from various tectonic units (main basin, Chwałowice Beds, main saddle, and Jejkowice Beds) from different depths (600-1180 metres). They belonged to different lithostratigraphic units (Mudstone Series, Upper Silesian Sandstone Series, and Paralic Series). The rocks were also of different geological ages. They belonged to the Załęże, Ruda, Saddle Beds, and the oldest exploited productive series in the USCB in Poland – the Jaklowiec Beds (Table 1).

For laboratory tests, 50 mm cube-shaped and 50 mm-diameter cylinder-shaped samples of accompanying sedimentary rocks and coal were prepared. The accompanying sedimentary rocks samples were evaluated in the air-dried (a-d) (80 samples) and capillary saturation states (80 samples). The coal samples were tested in air-dried conditions (28 samples) and gradually flooded with water (28 samples). In the further part of the article, regarding the state of capillary saturation of accompanying sedimentary rocks and the state of gradual flooding of coal

TABLE 1

Stratigraphic classification of Upper Carboniferous formations of the Polish part of the USCB (simplified version)

Geological period	Lithostratigraphic units/beds		No. of seams
Westfalian	Krakow sandstone series	Libiąż	110-119
		Łaziska	201-215
	Mudstone series	Orzesze	301-326
		Załęże	327-406
Namur	Upper Silesian sandstone series	Ruda	407-419
		Saddle	501-510
		Jejkowice	nonproductive series
	Paralic series	Poręba	601-630
		Jaklowiec	701-723
	Border layers	Gruszow	801-848 (exploitation ended)
		Pietrzkowice	901-915 (exploitation ended)

samples with water, the authors call the water saturation state (sat). Considering the number of cuboid or cylindrical laboratory samples in two moisture content states, parameter mean values were determined: uniaxial compressive strength, residual stress, Young's modulus, post-critical modulus and critical strain.

We determined the variation coefficients for individual parameters to obtain the tools to simulate the moisture state transfer from the laboratory to the rock mass. They were related to the parameter value for the moisture state (Water State Changes Coefficient – *C*) of the accompanying sedimentary rocks evaluated in the laboratory. Based on the average values of the parameters determined in the laboratory tests, their variability is caused by the differences in the moisture content in the rock under laboratory conditions (air-dried state) related to the rock of the moisture level in the rock mass (capillary saturation state) was determined. This coefficient was marked C^P, where P in the superscript is a simulated capillary moisture geomechanical parameter evaluated in air-dried conditions. Comparative tests determined this coefficient as the quotient of the value of the tested parameter in the water saturation state of rocks ($Parameter_{sat}$) to the value of this parameter obtained in the air-dried state ($Parameter_{a\text{-}d}$).

The influence of water on the mechanical properties of Carboniferous rocks was investigated by considering the following factors simultaneously: the full extent of their deformation under load (precritical and post-critical parameters), the state of water saturation, geological age, and depth of occurrence in the rock mass. Research on Carboniferous rocks has not been conducted to such a wide extent so far.

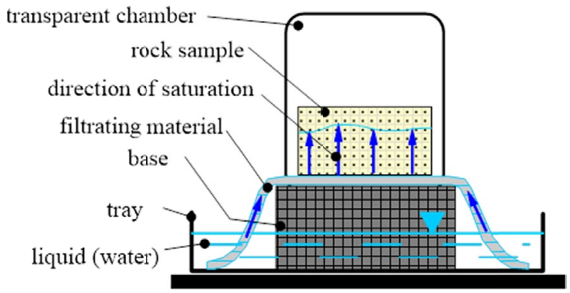
2.2. Geomechanical parameters and experimental methodology

Determining water *UCS*, residual stress, post-critical modulus, Young's modulus, and critical strain are crucial in assessing the impact of water during mines' operations and closures on the properties of rocks and the quality of the rock mass. Due to their importance, especially with possible changes in the value determined for variable moisture content states, the parameters are essential in the closing and flooding of mine workings. They can also be used in the current and prognostic assessment of the state of mining and general safety near groundwater reservoirs. The results of these studies have both cognitive and application significance.

- Uniaxial compression strength is the primary geomechanical parameter used in the essential geotechnical classification of rock mass (e.g., RMR, Q). Tensile and compressive strength can be used to assess the critical width of the pillars separating the water in underground reservoirs. Using Slesariev's formulas [24], one can assess the pillar's width at the design stage and the safety conditions at a given water pressure and forecast the permissible water pressure in the reservoir created near active mine workings. Compressive strength is also one of the main strength parameters when selecting support for mine workings in underground mining of mineral deposits and assessing the possibility of geodynamic phenomena, e.g., rock bursts. Determining the impact of water on the parameter's value might change rock mass classification due to its tendency to rock bursts [1,25]. The parameter is fundamental for assessing general, public-surface (sinkhole hazard) and mining safety, and the safety of methane and water resources accumulated in goafs near active mine workings, which are considered for possible energy purposes.
- Residual stress is a geomechanical parameter representing the critical load-bearing capacity of rocks when, because of loading, the post-failure stress decreases to a constant value when a decrease in stress no longer accompanies the increase in strain. The parameter is essential for assessing the maintenance or loss of goaf stability under the influence of water. It is applied to assess rock mass proneness to rock bursts and the rock-burst hazard and develop numerical models of stress distribution and rock mass displacements around the reactor chamber resulting from thermal stresses caused by the underground coal gasification process [26]. The residual stress value can be used to design pillars' width and height in a room-and-pillar mining system and assess the stability of old and shallow mining workings made in a room-and-pillar mining system.
- Young's modulus is an essential parameter for assessing the elastic energy level accumulated by loading the rocks forming the rock mass. The parameter is also used to evaluate the values of other specific deformation energies because of loading, which is applied to assess the rock mass tendency to rock bursts and rock-burst hazards in mine workings. It is also applied for numerical modelling of the stress-strain state of the exploited rock mass.
- The parameter's value is determined based on the shape of the stress-strain graph in the postcritical part. The postcritical modulus determines the dynamics of rock breakdown from loading after exceeding the maximum stress value. The curve's shape and angle, which is a linear approximation of the post-destruction curve, illustrate the differentiated dispersion of elastic energy accumulated in rocks due to loading. When the energy dissipation process is fast and the speed of the elastic energy dissipation increases (high value of the postcritical modulus), kinetic energy increases, causing a geodynamic phenomenon – a collapse. If the dissipating elastic energy is slow, the energy dissipation might be high, and the kinetic energy value tends to zero. Therefore, it is an essential parameter for assessing the rock mass tendency to rock bursts and the rock-burst hazard in mine workings [25].
- Critical strain is a geomechanical parameter obtained from the stress-strain curve of a compressed rock sample, determined for the maximum (critical) stress. The parameter and deformations determined at other stress levels in the precritical and postcritical parts of the stress-strain characteristic determine the loaded rock's deformability.

Changes in the indicated parameter values were assessed using the parameters that are significant from a practical viewpoint. They are essential for underground coal mining in the Polish part of the *USCB* area and for the subsequent use of mine workings as water and methane intakes for energy purposes. So far, to our knowledge, no such studies have been conducted to determine the influence of changes in rock moisture conditions on the reliability of laboratory test results and their application in mining geomechanics and hydrogeology. This applies in particular to the reference of the test results to the actual moisture conditions in the rock mass in the *USCB* area. Therefore, laboratory studies of the geomechanical properties of rocks accompanying coal beds were conducted in the air-dried and capillary saturation states.

The capillary infiltration process was initiated by placing rocks on the moist filter material (filter paper in the chamber) for a few hours to obtain the capillary saturation state (Fig. 1). Table 2 presents the methodology of the geomechanical property tests.



A

B

Fig. 1. Scheme of capillary soaking of regular rock (A) and samples before and after of soaking with water (B)

3. Results and discussion

The results of measuring the indicated geomechanical parameters were obtained following the uniform procedures for preparing the rock samples. They also complied with the recommendations for geomechanical tests in a servo-operated testing machine. The samples were macroscopically characterised and classified according to the type of analysed rock. Only laboratory rock samples with loss of mass while preparing cutting were evaluated.

TABLE 2

Physical parameters, including mechanical and research methodology

Parameters and methodology
Uniaxial compressive strength (*UCS*) The shape of the sample – a cube with a side of 50 mm or a cylinder with a diameter of 50 mm Slenderness – 1.0. An empirical factor of 0.89 was used to account for the slenderness of samples above 2.0 recommended by the International Society for Rock Mechanics (ISRM) [27] Load direction – perpendicular to the stratification Piston rate – approximately 0.008 mm/s – the strain rate of rocks near mining excavations [28]
Young's modulus (*E*), postcritical modulus (*M*), residual stress (σ_{res}), critical strain (ε_{cr}) [25] The data presented herein were determined for the entire height of a compressed rock sample as the tangent of the angle of inclination toward the *x*-axis of the line approximating the increasing stress-strain characteristics of the sample in the elastic deformations. One of the methods for obtaining the values of the postcritical modulus is determining the value of the tangent of the inclination angle of the line approximating the postcritical (falling) part of the stress-strain curve of a rock sample compressed in a highly stiff loading frame (Fig. 2.)

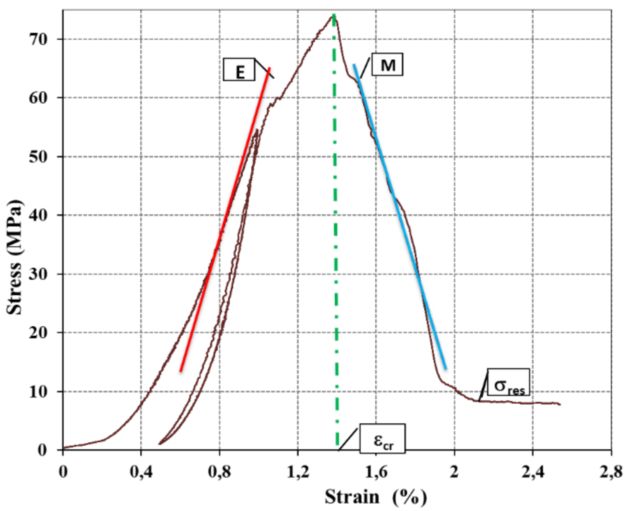


Fig. 2. Determining Young's modulus, postcritical modulus, residual stress, residual strain based on the course of the stress-strain curve

3.1. Geomechanical properties of rocks in the chronostratigraphic aspect

The youngest of the studied rocks belonged to the Załęże Beds. The sandstones were fine-grained and light-grey multi-grained. The claystones either contained plant detritus or sand or were layered with sandstone The coal was mostly semivitreous, rarely vitreous.

The sandstones surrounded by the coal of the Ruda Beds were mostly fine-grained, often layered with mudstone and claystone. Dark-grey claystones with plant detritus dominated among them. There were also claystones with sand content, which were locally layered with mudstones. Mudstones were grey, locally layered with claystones and sandstones. The coal of the Ruda Beds was mostly semivitreous, rarely vitreous, and layered with claystone and coal shale.

Sandstones surrounding the coal of the Saddle Beds were medium and fine-grained. Dark-grey claystone with plant detritus and sand was collected for the tests. Mudstones were grey, locally layered with claystones. The Saddle Beds coal was semivitreous and vitreous. Claystones represented the oldest exploited Jaklowiec Beds.

The change in the analysed geomechanical parameter values of accompanying sedimentary rocks and coals resulting from the influence of water is presented in Tables 3-4.

TABLE 3

Values of geomechanical parameters in the chronostratigraphic aspect – accompanying sedimentary rocks and hard coals

Rocks	***UCS*** **MPa**	σ_{res} **MPa**	ε_{cr} **‰**	***E*** **GPa**	***M*** **GPa**
Załęże Beds air-dried state / water saturation state					
Sandstone	61.5 / 36.1	12.4 / 4.5	12.9 / 12.7	7.8 / 4.5	17.4 / 16.8
Claystone	43.0 / 22.5	11.9 / 5.5	10.8 / 8.2	5.5 / 3.3	20.0 / 9.2
Coal	18.4 / 15.6	12.54 / 1.8	22.3 / 17.2	1.7 / 1.5	2.5 / 2.3
Ruda Beds air-dried state / water saturation state					
Sandstone	65.4 / 42.2	13.5 / 8.6	13.3 / 12.6	8.2 / 6.0	30.6 / 16.0
Mudstone	58.1 / 31.6	16.5 / 7.3	12.9 / 11.2	6.8 / 4.0	33.6 / 15.0
Claystone	43.8 / 22.3	13.1 / 5.9	13.6 / 11.5	5.1 / 2.9	23.6 / 7.8
Coal	19.4 / 11.7	5.3 / 3.5	15.8 / 15.2	2.0 / 1.2	9.1 / 3.1
Saddle Beds air-dried state / water saturation state					
Sandstone	55.1 / 42.4	8.3 / 7.6	15.1 / 14.7	8.5 / 6.8	9.4 / 7.0
Mudstone	49.5 / 48.4	16.4 / 15.5	20.1 / 17.6	7.6 / 6.4	6.9 / 6.7
Claystone	45.8 / 33.6	13.9 / 7.4	18.7 / 18.5	7.6 / 5.3	4.0 / 2.5
Coal	13.3 / 12.6	2.0 / 2.0	19.9 / 19.8	1.2 / 1.1	2.4 / 1.9
Jaklowiec Beds air-dried state / water saturation state					
Claystone	37.7 / 32.7	18.1 / 10.2	12.9 / 12.1	6.3 / 4.8	6.6 / 5.7

3.2. Geomechanical properties of rocks in the vertical profile (with depth)

The changes in the *UCS* value of Carboniferous rocks were assessed in the vertical profile in the depth range between 600 and 1180 m (Table 4). At this depth, hard coal is exploited in the *USCB*. Table 4 presents the changes in the *UCS* values of clay, detrital and organogenic rocks collected at different depths.

Fig. 2 shows examples of the uniaxial compression stress-strain curves of the selected laboratory rock samples in the MTS-815 testing machine.

TABLE 4

UCS changes with depth – accompanying sedimentary rocks and hard coals

State of humidity	Clay rocks		Detrital rocks		Organogenic rocks	
	Depth m	***UCS* MPa**	**Depth m**	***UCS* MPa**	**Depth m**	***UCS* MPa**
a-d sat	600	38.0 18.0	630	74.3 64.9	701	16.0 15.8
a-d sat	600	26.5 8.5	662	64.8 36.0	767	5.7 3.9
a-d sat	751	47.5 34.7	705	49.7 32.8	855	18.4 15.6
a-d sat	823	21.3 18.0	751	46.5 34.4	896	14.1 12.4
a-d sat	1055	39.4 37.0	833	49.5 48.4	987	16.3 16.1
a-d sat	1180	36.0 28.4	992	54.3 34.4		

3.3. The effect of water on the geomechanical properties of Carboniferous sedimentary rocks

From the laboratory tests, geomechanical parameter values determined in air-dried and water saturation states and structural weakening coefficient values (water influence coefficient) for the given parameters (Water State Change Coefficient – C^P) were determined. The formula determines that the change coefficient of a given parameter is

$$C^P = \frac{P_{water\ saturation\ state}}{P_{air-dried\ state}} \qquad (1)$$

The results of calculating the quotient of the given parameter values for the tested rock moisture conditions are expressed as coefficients of the changes in tested parameter values due to the capillary saturation state (Table 5) – C^{UCS}: uniaxial compressive strength; $C^{\sigma res}$: residual stress; $C^{\varepsilon cr}$: critical strain; C^E: Young's modulus; C^M: postcritical modulus.

TABLE 5

The coefficient values of the impact of changes in the geomechanical parameters (C^P) of differently aged accompanying sedimentary rocks and coals in the *USCB* in Poland

Rocks	**Beds**	C^{UCS}	$C^{\sigma res}$	$C^{\varepsilon cr}$	C^E	C^M
1	**2**	**3**	**4**	**5**	**6**	**7**
Sandstones	Załęże Ruda Saddle	0.59 0.65 0.77	0.36 0.64 0.92	0.98 0.95 0.97	0.58 0.73 0.82	0.93 0.52 0.74
Mudstones	Ruda	0.54	0.44	0.87	0.59	0.45
	Saddle	0.98	0.95	0.88	0.84	0.97

TABLE 5. Continued

1	2	3	4	5	6	7
Claystones	Załęże	0.52	0.46	0.76	0.62	0.45
	Ruda	0.51	0.45	0.85	0.57	0.33
	Saddle	0.73	0.53	0.99	0.70	0.63
	Jejkowice	0.87	0.56	0.94	0.76	0.86
Coals	Załęże	0.85	0.14	0.77	0.88	0.92
	Ruda	0.60	0.66	0.96	0.60	0.34
	Saddle	0.95	1.00	0.99	0.92	0.79

The coefficient values of reduction in the *UCS* of sandstones, mudstones, claystones and Carboniferous coals, tested in the air-dried state, related to natural conditions, reflected in laboratory tests of the rocks by bringing them to the water saturation state are presented in Table 6. The examined rocks were collected from the depths of the current coal exploitation in the *USCB* in Poland (<1200 m).

TABLE 6

The coefficient values of reduction in C^{UCS} of coal and Upper Carboniferous accompanying sedimentary rocks in the *USCB* in Poland caused by water and the changes in the depth obtained with the values of the tested parameters

Claystones		**Sandstones**		**Mudstone**		**Coals**	
Depth m	C^{UCS}	**Depth m**	C^{UCS}	**Depth m**	C^{UCS}	**Depth m**	C^{UCS}
600	0.40	630-662	0.72	833	0.98	701-767	0.84
751	0.73	705-751	0.70			855-896	0.87
1055-1180	0.87	992	0.63			987	0.99

The strength of the tested gangue and hard coals was assessed on the basis of the classification developed by [1] for the rocks of the coal-bearing formations of the USCB. On the basis of this classification, the uniaxial compressive strength of the tested rocks was assessed (Table 7).

TABLE 7

Assessment of the strength of the tested rocks

***UCS* / Rock waste**	**Sandstones**	**Mudstones**	**Claystones**	***UCS* / Coal**	**Coals**
Very low (<20 MPa)			✓	Very low (<10 MPa)	✓
Low (20-40 MPa)			✓	Low (10-19.9 MPa)	✓
Medium (40.1-60.0 MPa)	✓	✓	✓	High (20-30 MPa)	
High (>60 MPa)	✓	✓	✓	Very high (>30 MPa)	

The data presented in Table 7 show that the *UCS* of sandstones, mudstones, and coals has two strength classes. At the same time, claystones fall into four strength classes, according to [1].

Based on the *UCS* analysis of the tested rocks and the percentage of rocks in the lithological profiles determined for the *USCB*, it was shown that:

- Sandstones and mudstones of the highest strength classes (*UCS* > 60 MPa and *UCS* 40.1-60.0 MPa) most often occur in the *USCB*, and their share in lithological profiles is 59% and 26%, respectively (Fig. 3A, B).
- Clay rocks with a percentage, as shown in the figure (Fig. 3C), belonged to the four strength classes established for the *USCB*'s claystones, and their share in the lithological profiles is 7 to 49%.
- Following the *UCS* classification, coals fell into the two lowest strength classes established for the type of rocks in the *USCB*. The share of such coals in the lithological profiles is 13% and 32% (Fig. 3D).

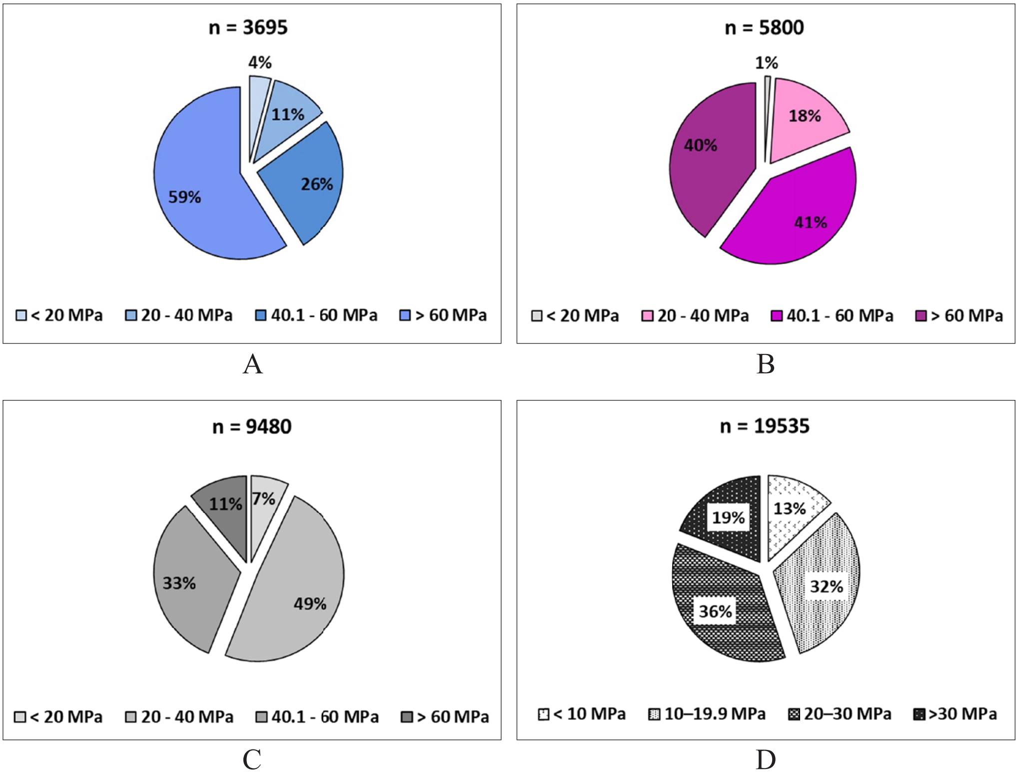


Fig. 3. Contribution of *USCB* rocks with medium uniaxial compressive strength in the adopted variability thresholds. Based on the results of [25]: A – sandstones; B – mudstones; C – claystones; D – coals; *n* – number of cylindrical or cubic laboratory samples

The analysis of the data determined with laboratory tests made it possible to assess the influence of water on the change in the value of the geomechanical parameters of Carboniferous rocks, taking into account the geological age of the rocks and the depth of their deposition in the rock mass. The values of individual geomechanical parameters of the geologically youngest layers of the Załęże area under the influence of water were compared with the behaviour of the oldest layers – the saddle and Jaklowiec Beds.

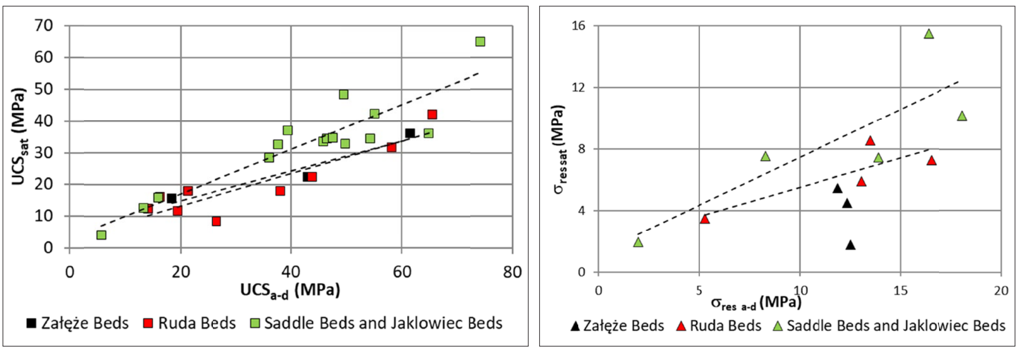
Based on the conducted research, it was proven that:

- The *UCS* and residual stress values decrease under the influence of water in the geologically youngest sandstones, mudstones, claystones, and coals compared to the oldest analysed rocks. It results from the geological age of the rocks and the associated greater degree of sediment compaction.
- A more significant decrease in the value of *E* under the influence of water was also found for detrital rocks and the geologically youngest claystones compared to the oldest studied rocks.
- For critical strain, tests showed a similar trend of changes which result from saturating rocks with water as for the *E* parameter.
- The post-critical module did not show the same trend of changes due to the saturation of rocks with water for all the studied groups/types of sedimentary rocks. For mudstones and claystones, there was a more significant decrease in the value of the post-critical modulus for the youngest siltstones and claystones compared to the oldest ones. For sandstones and coals, there was no such relationship.
- The influence of water on the *UCS* values of rocks in the vertical profile (depth: 600-1180 m) is unclear. As a result of the water saturation of claystones and coals samples, which were taken from smaller depths, the decrease in *UCS* value was more significant than in clay and coals collected at greater depths. However, there were no significant differences between the *UCS* determined for sandstones from the smallest and the greatest depths.

Based on the tests carried out on a statistical sample of $n = 216$ laboratory samples and the results presented in Tables 3-4, we developed linear functional dependencies for detrital rocks, claystones and coals of different age layers in the *USCB* (different sedimentation cycles) (Fig. 4-6).

The coefficients of determination R^2 are in the range of values (Table 8-10):

- $0.8 \leq R^2 < 1.0$ – the linear regression fits well to very well to the experimental data for dependencies $UCS_{sat} = f(UCS_{a\text{-}d})$, $\varepsilon_{cr\ sat} = f(\varepsilon_{cr\ a\text{-}d})$, $E_{sat} = f(E_{a\text{-}d})$ and $M_{sat} = f(M_{a\text{-}d})$ (Załęże Beds, Ruda Beds, Saddle Beds and Jaklowiec Beds)
- $0.6 \leq R^2 < 0.8$ – the linear regression fits occasionally and satisfactorily to the experimental data for the dependencies $\sigma_{res\ sat} = f(\sigma_{res\ a\text{-}d})$ and $M_{sat} = f(M_{a\text{-}d})$ (Załęże Beds).



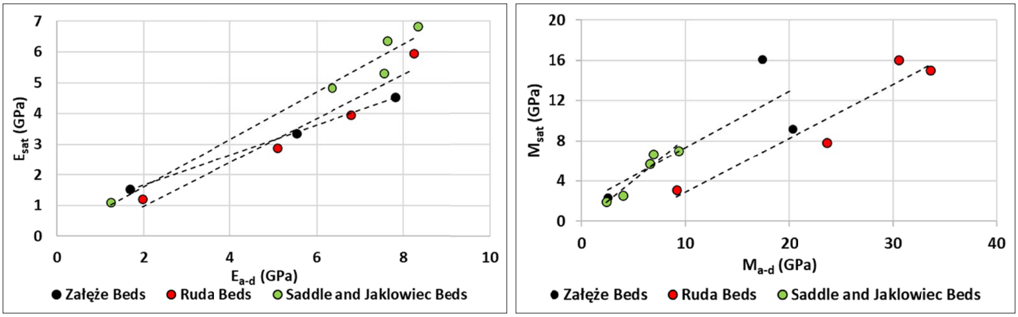
A B

Fig. 4. $UCS_{sat} = f(UCS_{a\text{-}d})$ (A) and $\sigma_{res\ sat} = f(\sigma_{res\ a\text{-}d})$ (B) dependence for the Carboniferous rocks

TABLE 8

Linear regression analysis results of $UCS_{sat} = f(UCS_{a\text{-}d})$ and $\sigma_{res\ sat} = f(\sigma_{res\ a\text{-}d})$ for sandstones, mudstones, claystones and coals of different age layers

Beds	Relationship	Coefficient of determination R^2	Standard error of estimate *SEE*
Załęże Beds	$UCS_{sat} = 0.5\ UCS_{a\text{-}d} + 5.68$	0.9	3.9
Ruda Beds	$UCS_{sat} = 0.5\ UCS_{a\text{-}d} + 2.84$	0.8	4.9
	$\sigma_{res\ sat} = 0.4\ \sigma_{res\ a\text{-}d} + 1.70$	0.7	1.4
Saddle Beds and Jaklowiec Beds	$UCS_{sat} = 0.7\ UCS_{a\text{-}d} + 2.97$	0.8	6.2
	$\sigma_{res\ sat} = 0.6\ \sigma_{res\ a\text{-}d} + 1.23$	0.7	3.1



A B

Fig. 5. $E_{sat} = f(E_{a\text{-}d})$ (A) and $M_{sat} = f(M_{a\text{-}d})$ (B) dependence for the Carboniferous rocks

TABLE 9

Linear regression analysis results $E_{sat} = f(E_{a\text{-}d})$ and $M_{sat} = f(M_{a\text{-}d})$ for sandstones, mudstones, claystones and coals of different age layers

Beds	Relationship	Coefficient of determination R^2	Standard error of estimate *SEE*
Załęże Beds	$E_{sat} = 0.5\ E_{a\text{-}d} + 0.7$	1.0	0.04
	$M_{sat} = 0.6\ M_{a\text{-}d} + 1.7$	0.6	6.1
Ruda Beds	$E_{sat} = 0.7\ E_{a\text{-}d} - 0.5$	0.9	0.6
	$M_{sat} = 0.5\ M_{a\text{-}d} - 2.5$	0.9	2.3
Saddle Beds and Jaklowiec Beds	$E_{sat} = 0.8\ E_{a\text{-}d} + 0.1$	1.0	0.5
	$M_{sat} = 0.8\ M_{a\text{-}d} - 0.1$	0.9	0.9

The relationships that are investigated and determine the influence of water on *UCS* or Young's modulus are widely described in the scientific literature as linear relationships. However, they mainly concern sedimentary rocks - sandstones, limestones, dolomites, and gypsum [7,11,13,15]. The value of correlation coefficients most often indicates a very high or high correlation, similar to the research results described by [3]. Our research also confirmed the linear relationship between *UCS*, *E* and the state of rock moisture forced by capillary soaking or gradual immersion of the samples in water. Fig. 7A presents the results of earlier tests by the authors of

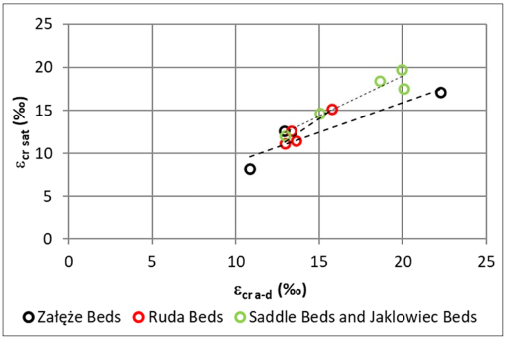


Fig. 6. $\varepsilon_{cr\ sad} = f(\varepsilon_{cr\ a\text{-}d})$ dependence for the Carboniferous rocks

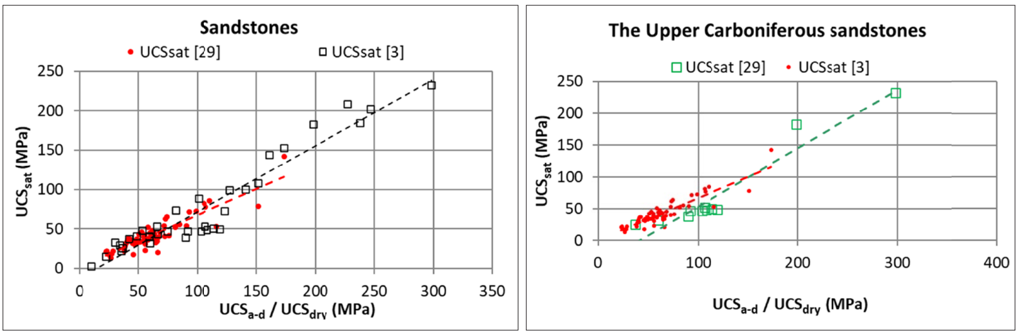
TABLE 10

Linear regression analysis results $\varepsilon_{cr\ sat} = f(\varepsilon_{cr\ a\text{-}d})$ for sandstones, mudstones, claystones and coals of different age layers

Beds	Relationship	Coefficient of determination R^2	Standard error of estimate *SEE*
Załęże Beds	$\varepsilon_{cr\ sat} = 0.7\ (\varepsilon_{cr\ a\text{-}d}) + 2.1$	0.9	2.1
Ruda Beds	$\varepsilon_{cr\ sat} = 1.3\ (\varepsilon_{cr\ a\text{-}d}) - 6.0$	0.9	0.8
Saddle Beds and Jaklowiec Beds	$\varepsilon_{cr\ sat} = 0.9\ (\varepsilon_{cr\ a\text{-}d}) + 0.3$	0.9	1.1

this article (in the range of $UCS_{a\text{-}d} = 22.9\text{-}173.3$ MPa) [29], which were compared with the tests of [3] (in the range of $UCS_{dry} = 10.5\text{-}298.2$ MPa). Fig. 7B shows the results of the study of Upper Carboniferous sandstones only. The regression equations and R^2 values are shown below. In both cases, the researchers found a very strong relationship between the variables:

– Fig. 7A
  - [29] $UCS_{sat} = 0.7\ UCS_{a\text{-}d} + 1{,}3$; $R^2 = 0.8$; $n = 65$; $SEE = 9.1$,
  - [3] $UCS_{sat} = 0.8\ UCS_{dry} - 12.2$; $R^2 = 0.9$; $n = 35$; $SEE = 18.0$;



A B

Fig. 7. Relationship $UCS_{sat} = f(UCS_{a\text{-}d})$ according to [3] and [29] sandstones of various geological ages (A) and according to [3] and [29] of the Upper Carboniferous sandstones

– Fig. 7B
  - [29] $UCS_{sat} = 0.7\ UCS_{a\text{-}d} + 1{,}3$; $R^2 = 0.8$; $n = 65$; $SEE = 9.1$,
  - [3] $UCS_{sat} = 0.9\ UCS_{dry} - 37.1$; $R^2 = 0.9$; n = 11; $SEE = 20.1$.

However, some researchers, such as [5], did not confirm the linear relationship because their experiments showed that the sandstones they studied did not significantly reduce *UCS* under the influence of water.

It is not clear from the publications on functional relationships between the values of post-critical parameters obtained from the full stress-strain curve (residual strength and post-critical modulus) and the critical strain, which were determined for the Carboniferous rocks in two humidity states – air-dried state, and water saturation state. The research results conducted on hard coal, which we have not published yet, are also new.

We do not know any publications presenting the results of research on the influence of water, including the capillary saturation state, on the geomechanical properties of Carboniferous rocks in such a wide range, i.e. in chronostratigraphic and depth terms, as well as in the full range of rock deformation under load. Hence, it was not possible to discuss them.

4. Application/significance of research results in mining practice

The study of geomechanical properties of Carboniferous rocks in the Polish part of the *USCB* described the variability of their values. The study considered the variability and differentiation of the water saturation states in mine workings and rock mass. The impact of changes in water supply concerns predominantly the hard coal mines in the process of closure as their mine workings are being flooded and changes occur in water flows and water supply, or the method for receiving groundwater. Rock behaviour in mines often determines the state of mining and general safety in their surroundings [30]. Therefore, this study might be significant for numerous practical applications in the current operations of active and closed mines and for safety assessments in developing the areas, including the intake and use of methane to produce energy and as geothermal reservoirs of groundwater. The hydrogeological consequences of decommissioning a mine are the main factor of changes in the general safety condition related to the stability of the surface (sinkhole hazard) and mining safety (risk of pillars' stability loss and the water flow from a closed mine into active mine workings). The consequences of such a breach are significant for the existence of water reservoirs in a mine, which must be transformed into a geothermal water reservoir. It might lead to the liquidation of the power source in the planned energy investment, as it was indicated in previous years [31]. The rock strength parameters ($UCS_{a\text{-}d}$ and UCS_{sat}) applied to calculate the critical width of the pillar separating a water reservoir in goafs, where the *UCS* values determined in the laboratory in the air-dried state are used [32], are a good example of why it is necessary to use the most realistic values of geomechanical parameters for such calculations.

In addition to being essential for predicting the conditions for closing and operating mines near closed mines, this research is fundamental for the assumptions and methodology of geomechanical research. It means developing and conducting research and research procedures, both laboratory and in situ ones, depending on local conditions occurring in the area to which the research results apply.

Therefore, the critical factor for conducting laboratory research is to refer to the actual conditions in the rock mass, where water conditions are essential. For example, it was emphasised for underground coal gasification investments planned in the *USCB* [33]. While collecting rock samples for the tests, be it from sidewalls, roof, floor, or borehole cores, the correct assessment of the geomechanical situation depends on the known hydrogeological conditions and the water saturation state in the rock mass and mine workings. Differences in the measurement results, typically performed in the air-dried state, are evident for the zones adjacent to water-saturated faults, aquifers, and water reservoirs separated from active mine workings only by narrow safety, barrier, or retaining pillars. Therefore, in assessing critical conditions (e.g., critical width of safety pillars, conditions for the foundations of damming structures), it is proposed to use geomechanical parameters determined for rocks in a capillary moisture state or to simulate such a condition using C^P factor values indicated in the article or developed functional dependencies. The air-dried state can refer to impermeable rocks forming near ventilated mine workings and in the inner area of a permanent cone of depression, existing for a long time, especially in the so-called hydrogeologically confined areas.

It is believed that this research on adapting to the water-failure conditions of mine workings is vital for assessing safety in the fall arches, roof conditions, conditions for planned mining works near barrier pillars and benches, the locations for the foundation of water dams, stoppers, or water insulation. Determining a specific geomechanical parameter, depending on the adopted pattern/model of moisture content in the rock mass, can be crucial for assessing the rock mass tendency to rock bursts and the rock-burst hazard [30]. These parameters can also assess water hazards, evaluate methane and mine water energy resources, or numerically model the stability of voids and mine workings in the rock mass applied for the aforementioned goals.

5. Conclusions

The intention of analysing the results and the article is to draw attention to the necessity of the best possible connection of the main geomechanical parameters to the existing and expected conditions in the analysed area at the planning and implementation stages. It applies to the tests in underground mines, boreholes drilled for geothermal purposes, and the search for methane deposits. This research simulated various states of water saturation in rocks. Using such research, it is possible to predict the future change in the values of the main geomechanical parameters determining the current and future general safety conditions for mining and planned energy investments based on mine water or methane. The importance of such studies increases, especially when water is dammed in closed mines, the flooding process is stopped, water is drained from a certain level, a mine is completely flooded, or the rock mass is subjected to seasonal water table fluctuations. It is equally important to correctly design research for mining activities in mines operating in the rock mass subject to intensive drainage processes and conducting or planning mining operations near existing groundwater reservoirs, including those intended to be geothermal water reservoirs. We indicate that adopting geomechanical parameters, which are unrelated to the actual flooding of mine workings and rock mass, might cause a significant calculation error. Consequently, it causes an error in assessing the energy potential of water in a given location due to the level of water hazards, rock mass proneness to rock bursts or possible mass movements of the rock mass.

We recommend using the values of the coefficients reducing the values of the geomechanical parameters under the influence of water and the developed linear regression equations indicated in this article in the geomechanical assessments of the rock mass and safety assessments of underground mine workings (assessing water and rock-burst hazards and rock mass proneness to rock bursts).

The values are recommended for analyses and assessments of conditions for estimating the possibility of building and maintaining installations to recover energy from water in underground mine workings. While considering the natural conditions of the assessed location and the purpose of the measurements, the coefficient should be used to verify the values obtained in the laboratory in standard conditions as a multiplier of the raw values obtained during laboratory tests conducted in the air-dried state.

Based on the tests, the following conclusions were drawn.

- The tested rocks are significantly heterogeneous because of the formation of the Upper Carboniferous sediments in the Polish part of the *USCB*.
- Sandstones exhibited different graining and were often layered with other sedimentary rocks, e.g., claystone or mudstone.
- Pre-critical, critical and post-critical geomechanical parameter values decrease because of soaking rocks in the water. The dependence of the $Parameter_{sat} = f(Parameter_{a\text{-}d})$ of detrital rocks, claystones and coals is linear. High values of the coefficients of determination R^2 indicate that the linear regression fits well to very well, and occasionally satisfactorily to the experimental data.
- For accompanying sedimentary rocks and coal of different geological ages, a relationship exists between their age and the change in geomechanical parameter values, indicating rock weakening caused by water saturation, which might indicate larger rock compaction.
- Coal and accompanying sedimentary rocks were collected from a depth range of 600-1180 m. For coals and claystones, the difference in the *UCS* value in air-dried and water saturation states decreased following the increase in depth. For sandstones, the tests did not reveal any tendency of change in the index percentage value of an increase or decrease in the *UCS* value due to the capillary saturation of rocks.
- The influence of soaking with water, related to the increasing geological age of rocks, on the change in their geomechanical parameters, is greater than related to an increase in the depth of their deposition in the Carboniferous rock mass.

The change coefficient values in the selected parameters presented in this study and the developed functional relationships can be used in comparative calculations and simulations of the natural moisture conditions in the rock mass to assess the mining and general safety and the conditions for geothermal energy recovery from groundwater in closed mines. It is a recommended method of researching the properties of hard rocks to be used in the study of rock series of other coal basins and underground mining of other mineral resources.

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