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Mirosława Bukowska*, Anna Smolorz

Influence of Humidity on the Energy of Specific Strain in the Process of Loading Sedimentary Rocks

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Abstract: This article presents the results of tests on the energy properties of sedimentary rocks in the Upper Silesian Coal Basin. The rocks were tested both in an air-dry state and in a water saturation state. Samples of sedimentary rocks were collected from boreholes drilled in the underground workings of coal mines located within the area of the city of Jastrzębie, in the areas of the Chwałowice Trough and Rybnik Trough (south-western part of the Upper Silesian Coal Basin) and in the Main Trough. Influence of saturation condition on the values of the tested energy parameters was observed. The values of elastic energy and dissipated energy obtained for the samples tested in water saturation were lower compared to the values obtained for samples tested in air-dry state. As observed, an increase in the values of the given types of specific energy corresponds to an increase in the uniaxial compression strength in air-dry state and in water saturation state. Results of the tests are original and they can be applied while analysing the possibility of the occurrence of some dynamic phenomena and hazards in mine workings in Carboniferous rock mass in the Upper Silesian Coal Basin, caused by mining operations.

Keywords: Elastic energy, dissipated energy, sedimentary rocks, Upper Silesian Coal Basin.

1 Introduction

The influence of humidity on the value of geomechanical parameters is well described in literature. Many researchers have attempted to present the influence of saturation condition on the strength and strain properties of rocks undergoing uniaxial compression tests.[4,6,17,19,20,21] Some of the researchers also conducted tests into axis-symmetrical stress state using rock samples saturated with water.[18] Bukowska[5] tested capillary saturated samples of sedimentary rocks from the Upper Silesian Coal Basin (USCB). These conditions roughly reflect the humidity of Carboniferous rock mass after free water is removed.

Destructive tests of the energy properties of rocks, such as loading samples in material testing machines, in the full range of deformation of the samples, are a relatively new type of tests for rocks from the USCB in Poland.[1,2,17] So far, there have been no publications aimed at a wide comparison of energy properties of rocks tested in air-dry state and in water saturation state.

Results of testing the energy properties of Carboniferous sedimentary rocks in water saturation state, including the capillary saturation method[7] and considering variable conditions of draining the rock mass,[8] are important for the safety of underground coal mining operations in the USCB. The results of these tests are important for reducing the specific energy of elastic deformations in rocks and rockmass.[14] Results of tests on the energy properties of rocks, considering the aforementioned factors, are important for assessing the occurrence of natural hazards, for example, rock burst hazard[15] and water hazard, in underground workings.[9]

The article presents the results of laboratory tests conducted on the samples of sedimentary rocks (including clastic rocks and clay rocks) of various ages, which were tested in air-dry state and in water saturation state. Among the energy parameters, values of elastic energy and dissipated energy were determined. An attempt was also made to determine the functional dependencies between specific energies and uniaxial compression strength.

***Corresponding authors: Mirosława Bukowska, Anna Smolorz,**
Central Mining Institute, Plac Gwarków 1, 40-166 Katowice,
E-mails: mbukowska@gig.eu; asmolorz@gig.eu

Figure 1: Location of polish part of the Upper Silesian Coal Basin, Poland.

2 Characteristics of the testing areas and sedimentary rocks in the USCB

The Upper Silesian Coal Basin spreads from the southern part of Poland, to Ostrava – Karviná District in the Czech Republic (Fig. 1).

The strata of the USCB consists of Precambrian, Cambrian, Devonian and Upper Carboniferous formations.[13] The USCB area has diverse lithology and thickness. In the USCB, there are four lithostratigraphic series of different ages:

- Cracow Sandstone Series (Westfalian C and D),
- Mudstone Series (Westfalian A and B),
- Upper Silesian Sandstone Series (Westfalian A and B),
- Paralic Series (Namurian A).

The areas belong to the zones of fold tectonics, fold-block tectonics and disjunctive tectonics (block).[16] Structurally, the area of the USCB is in the form of three basic structural levels: the Caledonian and Variscan structural level, the Variscan and Upper Carboniferous molasse and cover deposits of coal-bearing Carboniferous.

The USCB sedimentary rocks, in terms of their origin, mineral composition and grain size are divided into:

- clastic rocks (coarse-grained, medium-grained and fine-grained),
- clay rocks,
- chemical rocks,
- biogenic rocks.

3 Rock material and laboratory tests

The article presents the results of tests on sedimentary rocks (clastic rocks and clay rocks) occurring in sedimentary cyclothems in the vertical profile of coal-bearing Carboniferous of the USCB, Poland. Sandstones, mudstones and claystones were collected in four coal mines, which are located in different geological structures and areas of the USCB (south-western part of the USCB – area of Jastrzębie, the Chwałowice Trough, the Rybnik Trough and the Main Trough) and belong to Załęże Beds (Mudstone Series), Ruda Beds and Saddle Beds (the Upper Silesian Sandstone Series).

The tests were performed on the following types of sandstones: coarse-grained, medium-grained and fine-grained, light grey and grey. The majority were fine-grained sandstones, constituting 76% of the tested sandstones. Coarse-grained sandstones and medium-grained ones made up 24% of the tested samples of sandstones. Among the sandstones, there were local inclusions of coal matter and laminae of claystone. Inclusions of coal matter lowered the values of the tested parameters, including uniaxial compression strength. In a few cases, sandstones also contained calcite cement. Mudstones were grey and dark grey. Locally, mudstones were interlaced with claystone and sandstone. Among the five primary samples of mudstones, there were inclusions of plant detritus. Locally, inclusions of coal matter could be observed. Claystones constituted a small share – 22% of the tested laboratory samples. Among the claystones, there were claystones with plant detritus, claystones laminated with coal and claystones with sand and laminae of mudstone. Some of the primary samples of claystones without impurities, inclusions and interlacing were tested. Claystones were dark grey and, locally, grey.

A total of 25 series of sandstones, 18 series of mudstones and 12 series of claystones were tested. Each series consisted of 12 cylindrical laboratory samples. 660 cylindrical laboratory samples of sedimentary rocks were tested, which consisted of: 300 samples of sandstones, 216 samples of mudstones and 144 samples of claystones. For each group of rocks, separately for sandstones, mudstones and claystones, an average value of the analysed parameter was determined. Average values of energy parameters and uniaxial compression strength were analysed in this project.

Tests were conducted with material servo-control testing machine MTS-815. Conditions of the experiments and tested parameters are presented in Figure 2.

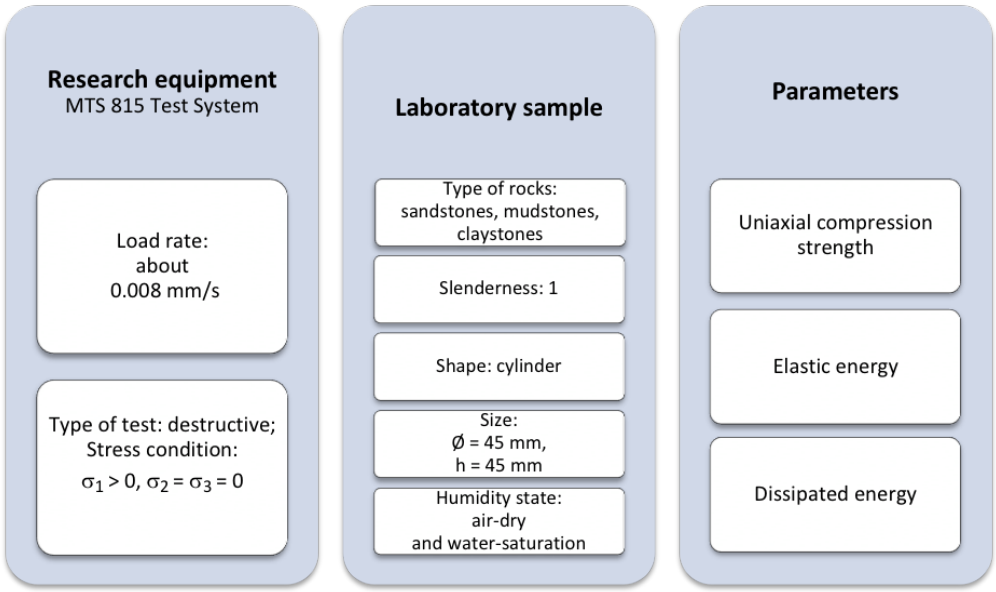

Figure 2: Conditions of experiments and parameters (ϕ – diameter of a sample; h – height of a sample).

Due to the high rigidity of material testing machine MTS-815 and the efficiency of the supply hydraulic system, it was possible to obtain a complete stress-strain curve of the loaded rock samples, in the full range of deformation.[11] The obtained stress-strain characteristics allowed us to determine, in the ascending and descending part of the characteristics, stress and energy parameters characterising both the pre-critical and post-critical state of a rock sample.

Energy parameters (elastic energy and dissipated energy) and stress parameters (uniaxial compression strength) were tested in the two states of humidity, in air-dry state and in water saturation state.

In laboratory conditions, the water saturation state was obtained through submerging a rock sample in water, at room temperature, until it reached steady mass. In general, for 85% of the tested rocks, the water immersion time did not exceed 24 hours. Claystones of slakeability index, according to the GIG scale, of 0.6 and 0.8 were an exception. Values of the slakeability index mean that a sample breaks along the layering and rarely along a line vertical to the layering (0.6) or a sample breaks along the layering (0.8).[12] The time of immersing claystones in water was shortened because samples could dissolve in water as a result of overly long immersion time. Disintegration of claystones would render tests with a material testing machine impossible.

The basis for the determination of elastic energy and dissipated energy is area under a stress-strain curve (Fig. 3).

For the above graph of the total strain energy of the loaded sample, it was assumed that:

– AB line approximates non-linear course of the strain curve in the pre-critical area,
– DF line in post-critical area is parallel to initial load (line AB) in pre-critical area,
– ABDF area – dissipated energy transferred to the surrounding,
– ABC area – elastic strain energy,
– DFG area – recoverable strain energy according Heasley's,[10]
– ABDG area – total energy.

4 Results and Discussion

The tested parameters of specific energy, elastic energy and dissipated energy were determined from the samples of sandstones, mudstones and claystones in air-dry state and in water saturation state. In water saturation state, the values of some geomechanical properties of rocks are usually lower. Understanding this problem is important for geoengineering issues such as the Carboniferous susceptibility to bumps and rock bursts hazards in underground coal mines, as Bukowska showed in her research.[3] Another problem presented here is the influence of saturation condition on the energy properties of sedimentary rocks, which were tested and discussed for the first time.

Table 1: Average values of energy and stress parameters of tested sedimentary rocks of the USCB.

Lithostratigraphic Series/ Beds	air-dry state			water saturation state		
	uniaxial compression strength, MPa	elastic energy, kJ/m^3	dissipated energy, kJ/m^3	uniaxial compression strength, MPa	elastic energy, kJ/m^3	dissipated energy, kJ/m^3
	sandstones					
Mudstone Series/Załęże Beds	38.3–112.5	108.880–392.147	304.091–838.938	28.8–75.5	104.941–224.812	230.053–509.024
Upper Silesian Sandstone Series/Ruda Beds and Saddle Beds	51.4–113.5	147.846–410.281	260.903–829.553	29.9–79.8	88.049–262.362	205.723–567.799
	Mudstones					
Mudstone Series/Załęże Beds	23.2–44.6	63.881–188.821	196,431–411.404	21.6–37.0	62.431–131.335	145.995–243.183
Upper Silesian Sandstone Series/Ruda Beds and Saddle Beds	44.4–81.4	135.826–347.182	281.942–682.093	21.4–52.0	85.708–194.954	187.339–348.384
	Claystones					
Upper Silesian Sandstone Series/Ruda Beds and Saddle Beds	35.1–74.4	112.239–247.469	217.989–532.515	8.8–52.9	44.644–211.095	119.035–392.818

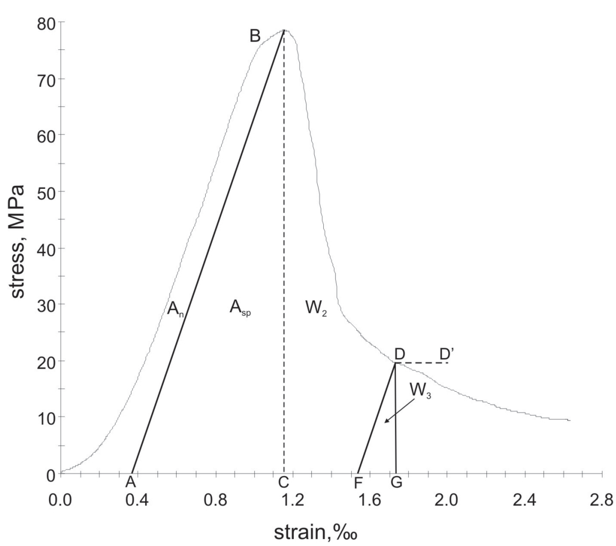

Figure 3: Balance of specific energy of compressed sample of rock (σ - stress; ε - strain) [1].

Results of uniaxial compression strength, elastic energy and dissipated energy are presented in Table 1 and in Figures 4 and 5.

By analysing the results of the laboratory tests, it was possible to show that for 90% of the rock samples tested in air-dry state and in water saturation state, for both elastic energy and dissipated energy, the values decreased in water saturation state. Values of elastic energy for given samples in an air-dry state are between 63.881 kJ/m^3 and 410.281 kJ/m^3; for the samples in water saturation state, they are between 44.644 kJ/m^3 and 262.362 kJ/m^3. For the samples in air-dry state, the values of dissipated energy fall within the range of 196.431 kJ/m^3 and 838.938 kJ/m^3. Values of dissipated energy of rock samples determined in water saturation state are between 119.035 kJ/m^3 and 567.799 kJ/m^3. In a few cases, elastic energy and dissipated energy in an air-dry state is lower than energy in water saturation state. It is an effect of non-homogeneous petrographic structure and the mineral composition of certain rock samples. There are often inclusions of plant detritus, coal, siderite, calcite and others.

The next stage of the analysis was the determination of functional dependencies between values of specific energies and the uniaxial compression strength of the tested rocks in air-dry state and in water saturation state. Matching the proper function with the obtained test results allowed us define both the elastic energy (E_{el}) – as well as dissipated energy (E_{dys}) as linear function of uniaxial compression strength (*UCS*). The dependencies for elastic energy and dissipated energy for Carboniferous rocks in Table 2 and Fig. 6 and 7 are presented.

The claystones consisted of claystones of different mineral composition, with inclusions and interlacing of other rocks and plant detritus. The number of tested samples of claystones of similar mineral composition was

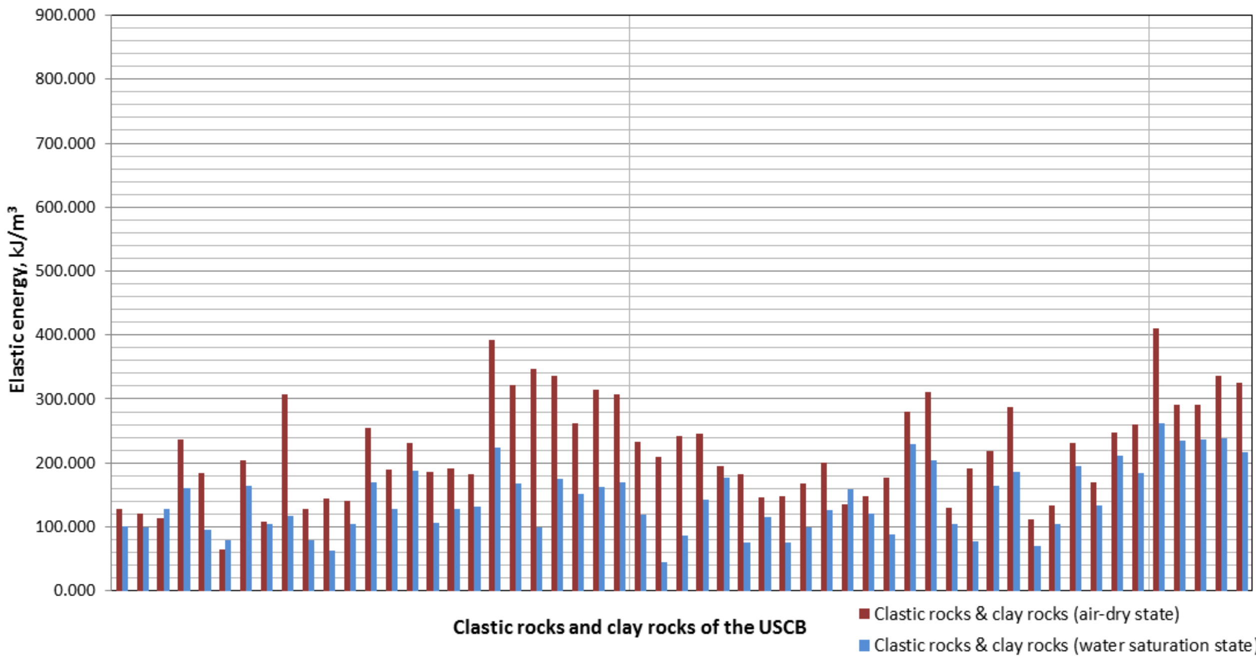

Figure 4: Graphic presentation of average values of elastic energy of clastic rocks and clay rocks of Załęże Beds, Ruda Beds and Saddle Beds of the USCB in air-dry state and in water saturation state.

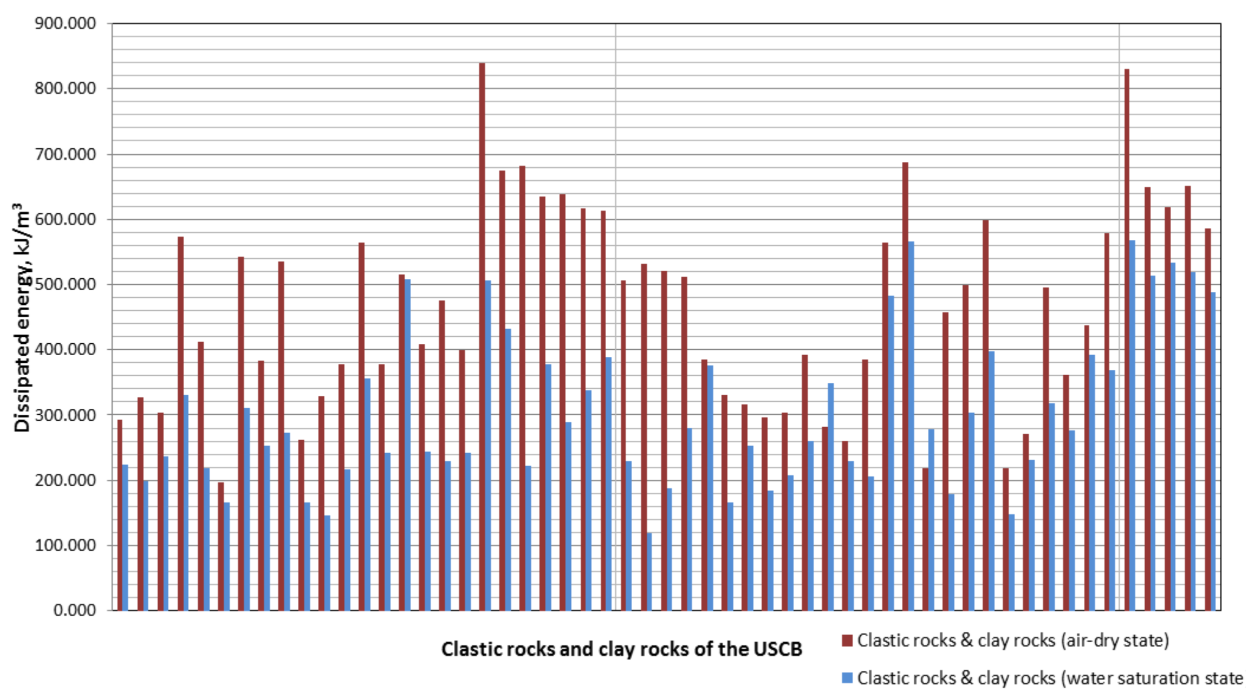

Figure 5: Graphic presentation of average values of dissipated energy of clastic rocks and clay rocks of Załęże Beds, Ruda Beds and Saddle Beds of the USCB in air-dry state and in water saturation state.

Table 2: Functional dependencies of elastic energy and dissipated energy on uniaxial compression strength of sedimentary rocks of Załęże Beds, Ruda Beds and Saddle Beds of the USCB.

Type of rock	Air-dry state		Water saturation state	
	Elastic energy, kJ/m³	Dissipated energy, kJ/m³	Elastic energy, kJ/m³	Dissipated energy, kJ/m³
	equation/ correlation coefficient	equation/ correlation coefficient	equation/ correlation coefficient	equation/ correlation coefficient
Clastic rocks and clay rocks Załęże Beds, Ruda Beds and Saddle Beds	E_{el} = 3.537 UCS + 12.173 r = 0.83 Fig. 6a	E_{dys} = 6.475 UCS + 88.761 r = 0.78 Fig. 6b	E_{el} = 3.213 UCS + 17.323 r = 0.89 Fig. 7a	E_{dys} = 6.844 UCS + 39.869 r = 0.83 Fig. 7b
Clastic rocks Załęże Beds, Ruda Beds and Saddle Beds	E_{el} = 3.675 UCS + 6.771 r = 0.86	E_{dys} = 6.631 UCS + 93.17 r = 0.84	E_{el} = 3.163 UCS + 19.67 r = 0.85	E_{dys} = 6.992 UCS + 34.327 r = 0.79
Sandstones Załęże Beds, Ruda Beds and Saddle Beds	E_{el} = 3.580 UCS + 15.743 r = 0.83	E_{dys} = 6.218 UCS + 129.91 r = 0.81	E_{el} = 2.3973 UCS + 59.585 r = 0.79	E_{dys} = 5.2139 UCS + 134.85 r = 0.69
Mudstones Załęże Beds, Ruda Beds and Saddle Beds	E_{el} = 3.588 UCS + 7.735 r = 0.82	E_{dys} = 6.483 UCS + 89.061 r = 0.78	E_{el} = 5.5486 UCS + 55.522 r = 0.85	E_{dys} = 3.2295 UCS + 10.163 r = 0.81

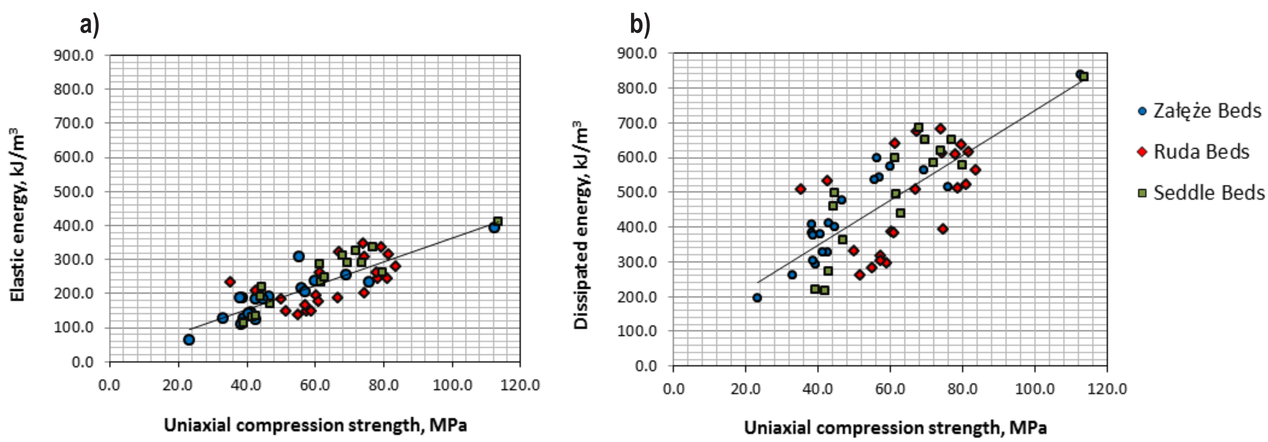

Figure 6: Dependence average of elastic energy (a) and dissipated energy (b) of clastic rocks and clay rocks of different ages on uniaxial compression strength in air-dry state

too small to show any significant functional dependencies between values of given energies and uniaxial compression strength. For the tested claystones, we did not obtain any functional dependencies between values of the given energies and uniaxial compression strength. We are currently conducting further tests on claystones, that is why, in the nearest future, we will add results for claystones from the USCB to the data base and the data will be analysed statistically again to obtain dependencies of between values of energies and uniaxial compression strength.

In all the tested rocks, both in an air-dry state and in water saturation state, we observed that an increase in elastic energy and dissipated energy corresponds to an increase in the value of uniaxial compression strength, which shows a high correlation coefficient for the values of the given energy.

Also, for sandstones and mudstones separately, we observed that an increase in the value of elastic energy and dissipated energy corresponds to an increase in uniaxial compression strength. Linear dependence was demonstrated for both states of humidity.

Linear dependence E_{dys} – UCS determined for samples of sandstones and mudstones in air-dry state from Załęże Beds, Ruda Beds and Saddle Beds is similar to equations developed separately for fine-grained and

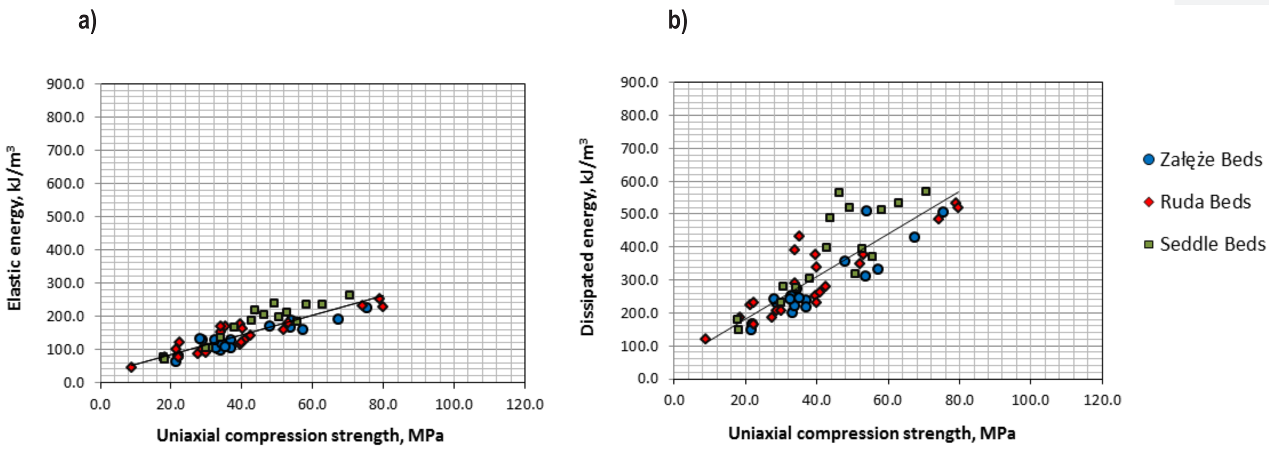

Figure 7: Dependency average of elastic energy (a) and dissipated energy (b) of clastic rocks and clay rocks of different ages on uniaxial compression strength in water saturation state

medium-grained sandstones of Orzesze Beds and Załęże Beds (Mudstone Series), Saddle Beds (Upper Silesian Sandstone Series and Jaklowieckie Beds and Gruszowskie Beds (Paralic Series) of the USCB, presented for coals in the article.[2]

5 Summary

The result of the laboratory tests conducted on rock samples with a material testing machine in a uniaxial compression test is shown through a stress-strain curve. A full-range stress-strain curve enables the determination of geomechanical and energy parameters from pre-critical and post-critical parts of the deformation area of a loaded rock sample.

The results of the tests on sandstones, mudstones and claystones of the selected areas and tectonic structures of the USCB were analysed. Dependencies between elastic energy and dissipated energy, and the uniaxial compression strength of rock samples in air-dry state and in water saturation state were determined. Influence of saturation condition on energy properties of selected sedimentary rocks were also analysed. The dependencies were described with a linear function.

An analysis of the tested sedimentary rocks allowed us to formulate the following conclusions:

- We observed a decrease in the value of elastic energy and dissipated energy after saturating rock samples with water.
- We observed that an increase in the value of elastic energy and dissipated energy corresponds to an increase in the value of uniaxial compression strength of sedimentary rocks of the USCB of different ages, both in an air-dry state and in water saturation state.
- We confirmed the compatibility of the determined linear dependencies E_{dys} – UCS for sandstones and mudstones of the Załęże Beds, Ruda Beds and Saddle Beds of the USCB, which were tested in air-dry state, with functional equations calculated separately for fine-grained sandstones and medium-grained sandstones of layers of the same age and older layers (Jaklowiec Beds and Gruszow Beds – Paralic Series) of the USCB presented for coals in the article.[2]
- Due to significant differences between hitherto tested claystones, we still continue research into the connection between energy parameters and uniaxial compression strength.

Results of the tests are original and can be applied to the designing and conducting of underground mining operations in a safer way. Clastic rocks form layers, which can potentially generate tremors. The occurrence of potentially tremor-generating thick layers of sandstones in the vertical profile of Carboniferous rock mass results in tremor hazard and rock burst hazard in the Carboniferous rock mass where mining operations are conducted. Water reservoirs, often located in sandstone layers, also can be a source of water hazard in underground mine workings.

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