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The impact of the mineral composition of Carboniferous claystones on the water-induced changes of their geomechanical properties

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Abstract: In this article, the authors describe the characteristics and changes of geomechanical properties of Carbonifeorus claystones as related to their mineral composition and the time of soaking in water. Geomechanical properties, including bulk density, Young modulus, Poisson ratio, unconfined compressive strength, durability index, and swelling index were examined in dry rock samples, and in water-soaked samples after 3 hours of soaking, and 6 hours of soaking respectively. Changes in the geomechanical properties of rocks were also examined as a function of their mineralogical composition. In particular, the properties of rocks were examined in relation to present aluminosilicates and layered aluminosilicates, respectively. Changes in the geomechanical properties were also examined relative to the presence of minerals anatase and siderite. Correlation coefficients between physical parameters and mineral composition were examined. It was determined that the total quantity of aluminosilcates is a better predictor of geomechanical properties after soaking, than only the content of layered aluminosilicates. Calculated correlation coefficients were generally higher for most samples after 6 hours of soaking than after 3 hours of soaking. It was also determined that the increase of bulk density correlates much better with the mineral anatase content, than with the siderite content.

Keywords: Carboniferous claystones, geomechanical properties, water-induced changes, mineral composition

INTRODUCTION

Geomechanical properties of rocks such as claystones vary considerably depending on the water content and soaking time. These changes of geomechanuical properties are likely to influenced by the mineral composition of claystones. This article describes the study of the geomechanical properties of Carbonifeorus claystones of variable mineral composition at various soaking times. The initial part of the article describes the impact of water on the mechanical properties of rocks. In the later part of the article, water-influenced properties are discussed in more detail as a function of mineral composition.

IMPACT OF WATER ON MECHANICAL PROPERTIES OF ROCKS

The impact of water on the mechanical properties of rocks is observable in all rock varieties. Among compact rocks it refers mainly to those of sedimentary origin and is revealed first of all as a loss

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of strength that is often associated with a loss of consistency and even the disintegration of the whole rock. Its intergranular structure becomes loose and weak, thus the rock may be more easily deformed. A significant lowering of strength and strain parameters of sedimentary rocks due to their wetting was confirmed by laboratory investigations (Hoek & Brown 1997, Vásárhelyi & Ván 2006, Bukowski & Bukowska 2012, Li at al. 2012, Abd El Megeed 2013, Małkowski at al. 2014, Lyu at al. 2015) and mainly depends, according to specialists (Moore & Reynolds 1989, Vásárhelyi & Ván 2006, Josh et al. 2012), on the type of cement in the intergranular spaces and the overall mineral composition. Determinations of geomechanical parameters of the Carboniferous rocks (Bukowska 2012) show that the least resistant to the water presence are claystones, and a high increase of their moisture due to stagnant water is attributed mainly to their mineral composition and hygroscopic properties. Hoek & Brown (1997) report that the lowering of the strength parameters of wet claystones may reach 30-100% of the respective values of these rocks in the air-dry state. Similar results were obtained by Bukowska (2012) and Małkowski et al. (2014), who determined, respectively, the values 50 and even 80% lower. Li et al. (2012) additionally indicate that at low confined pressures in the damp clay-rich rocks (siltstones) compared to their dry varieties an increase in the residual strength may be expected and a general lowering of rock brittleness associated with a growth of their plasticity. In mining practice, such a behaviour of the claystones contacting with water results in the fracturing and splitting of roof and side wall rocks, and an intensive floor bulging of a continuous character, favoured by an increase of plasticity in the rocks in a post-failure phase.

A tendency to change their volume is a characteristic property of the damp claystones. The swelling of clay rocks depends mainly on the presence of such layered aluminosilicates as smectites (including montmorillonite), illite, kaolinite and chlorites (Stoch 1974, Kabiesz 1988, Moore & Reynolds 1989, Bukowska 2012, Josh et al. 2012). This phenomenon may result in increasing the volume of clay rocks by several to even 20–30% in a short time (Li et al. 2012, Labani & Rezaee 2015), the dynamics of this process depends on the adsorption rate of water by clay minerals (Li et al. 2012, Małkowski et al. 2014, Labani & Rezaee 2015, Pimentel 2015).

Since soaking of rocks with water is combined with the loosening of their internal structure, the parameters that can effectively measure the degree of rock weakening due to water action are the wave properties of rocks associated with the propagation of elastic waves. The average velocities of the longitudinal waves in the clayrocks range between 1100–5450 m/s (Mitin & Timofeev 1970, Kabiesz 1988, Hoek & Brown 1997, Yang, 2014, Lyu et al. 2015). Josh et al. (2012) distinguished two groups of claystones: the weak ones, in which the longitudinal wave travels at 1100–3450 m/s, and the strong ones, in which this speed is higher – 2430–4980 m/s. Mitin & Timofeev (1970) observed a lowering of the longitudinal wave velocity as much as 75% depending on the quantity of water adsorbed by claystones.

Since the coal seams in Polish mines occur very often within wet claystones, the authors investigated the dependency between the mineral composition of claystones, focusing mainly on their content of clay minerals, and the structural, mechanical and wave parameters of these rocks. The investigations were carried out on the claystones of the coal-bearing Łaziska Beds (ZG Janina = Janina colliery, and KWK Piast = Piast coal mine) and Lower Ruda Beds (Ruch Zofiówka and Ruch Borynia = Zofiówka coal mine and Borynia coal mine – they are now divisions of the united coal mine Jastrzębie-Zofiówka-Borynia). The parameters analyzed and their changes included: bulk density, compressive strength, modulus of linear elasticity, Poisson ratio, longitudinal wave velocity. The mineral composition was determined using the method of X-ray diffraction.

X-RAY DIFFRACTION ANALYSES

X-ray diffraction (XRD) is a nondestructive method of mineral identification, used for a wide variety of crystalline materials (Moore & Reynolds 1989). The analyses were carried out on eight samples (two claystones from each of the four coal mines). The mineral composition was determined using the powder Debye-Sherrer method (PXRD), as their very-fine nature precluded identification of clay minerals using optical microscopy (Bolewski & Manecki 1984). X-ray patterns were recorded with a Rigaku MiniFlex 600 diffractometer applying the following working parameters: Cu_{Ka} cathode, reflection monochromator, lamp voltage 40 kV and current 20 mA, measuring range 5–65°2Q, step 0.05°2Q, acquisition time 1 s/step.

The interplanar spacings (*d*) obtained from the X-ray patterns were used for the phase identification based on the data catalogue of the International Centre for Diffraction Data (ICDD) and the XRAYAN software. Additionally, the mineral composition was evaluated by applying the method of the internal quartz standard. The results are summarized in Table 1 and discussed below.

Quartz is the main mineral component of the claystones (Fig. 1). Among clay minerals, kaolinite and illite dominate, and are accompanied by a relatively high content (10–16 wt.%) of mixed layered clay minerals of the illite-smectite type. Other phases include Na-rich plagioclases (albite type), K feldspars (microcline) and carbonate minerals (ankerite, calcite and siderite). The content of the carbonates is minor, the higher only (about 8 wt.%) in the claystones from the Zofiówka coal mine. In most of the rocks also occur traces of secondary chlorites (weathering products). The presence of anatase TiO_2 is worth mentioning: it occurs in all the samples in the quantities from 0.5 wt.% to 2.0 wt.%.

The total of all aluminosilicate minerals ranges from around 44 wt.% in the Zofiówka claystones to around 56 wt.% in the claystones from the Piast coal mine. The content of the layered aluminosilicates, which are mainly responsible for the water adsorption of rocks, is the highest (around 50 wt.%) in the claystones from the Borynia colliery, and the lowest (around 38 wt.%) in the claystones from the Zofiówka colliery. It should be noticed that smectite, the clay mineral of the highest water adsorption, occurs in the claystones of the Piast, Borynia and Zofiówka collieries in comparable quantities around 11wt.%, and its quantity is significantly higher in these rocks from the Janina coal mine – 15.5 wt.% (Tab. 1).

Substantial differences are related to the contents of minor mineral phases. For instance, in the claystones of the Piast colliery, the microcline content of 8.1 wt.% is 3–5 times higher than that of other samples, while the claystones of the Zofiówka colliery contain 4.5 wt.%, of ankerite which occurs in trace amounts in the remaining samples.

Table 1
Mineral composition of the Carboniferous claystones

Mineral	Łaziska Beds				Dolna Ruda Beds			
	Piast		Janina		Borynia		Zofiówka	
	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
	[wt.%]							
Quartz SiO_2	40.0	41.5	40.0	41.2	40.0	41.0	46.0	46.0
Albite $NaAlSi_3O_8$	3.0	1.2	5.0	1.5	5.0	2.8	0.0	5.1
Microcline $KAlSi_3O_8$	8.0	8.1	1.9	2.6	1.5	1.8	3.2	3.0
Illite $(K,H_3O)(Al,Mg,Fe)_2$ $[(Si,Al)_4O_{10}](OH)_2$	15.1	14.0	15.0	15.1	15.1	14.3	10.0	10.9
Kaolinite $Al_4[Si_4O_{10}](OH)_8$	18.4	18.5	18.5	19.5	24.9	24.0	18.5	15.4
Illite/smectite	10.0	10.7	16.0	15.0	11.0	10.9	12.0	10.0
Chlorite $Fe,Mg,Al)_6[(OH)_2(Si,Al)_4O_{10}$	4.0	5.1	2.0	3.1	0.0	0.8	1.8	1.3
Calcite $CaCO_3$	0.0	0.0	1.0	0.5	0.0	0.0	3.0	1.6
Siderite $FeCO_3$	0.0	0.0	0.0	0.0	0.0	2.2	0.0	2.2
Ankerite $CaFe[CO_3]_2$	0.5	0.1	0.1	0.1	0.5	0.1	5.0	4.0
Anatase TiO_2	1.0	0.8	0.5	1.4	2.0	2.1	0.5	0.5
Aluminosilicates – total	58.05		57.60		56.05		45.60	
Layered aluminosilicates – total	50.10		49.55		43.35		38.40	

X-ray diffraction patterns of all the examined samples are shown in Figure 1.

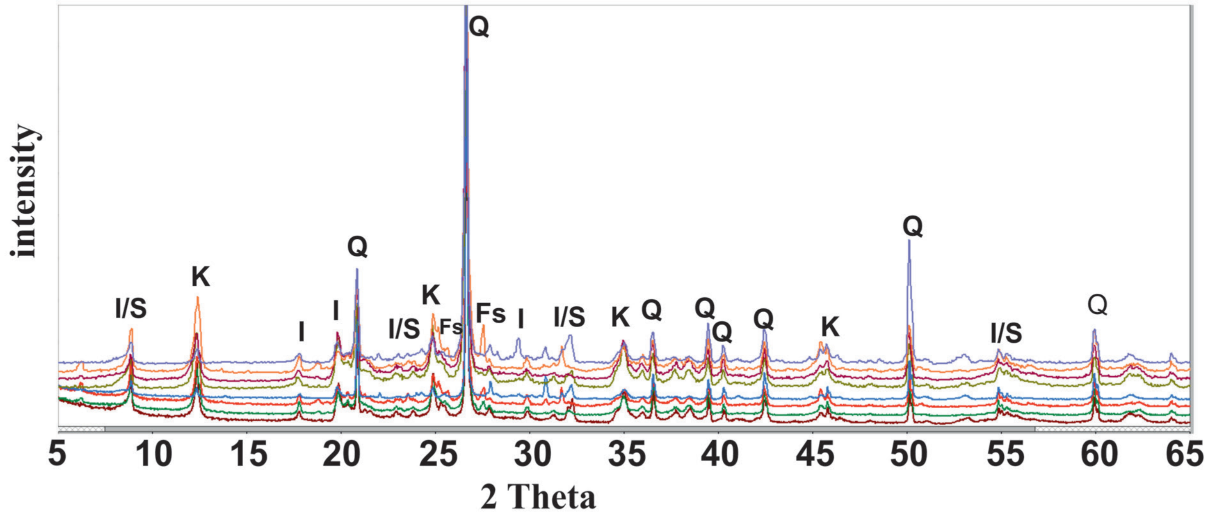

Fig. 1. *X-ray diffraction patterns of examined samples. Symbols: Q – quartz, K – kaolinite, I – illite, I/S – illite/smectite, Fs – feldspar*

INVESTIGATIONS OF GEOMECHANICAL PARAMETERS

The following geomechanical parameters were determined: bulk density ρ_0, unconfined compressive strength R_c, modulus of the linear elasticity E_i (tangent Young modulus for the range of 20–80% of ultimate stress (Ulusay & Hudson 2007), Poisson ratio v, longitudinal wave velocity V_P, slake durability index r according to (Kidybiński 2004) and swelling index. Also, the values of total water content W_t attained by claystones after a specified time of being exposed to soaking in stagnant water were determined. All these parameters were measured initially on dry samples, and then on the samples exposed to the water soaking for successively 3, 6, 12 and 24 h. A fast water-induced disintegration of the claystones from the Łaziska Beds made possible determining of some parameters only after 3 and 6 hours after submerging them in water (slake durability index r in the range 0.2–0.6 and 0.4–0.8). Since claystones of the Lower Ruda Beds reveal a high rock slake durability index, their exposition time on stagnant water was 24 h.

All the claystones enclosing coal seams, both within the Łaziska Beds and Lower Ruda Beds, reveal decreases of the uniaxial compression strength, modulus of the linear elasticity and the velocity of the longitudinal waves, and at the same time increases in their bulk density and Poisson ratio (Tab. 2). These changes closely depend on the time of water soaking, as the water content was gradually increasing: claystones of the Łaziska Beds adsorb after 6 h around 3%, and claystones of the Lower Ruda Beds around 1% water (Fig. 2). Changes of compressive strength and Young modulus expressed in per cent values are almost equal (Fig. 3). In claystones of the Łaziska Beds after 6 h these values are reduced by 60–70% before claystones disintegrate, while in claystones of the Lower Ruda Beds the reduction is 30–55%, but only after 24 h. Therefore, the strength of claystones may decrease 2–3-fold at the simultaneous 2–3-fold increase of deformability. The mechanical properties of claystone of any of the two sampled horizons are similar, but significantly differ among the horizons. In the rock samples in the air-dry state the compressive strength of the Łaziska Beds claystones is around 20 MPa and those of the Lower Ruda Beds in the range 60–70 MPa. Their deformation parameters are: linear elastic modulus 1.7–2.4 GPa and 5.2–6.5 GPa, respectively and the Poisson coefficient from 0.26 to 0.28 and from 0.20 to 0.21, respectively (Tab. 1).

The course of changes of the Poisson coefficient is practically identical for the air-dry state claystones from the same horizon, ranging from 0.26 to 0.35 in 6 h (Łaziska Beds) and from 0.20 to 0.33 in 24 h (Lower Ruda Beds) (Fig. 4).

Although the changes of the velocity of the longitudinal waves (Tab. 1, Fig. 5) should depend theoretically on density and natural moisture content, they change in wide ranges, from 3087 to 6068 m/s, particularly for claystones of the Lower Ruda Beds. The relationship between the rock strength and their moisture content is almost the same for claystones of the same stratigraphic horizon (Fig. 5). After 6 h it is 22–26% for the Łaziska Beds and 8–12% for the Lower Ruda Beds. After 24 h the decrease of the velocity of the longitudinal wave in the Lower Ruda claystones is 16–18%.

Weakening of rock structure resulting from water soaking in the case of claystones from various stratigraphic horizons differs, but the changes of parameters of the claystones from the same horizon are similar. The factor that changes the impact of water on the Lower Ruda claystones is the high sand content of the rocks from the Zofiówka coal mine. It should be mentioned that the fastest rate of lowering the values of the geomechanical parameters always occurs in the first three hours of the rock contact with water.

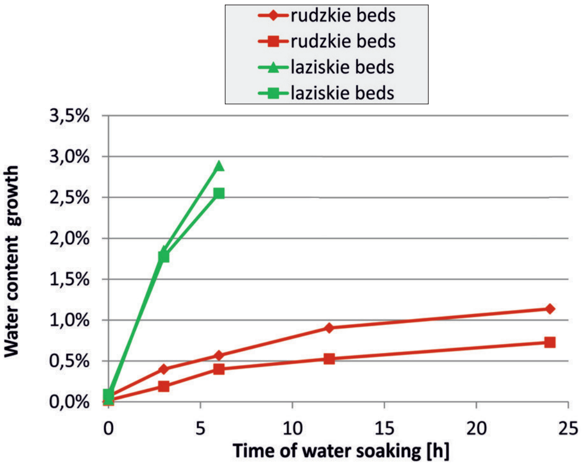

Fig. 2. *Growth of water content in claystones vs. time of water soaking*

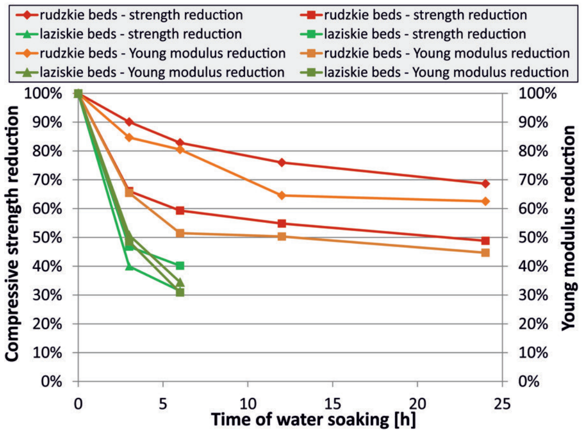

Fig. 3. *Compressive strength and Young modulus reduction of claystones vs. time of water soaking*

Table 2
The water influence on the claystones geomechanical parameters

Beds – colliery	Sample status	W_t [%]	ρ_0 [kg/m^3]	R_c [MPa]	E_i [GPa]	ν	V_p [m/s]	Slake durability index r	Swelling index S_i [%]
Łaziska – Piast	air-dry	0.09	2353	19.64	1.71	0.26	3087.37	0.2–0.6	4.16
	3 h water soaking	1.77	2421	9.19	0.85	0.31	2772.04		
	6 h water soaking	2.55	2439	7.89	0.53	0.33	2385.62		
Łaziska – Janina	air-dry	0.03	2387	21.46	2.42	0.28	3341.79	0.2–0.6	8.25
	3 h water soaking	1.85	2413	8.57	1.16	0.33	2985.13		
	6 h water soaking	2.89	2445	6.75	0.69	0.35	2489.52		
Lower Ruda – Zofiówka	air-dry	0.07	2517	56.13	5.16	0.21	4655.71	1.0	1.33
	3 h water soaking	0.40	2529	50.57	4.84	0.25	4149.80		
	6 h water soaking	0.57	2536	46.50	4.00	0.29	4084.43		
	12 h water soaking	0.90	2544	42.65	3.48	0.31	3988.26		
	24 h water soaking	1.14	2547	38.52	3.18	0.34	3912.42		
Lower Ruda – Borynia	air-dry	0.02	3066	69.09	6.54	0.20	6068.46	0.8–1.0	2.70
	3 h water soaking	0.19	3072	45.66	4.56	0.23	5867.55		
	6 h water soaking	0.40	3085	40.96	4.14	0.27	5572.80		
	12 h water soaking	0.53	3098	37.85	3.33	0.30	5239.61		
	24 h water soaking	0.73	3113	33.73	3.10	0.32	4982.04		

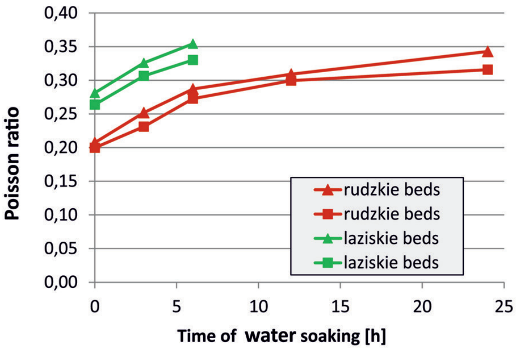

Fig. 4. *Growth of Poisson ratio in claystones vs. time of water soaking*

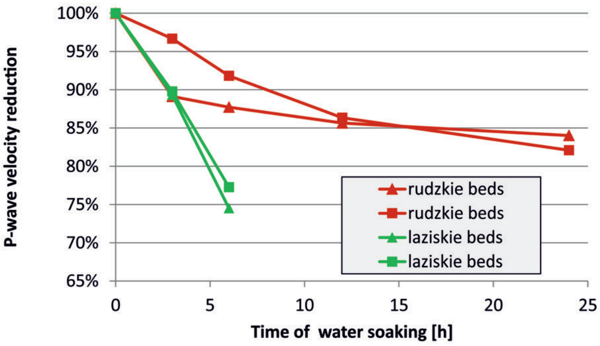

Fig. 5. *P-wave velocity reduction in claystones vs. time of water soaking*

The dynamics of water absorption by the Carboniferous claystones shows that the rocks of the Łaziska Beds absorb water rapidly and completely disintegrate into small fragments after 10 hours (Fig. 6). The Lower Ruda Beds claystones maintain their load capacity and cohesiveness for many hours after their contact with water. In some cases, they only crack along their bedding planes (Fig. 7). The swelling index of the Łaziska claystones ranges from 2.5–9.8%, and the moisture content after 10 h is 4.5–17.8%. Their change of volume attains its maximum after 3–5 h of soaking and, after which the samples started to crack intensively, which prevented carrying out further laboratory tests. The respective data of the five samples from Janina coal mine are shown in Figure 8.

The Lower Ruda claystones ceased to respond to their volume changes after 120–144 hours of water soaking. During this time, they absorbed 0.9–3.2% of water at the average swelling index 2.1%, which ranged between 1.0–2.9%. Their swelling tests were aborted when the volume changes stopped to be recorded. The highest volume rate increase was observed after 14–18 hours from soaking these claystones. The results of the test for claystones from Borynia coal mine is shown in Figure 9.

Despite comparable results of volume changes in time of all the claystones, the changes of their bulk densities are not consistent with the moisture increase in time (comp. Figs. 2–10) and not reflected in the change of the volume changes of these rocks. The increase of mass of the Łaziska claystones is, however, 4- to 6-fold higher than those of the Lower Ruda ones, which after 24 h increase their specific density by a maximum of 1.2% (Fig. 10). Nevertheless, there is a linear relationship between the swelling index and the water content after swelling (Fig. 11) with a relatively high correlation coefficient R^2 of 0.73.

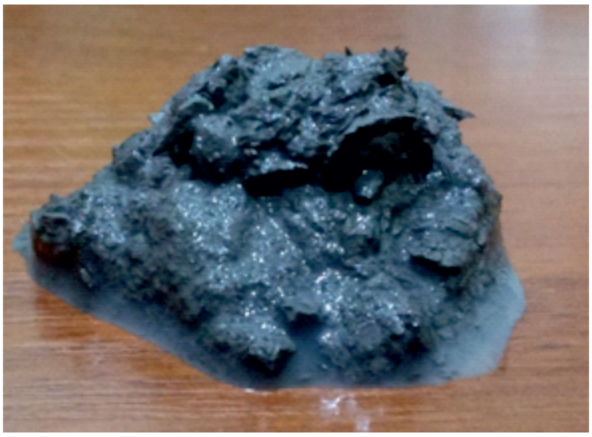

Fig. 6. *Claystone from the Łaziska Beds after 10 hours in water – slake durability index r = 0.2*

Fig. 7. *Claystone from the Lower Ruda Beds after 120 hours in water – slake durability index r = 0.8*

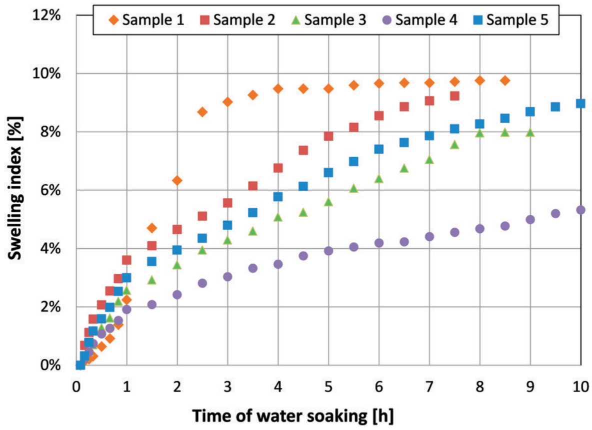

Fig. 8. *The changes of swelling index in claystones from the Łaziska Beds (Janina colliery)*

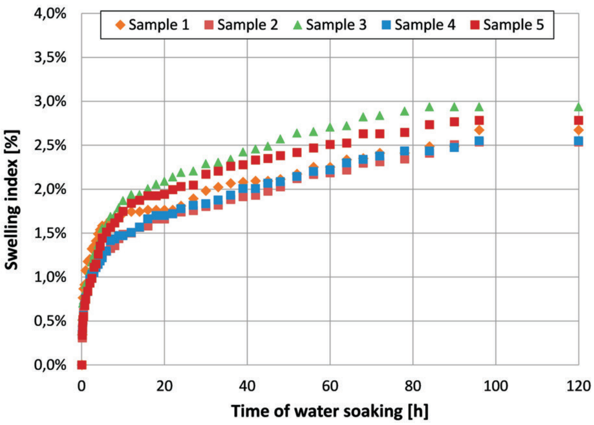

Fig. 9. *The changes of swelling index in claystones from the Lower Ruda Beds (Borynia colliery)*

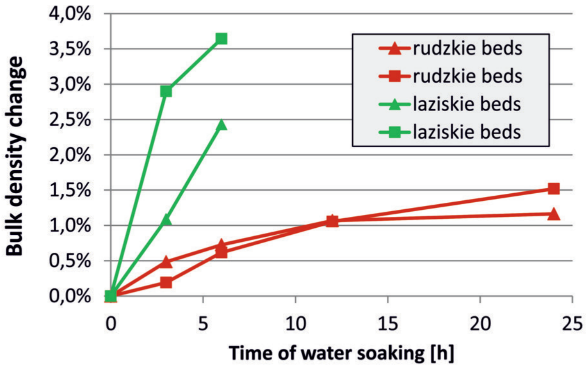

Fig. 10. *Change of bulk density vs. time of water soaking of claystones*

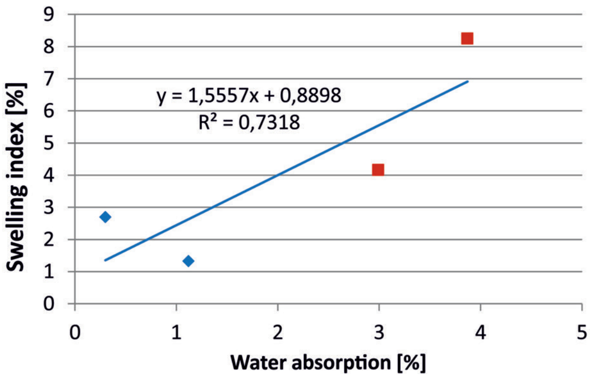

Fig. 11. *Correlation between swelling index and water absorption. Red squares – Łaziska Beds, blue diamonds – Lower Ruda Beds*

The results indicate the significant impact of the moisture content of the claystones on their elastic and mechanical parameters. The lowering values of the parameters tested (Tab. 3) by the authors is consistent with other results obtained in Poland (Bukowska 2012, Bukowski & Bukowska 2012, Josh et al. 2012, Małkowski et al. 2014) and elsewhere (Mitin & Timofeev 1970, Hoek & Brown 1997, Josh et al. 2012, Li et al. 2012, Abd El Megeed, 2013, Labani & Rezaee 2015, Lyu et al. 2015).

The unconfined compression strength values of the Carboniferous claystones soaked in water decreases by 31–68% of such strength values in the air-dry state. The range of this reduction is contained within the range of the values obtained in the Upper Silesian Coal Basin by Kabiesz (1988) (fall 0.5–0.9R_c) and Bukowska (2012) (fall 0.5–0.8R_c). Earlier investigations of two of the current authors limited to the Łaziska Beds claystones (Małkowski et al. 2014) showed much higher reduction (0.1–0.6R_c) of their strength values induced by water and similar to changes of the modulus of the linear elasticity. The results presented in the current paper are well comparable with those contained in several other papers on claystones: in Canada by Hoek and Brown (Hoek & Brown 1997) (strength fall by 30–90%), Australia (Labani & Rezaee 2015) (swelling – P_V = 1–12%, and Rusia – the Ural region (Mitin & Timofeev 1970) (velocity of a longitudinal wave fall by only 10% after soaking).

On the other hand, there are some data on water absorption reporting its higher values 22–25%. than those obtained here for the Carboniferous claystones (Abd El Megeed 2013, Lyu et al. 2015). However, the groups Abd El Megeed (2013) and Lyu et al. (2015) did not carry out the investigations of other mechanical properties of claystones.

Among the data collected in Table 3 there are no references to the Poisson ratio, since this parameter is only occasionally determined. Therefore, in the case of the Carboniferous claystones in question, the authors may compare the increase of the Poisson coefficient by 25–65% to another deformational index of these rocks. i.e., to the Young modulus, which increased in the range 27–69%.

Table 3
The changes of geomechanical parameters induced by water – a literature survey

Author	**Change of parameter value**
Małkowski, Ostrowski, Bożęcki (this study)	$\sigma_{cws} = 0.31–0.68\sigma_{cd}$ $E_{ws} = 0.31–0.63E_d$ $V_d = 0.74–0.84V_{ws}$ $P_V = 1.3–8.3\%$
Bukowska (2012), Bukowski & Bukowska (2012)	$\sigma_{cws} = 0.5–0.8\sigma_{cd}$
Hoek & Brown (1997)	$\sigma_{ws} = 0.1–0.7\sigma_{cd}$
Kabiesz (1988)	$\sigma_{cws} = 0.5–0.9\sigma_{cd}$
Małkowski et al. (2014)	$\sigma_{ws} = 0.1–0.6\sigma_{cd}$ $E_{ws} = 0.1–0.8E_d$
Mitin & Timofeev (1970)	$V_d = 0.25–0.9V_{ws}$
Abd El Megeed (2013)	$P_V = 5–25\%$
Labani & Rezaee (2015)	$P_V = 1–12\%$
Lyu et al. (2015)	$P_V = 3–22\%$
E_d – tangent Young modulus, dry rocks E_{ws} – tangent Young modulus, water saturated rocks σ_{cd} – compressive strength, dry rocks σ_{cws} – compressive strength, water saturated rocks V_d – P-wave velocity, dry rocks V_{ws} – P-wave velocity, water saturated rocks P_V – volume swelling index	

RELATIONS BETWEEN THE MINERAL COMPOSITION AND PHYSICAL PROPERTIES OF CARBONIFEROUS CLAYSTONES

In addition to water induced changes, the relationship between the mineral composition and mechanical properties of rocks was investigated. We have examined the effects of heavy minerals on the bulk density, although they occur usually in trace amounts and are often ignored in most investigations. It has been determined that the role of anatase, dioxide of titanium, on the density of the Carboniferous claystones is higher than that of siderite – carbonate of iron. The correlation coefficients of the averaged values of the bulk densities and contents of both minerals R^2 are 0.76, and 0.54, respectively (Figs. 12, 13). Interestingly in geological descriptions carried out by mining geologists anatase is usually overlooked, as a mineral occurring only occasionally and difficult to be identified. On the other hand, the brown-beige colour of siderites is striking and usually reported in the course of profiling.

To assess the impact of water on the Carboniferous claystones, the authors did not correlate the absolute values of the physical parameters, but their changes in time induced by water soaking of these rocks. Since the Łaziska claystones disintegrated after 6 h of the contact with water, the time-dependence could be tested only in 3 and 6 h intervals. Considering the mineral composition, the authors also tested whether the changes of the claystone parameters took place due to all the aluminosilicates present (illite, kaolinite, smectites, chlorite, albite and microcline) or only due to the layered aluminosilicates (illite, kaolinite smectites and chlorites), whose volumetric changes caused by water absorption are the highest.

Since the rocks affected by water lose their strength and increase their deformability, the most significant parameters to compare with the mineral composition are Young modulus and the compressive strength. The conducted analysis shows that the 3-hour contact of the claystones with water is too short to correlate the relation between change of geomechanical properties and content of clay minerals (although this effect is visible). The change of these geomechanical properties better fits to the content of all aluminosilicates than to the content of their layered varieties. Considering a low number of samples, only were taken into consideration the linear correlations. The changes of the tangent Young modulus (in the range of 20–80% R_c) show that after 3 h of claystones contact with water, the correlation coefficient R^2 between Young modulus and the content of the layered aluminosilicates is 0.39 (Fig. 14), and if calculated in relation to the total content of all aluminosilicates 0.89 (Fig. 16). After 6 h the correlation coefficients were 0.45 and 0.92, respectively (Figs. 15, 17).

It has been determined that there is a stronger correlation between the unconfined compressive strength with the content of all aluminosilicates than with only layered aluminosilicates.

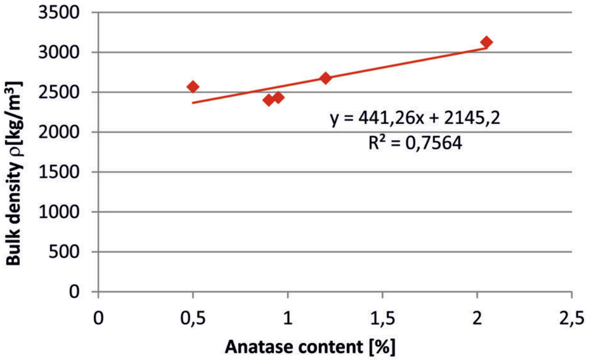

Fig. 12. *The influence of anatase content on bulk density of claystones*

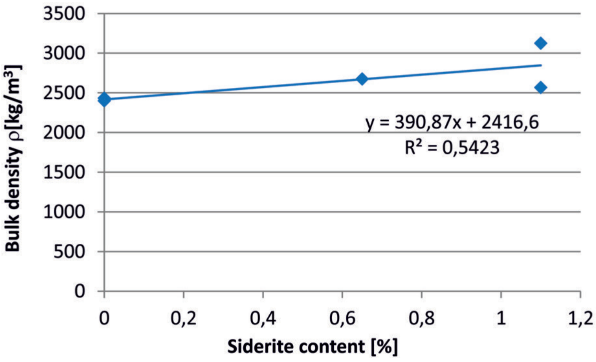

Fig. 13. *The influence of siderite content on bulk density of claystones*

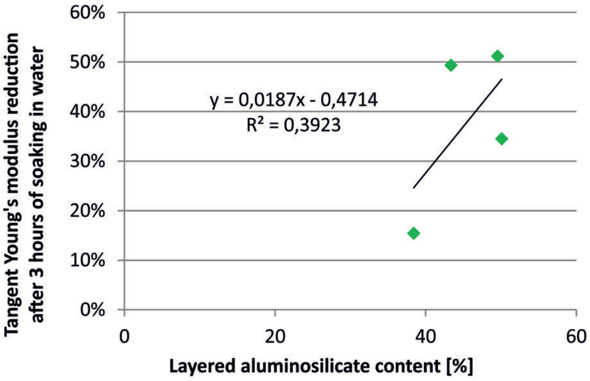

Fig. 14. *The influence of the layered aluminosilicate content on Young modulus reduction of claystones after 3 hours of soaking in water*

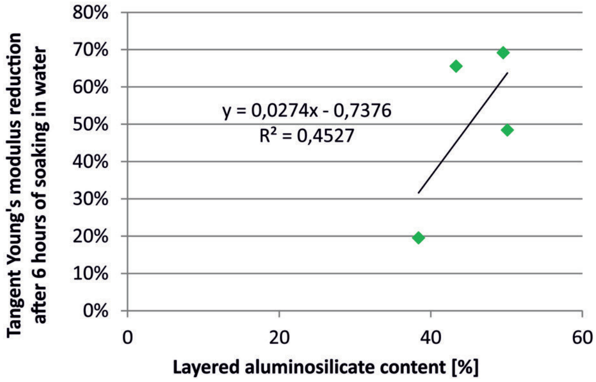

Fig. 15. *The influence of the layered aluminosilicate content on Young modulus reduction of claystones after 6 hours of soaking in water*

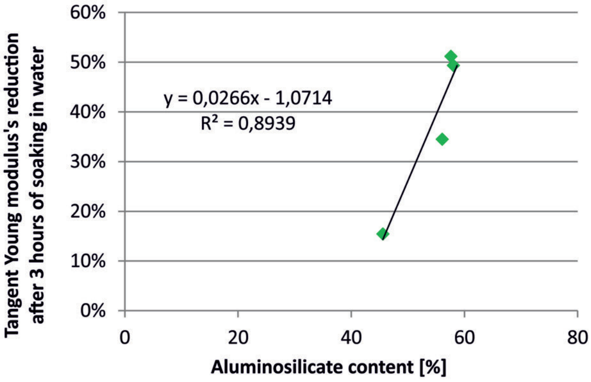

Fig. 16. *The influence of the total aluminosilicate content on Young modulus reduction of claystones after 3 hours of soaking in water*

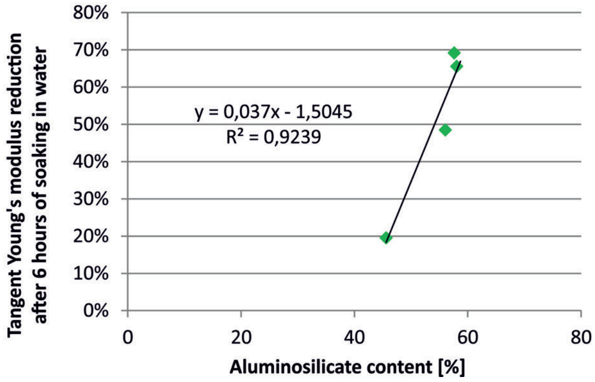

Fig. 17. *The influence of the total aluminosilicate content on Young modulus reduction of claystones after 6 hours of soaking in water*

The values of the correlation coefficients after 3 h of contact with claystones with water are 0.40 (Fig. 18) and 0.86 (Fig. 20), whereas after 6 h they are 0.41 (Fig. 19) and 0.84 (Fig. 21). In this case, the 3-hour contact of claystones with water was sufficient to set the dependency of the mineral content vs. the change of strength. The differences between the impact of only the layered aluminosilicates and that of all the aluminosilicates on the change of claystone strength are practically the same as the change of their modulus of linear elasticity *E*. Therefore, the graphs that follow present only the relations between all the aluminosilicates and a specified geomechanical parameter.

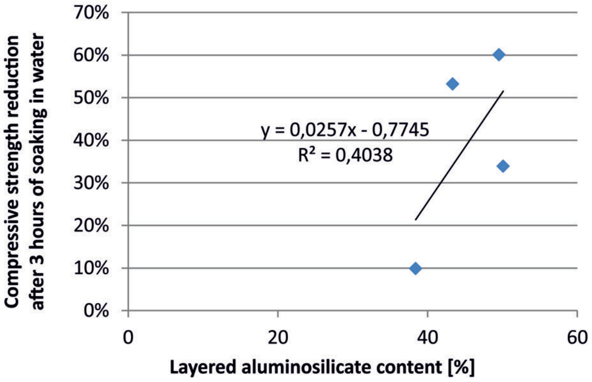

Fig. 18. *The influence of the layered aluminosilicate content on compressive strength reduction of claystones after 3 hours of soaking in water*

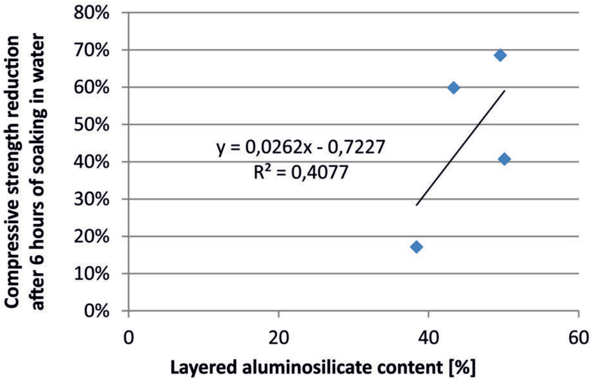

Fig. 19. *The influence of the layered aluminosilicate content on compressive strength reduction of claystones after 6 hours of soaking in water*

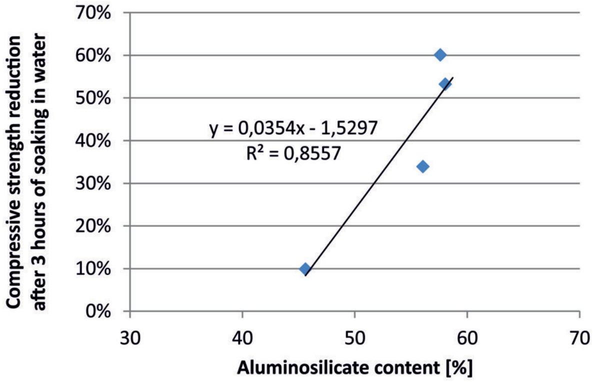

Fig. 20. *The influence of the total aluminosilicate content on compressive strength reduction of claystones after 3 hours of soaking in water*

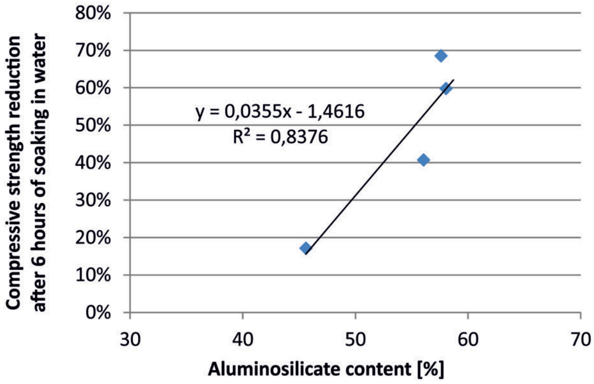

Fig. 21. *The influence of the total aluminosilicate content on compressive strength reduction of claystones after 6 hours of soaking in water*

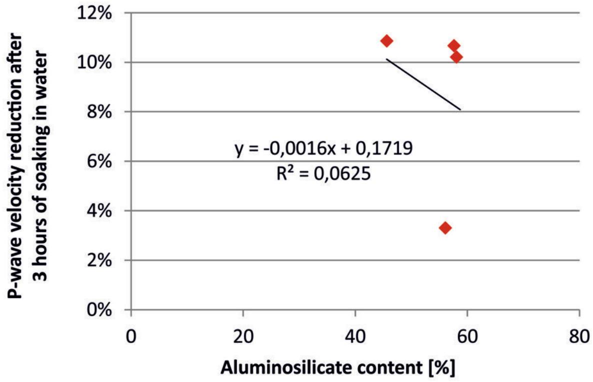

Fig. 22. *The influence of the total aluminosilicate content on P-wave velocity reduction in claystones after 3 hours of soaking in water*

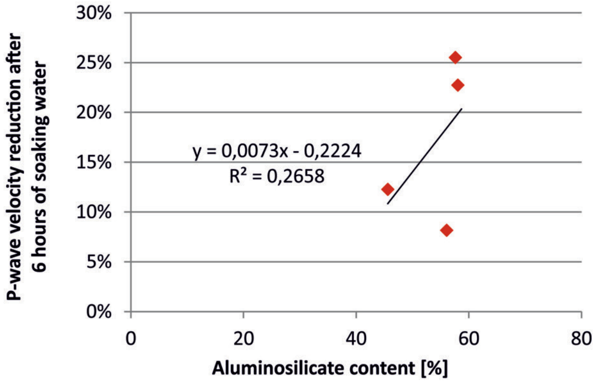

Fig. 23. *The influence of the total aluminosilicate content on P-wave velocity reduction in claystones after 6 hours of soaking in water*

The changes of the elastic properties of the claystones compared to the decrease of the longitudinal wave (Figs. 22, 23) and Poisson coefficient (Figs. 24, 25) were examined. In the case of the wave motion, in samples after the 3-hour contact there is no correlation with the content of aluminosilicates (Fig. 22) and after 6 hours the correlation is very weak (R^2 = 0.26, Fig. 23). The changes of the Poisson coefficient show a similar relation, i.e., after 3 hours the correlation between deformability vs. content of aluminosilicates is hardly visible (correlation coefficient equals only 0,09 – Fig. 24), while after 6 h it increases to 0.66 (Fig. 25).

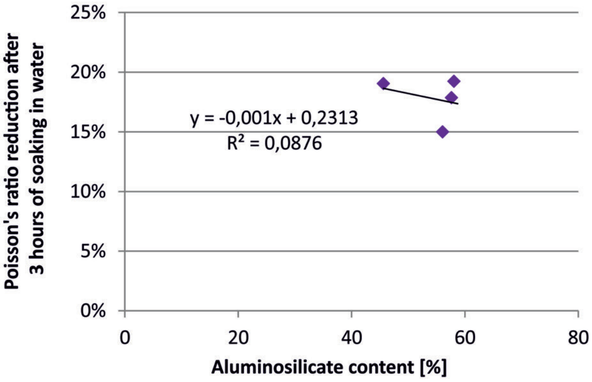

Fig. 24. The influence of aluminosilicate content on claystones Poisson ratio reduction after 3 hours of soaking in water

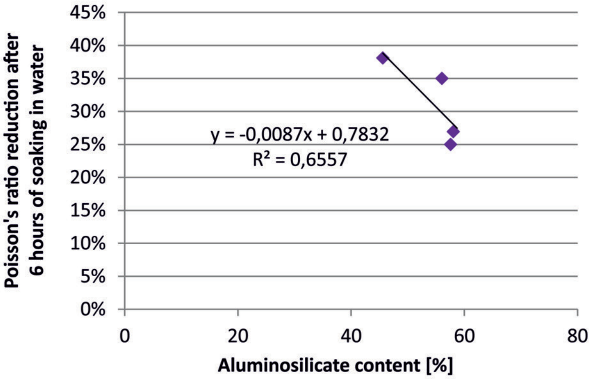

Fig. 25. The influence of aluminosilicate content on claystones Poisson ratio reduction after 6 hours of soaking in water

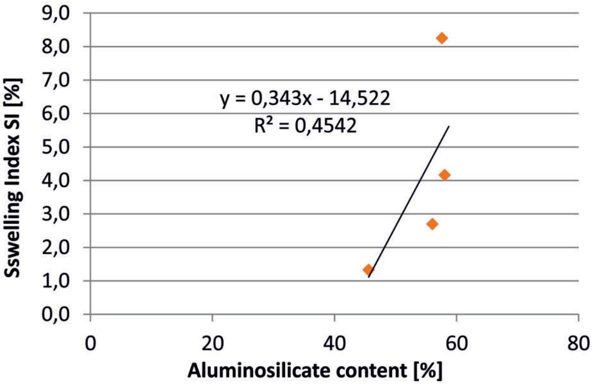

Fig. 26. The influence of aluminosilicate content on swelling index for claystones

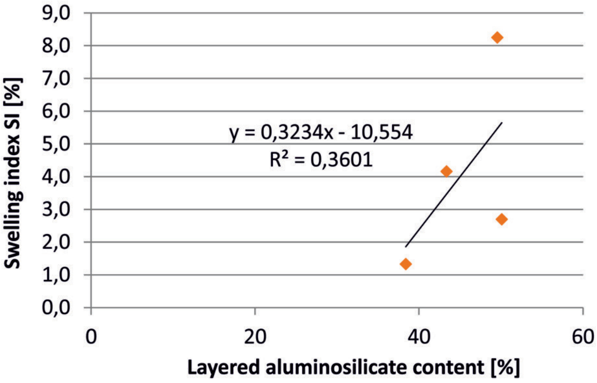

Fig. 27. The influence of layered aluminosilicate content on swelling index for claystones

Summarizing, it seems that the 6-hour soaking is still too short to reveal an impact of aluminosilicates on the geomechanical properties of the claystones.

The relations discussed above clearly indicate that the changes of physical properties of claystones due to their contact with water result from all the aluminosilicate minerals contained in these rocks. The correlation coefficient R^2 of the swelling index with the mineral composition of the claystone is 0.45 if calculated against all the aluminosilicates (Fig. 26) and only 0.36 if calculated against the clay minerals only (Fig. 27). The conclusion is that the structure of the exanimated claystones becomes weakened not only because of the internal absorption of water by minerals but also by the action of water molecules present on the surfaces of minerals where they weaken the intramolecular bonds.

CONCLUSIONS

The physical properties of the Carbonifeorus claystones are strongly variable. Despite relatively minor differences in their mineral compositions, the physical properties depend on the diagenetic changes of these rocks. An increase of the bulk density of the claystones is associated mainly with their anatase content, and not with the siderite content as it is commonly accepted. The strength and deformational properties of the claystones may be even more than 3 times higher if determined in the air-dry state. When claystones are immersed in water, these properties decrease depending on the rock diagenesis. The effects of water soaking differ between the claystones of the Łaziska Beds and those of the Lower Ruda Beds.

The impact of water on the Łaziska claystones is significant and can be observed as soon as several tens of minutes when water weakens the rock structure, which after 5–6 h may reveal cracks of a considerable size. Adsorption and absorption of water results mainly in the strength and deformational properties, but also increases the claystone bulk density by 2–3%, simultaneously, the volume of the claystones grows even by 10% at the 18-percent increase of the moisture content. The claystones of the Lower Ruda Beds usually do not disintegrate if immersed in water, nevertheless they may increase their volume by around 1–3% at the change of the bulk density around 1–1.5% and a water absorption around 3%.

The progress of changes of the mechanical properties is characteristic of the claystones of the stratigraphic horizon, although in the case of the rocks from the Łaziska Beds the changes can only be traced during the first 6-8 hours, i.e., prior to the beginning of the disintegration these claystones in water.

The changes of the mechanical and elastic properties of the claystones of the Łaziska Beds ŁB (after 6 hours of soaking in water) and those of the Lower Ruda Beds LRB (after 24 hours) are compared below:

- compressive strength
  $0.31–0.40\sigma_{cd}$ ŁB and $0.49–0.69\sigma_{cd}$ LRB,
- Young modulus
  $0.31–0.34E_d$ ŁB and $0.45–0.63E_d$ LRB,
- Poisson coefficient
  $1.25–1.26\nu_d$ ŁB and $1.58–1.66\nu_d$ LRB,
- velocity of the longitudinal wave
  $0.74–0.77V_{Pd}$ ŁB and $0.82–0.84V_{Pd}$ LRB.

The reaction of claystones on the impact of water after soaking depends more on their total content of aluminosilicates (46–58%) than the content of more swelling layered aluminosilicate (38–50%). The individual contents of clay minerals, determined using XRD analyses, are: kaolinite 15–25%. smectites 10–16% and illite 10–15%. A comparison of correlation coefficients of the changes of a single physical parameter and the content of total aluminosilicates indicates them as being at least 2–3 stronger than those coefficient correlations calculated against the content of layered aluminosilicates only. When calculated after 3-hour contacts with water, correlation coefficients were lower than those calculated after 6-hour contacts. It means that a sufficient time should elapse before water permeates the rock structure and weakens its interparticle bonds. The correlations of the compressive strength (σ_{cd}) and rock deformability (E and ν) versus the claystone content of total aluminosilicates are the strongest and range from 0.65 to 0.90. Simultaneously, these correlations are highly comparable, which indicates a significant impact of clay minerals on the strength-deformational parameters of the Łaziska and Lower Ruda claystones.

The authors intend to follow up these investigations to gather more data for statistical determinations and to measure the changes of claystones after their longer contact with water.

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