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CHANGES OF SOME OF THE MECHANICAL PROPERTIES OF ROCKS AND ROCK MASS IN CONDITIONS OF MINING EXPLOITATION AND MINE WORKINGS FLOODING

1. Introduction

In the period of hard coal mine functioning and at various stages of its development, generates an impact on geological environment to a various extent. This impact can occur both in connection with mining induced activity but also in the final stage of mine abandoning, and even in post-abandoning stage.

During the time of mining exploitation, especially with caving, processes of its destruction have the most profound influence on rock mass. Their outcome is a lack of continuity of rock stratification, which leads to damage of the structure of rock mass and to intensive drainage of water-bearing formations of free water. These processes in a significant way change properties of rocks and rock mass, including geomechanical and sometimes hydrogeological ones. In the case of rock mass destruction, the decrease of its elasticity takes place as well as the values of rock strength parameters, whereas the values of strain parameters are increased. Drainage of the rock mass with the advance of dewatering and loss of water contained in pores of rocks, in general causes a reinforcement of rock mass, which is expressed by an increase of rock strength and decrease of their deformability.

In the case of secondary saturation of rocks forming a rock mass with water, despite the lack of the destructive impact development is due to the effect of mining exploitation, this process leads to the attenuation of rocks and an intensification of the strain processes. Such a situation takes place in the case of withdrawing from mines when fields are worked out, or in the situation of abandoning and flooding of the whole mine or a part of it.

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Changes in rocks and rock mass under the influence of mining exploitation, and under the influence of the drainage processes as well as flooding workings and the surrounding rock mass, are of considerable significance in forecasting the exploitation conditions and mine abandonment. They are particularly important in the assessment of natural hazards in underground mines and possible common threat after mine abandoning.

2. Changes of rocks and rock mass properties subject to destruction processes induced by influence of mining exploitation in the USCB

A consequence of rock mass destruction caused by mining activity is a change in its properties, including geomechanical ones. The state of the rock mass loosening depends on various factors, including the distance between the undermined and the undermining seam, the thickness of the undermining seam and compactness of rocks which surround undermined seam. By means of field and laboratory testing it has been proven that the first undermining has the most enormous influence on the undermined seam (about 80% of the total influence).

Changes in rock properties, which take place as a result of the undermining of seam can be known i.a. through the application of a comparative method based on the utilization of data from research before and after going through the mining exploitation front. Investigations consist of the assessment of the properties of rocks coming from the drill cores collected from particular roof layers (superstrata), but also in the estimation of results obtained from tests with the use of non-destructive methods (e.g. with rebound hammer) and from penetrometer tests, geodetic and seismic measurements [12, 14]. Results of tests carried out with adoption of some of the above mentioned methods are presented in Table 1.

The results of the testing of the strength of a rocks forming rock mass untouched by mining exploitation and in areas which have passed through the exploitation front visibly differ between each other. The reason of their diversification within the same type of rock is the diverse research methodology adopted – laboratory testing of core samples and in situ testing. On the basis of the investigations conducted and the verification of the results of the tests carried out previously it was shown that the compressive strength after passing through the exploitation front decreases [15]. In the paper [15] it has been stated that weaker rocks are subjected to greater damage than strong rocks. The level of the drop in the strength of undermined rock considerably differs depending on the adopted research methods. On average, it can be assumed that with the index of undermining $5 \leq M \leq 10$ (M the smallest distance between seams at which exploitation of undermined seams is possible; constitutes quotient of thickness of rock layers between destressing and destressed seam and thickness of destressing seam) compressive strength of coal decreases by 10–20% and tensile strength by 10–18%, clay slate respectively by 5–15% and 5–12%, and sandstone by 4–8% and 5–8%. Fissuring of undermined rocks with the index of undermining $5 \leq M \leq 10$ increases by 20–60% for clay slate and 10–30% for sandstone while. At the same time, it ought to be emphasized that weaker rocks are subject to greater failure than strong rocks. It has a significant meaning for drivage conditions and mine workings maintenance. Later investigations of Carboniferous

TABLE 1

Changes of compressive strength of rocks as a result of mining exploitation impact

Type of studies	**Compressive strength before passing through of exploitation front MPa**	**Compressive strength after passing through of exploitation front MPa**	**Changes of compressive strength values %**	**Seam Index of undermining Rock**
Changes of compressive strength of rocks as a result of undermining seam				
Testing *in situ* with rebound hammer	37.6	26.1	30.6 (fall)	**seam 358**, index of undermining 13.3 coal
Laboratory testing on drill cores	67.1	46.0	31 (fall)	clay slate
	83.3	64.7	22 (fall)	fine-grained sandstone
	53.7	45.8	15 (fall)	**seam 360/1**, index of undermining 5.8, clay slate
	45.0	39.3	12.7 (fall)	**roof of the seam 502**, index of undermining 4.5 or more clay slate with admixture of sand and mudstone
Penetrometer testing of rocks in boreholes	19.2	15.8	17.7 (fall)	**roof of the seam 502**, 4.5 or more, coal
	36.6	33.1; 34.8	9.6–4.9 (fall)	clay slate
	82.0	77.5; 78.6	4.1–5.5 (fall)	sandstone
Changes of compressive strength of barren rocks depending on testing area location from the longwall front				
Location of observation point towards longwall front		Behaviour of compressive strength R_c		**seam 406/3**
Up to the distance of 60 m behind longwall front		R_c barren rocks inconsiderably changes		
Up to the distance of about 350 m behind longwall front		R_c barren rocks decreases by 50%		
Changes of compressive strength of rocks as a result of overmining of seam				
Laboratory testing	51.7% strength fall		coal	**roof and floor of the seam 358**
	77.7% strength fall		mudstone	

rocks of the USCB allowed for the overall estimation of a fracture impact and other surfaces of weakening on compressive strength of sandstone and clay slate (Tab. 2).

In a multilayer coal exploitation with a system of caving of roof rocks, roadways are often located directly under caving debris. In a situation of sufficient reconsolidation of caving debris under the influence of rock mass and water pressure, as in the case of large surface areas of goafs and in general, after several years have passed since exploitation termination in a given place – roadways are maintained in a good condition despite the damaged structure of rocks, which leave characteristic caving debris. The substantial threat of the fall

TABLE 2

Influence of fracturing and other surfaces of weakening on compressive strength of Carboniferous rocks [3]

Rock	Decrease factor of compressive strength of rocks as a result of the presence of fracturing and other surfaces with weakening
Fine-grained sandstone	0.34–0.77
Clay slate	0.39–0.59

of rocks takes place at the front due to the drilling of workings under caving debris or in the case of lining damage as a result of „knocking out" of double timber [2].

3. Changes of properties of rocks and rock mass subjected to processes of dewatering and flooding of workings at the background of mine activities in the USCB

The rapidly advancing intensification of mining works and the considerable increase of the surface area of rock mass in new and in old mining areas causes the intensification and substantial acceleration of the process of rock mass dewatering. In the period following 1945, a considerable number of old and shallow mine workings has been flooded. The average depth of the mining exploitation of old mines did not exceed 400–500 m, in most cases and their total output was 25 Mg of coal for the year (1945). Workings of existing, old (built before 1945) mines caused effects in the rock mass displayed by i.a. facilitated infiltration of waters from the surface of the ground and sub-surface layers. Parts of the rock mass located at deeper depths were not dewatered to a greater degree (Fig. 1.).

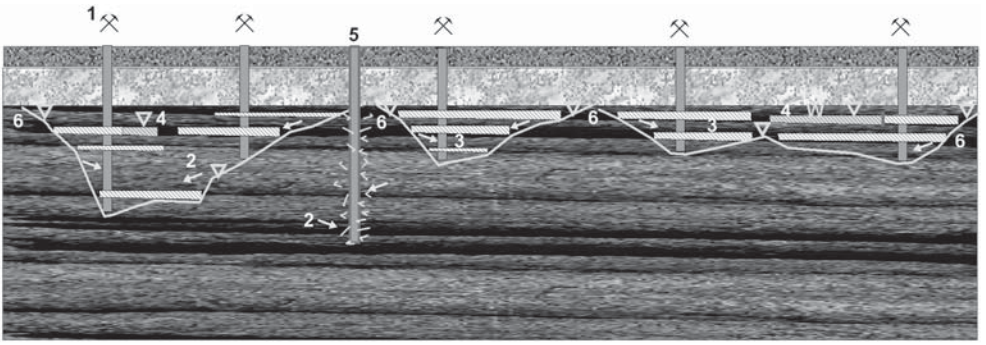

Fig. 1. Diagram of the scope of rock mass dewatering in the USCB in the initial period of underground coal mining
1 — active mine, 2 — directions of flow connected with drainage, 3 — goafs and not watered and not flooded mine workings, 4 — watered and flooded mine workings, 5 — mine workings under constructoins, 6 — schematic reach of cone of depression

The relatively shallow depth of the exploitation carried out in the area of these mines caused the cone of depression in deposit series was marked by an expansion in a horizontal

direction and in the direction of formations of overlay of deposit series, up to sub-surface formations. The spreading of the cone of depression in horizontal directions was greater, the closer they got to the workings of neighbouring mines. With the development of exploitation, old mines were connected directly with new mine workings. It most often resulted in changes in the property rights of exploited deposits or the overlapping of impact boundaries of mining exploitations. The overlapping of areas of exploitation, their conglomeration and overlapping of the exploitation influences led to slow regionalization of influences and an increase of areas of mining influence on underground waters and rock medium. In general, it can be stated, that the cone of depression could have originally consisted of combined, shallow placed local cones of depression of in single mines or groups of neighbouring mines (Fig. 1).

During this time the rock mass could have been marked by a considerable degree of saturation of rocks and crevices with water. The pillar and chamber system of exploitation caused conditions of considerable watering of the rock mass and facilitated water infiltration could have, in many cases, caused the strength parameters of rocks to be less than those currently under examination and their strain properties higher. At a slightly higher vertical pressure the rock mass and roof shelf disturbance as well as the change of properties of rocks neighbouring and forming a pillar (so called rance) strength values in a pillar could have repeatedly been exceeded. At that time, falls of roof rock took place causing formations of overburden, isolation rupture and occurrence of water hazard.

Changes in hydrodynamic conditions in the USCB induced by mining development (Fig. 1) in post-war periods of building mining infrastructure and the intensification of mining works could have taken place in accordance with the diagram presented in Figure (Fig. 2). It meant that the area of rock mass subjected to drainage widened quickly and the watering of mine workings having an effect on the shaping of the water conditions was connected and repeatedly described by researches as a regularity of variability of hydrogeological properties of rocks and rock mass with depth [18, 19, 22].

At that time (the 1960–1980s) many methods of investigation the hydrogeological properties of rocks were devised and implemented. Research was conducted among others, in the scope of the determination of open porosity — the vacuum method adopted according to [10], draining capacity — the method of index of draining according to [21], the method of hydroextracting adopted by [16] and the method of capillary drainage according to [1], permeability — the method based on the formulas of French researchers with the utilization of the partial vacuum of atmospheric air according to [17].

Geomechanical research in the period of the 1960–1980s was based on tests obtained from the so called soft testing machine and on parameters received from pre-critical part of characteristics of the destruction of Carboniferous rocks samples. For the rocks of the USCB, testing was conducted in various states of saturation with water, from desiccated in 105°C, through air-dry state, to the state of saturation with water during a period of several dozen hours [9, 11]. Generally, for geomechanical testing it was a time of adjusting or working out methodology with respect to geomechanical hazards, the frequency of especially bumps, similarly the frequency of inrushes in the 1950s and 1960s began to grow. The development of

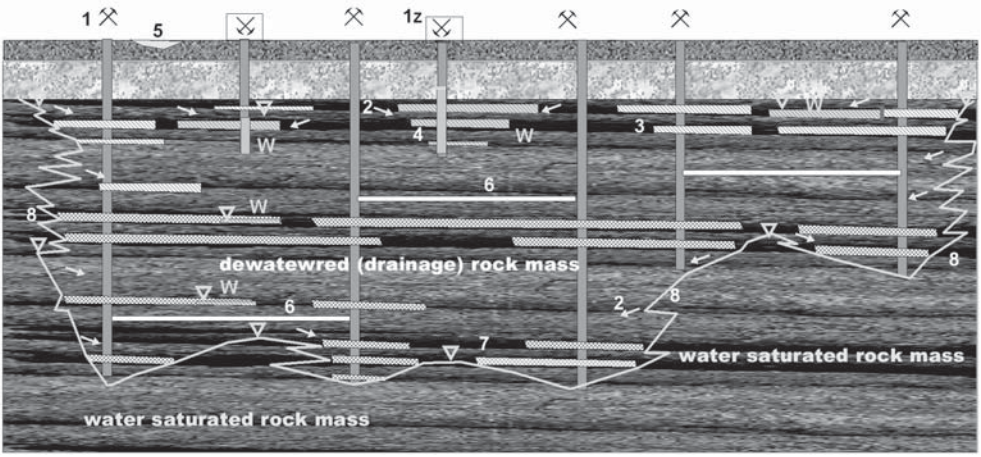

Fig. 2. Diagram of changes in spreading of cone of depression in the USCB with reference to changes in development of underground mining of hard coal — developed and mechanized mining of the 70s and 80s of the 20th century
1 — active mine, 1z — abandoned mine, 2 — directions of flow connected with drainage and mines flooding, 3 — goafs and not watered and not flooded mine workings, 4 — watered and flooded mine workings, 5 — postmining innundation, 6 — active levels of the mine, 7 — levels of mine under construction, 8 — schematic reach of regional cone of depression

mining activity began in conditions of strong watering of the rock mass and mine workings (Fig. 1, 2).

During the 1970s and 1980s the century occurrence of the phenomena which signified water hazards in mines gradually decreased to slightly above 1 occurrence a year (Fig. 3.).

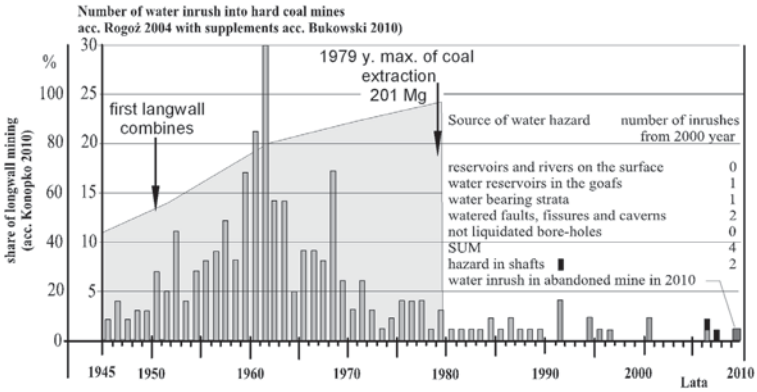

Fig. 3. Number of inrushes into active mine workings of hard coal mines in the USCB in conditions of increase of exploitation with longwall system and output increase

Simultaneously an advance of exploitation fronts and the exploitation impact on rock mass reached a maximum. The range of exploitation, its scope and impact range is signified

by the existence of about 68 coal mines in the USCB. At that time, in the area of the USCB, regional cones of depression were formed in the area of mines located on the territory of the Upper Silesian Industrial Region (Polish: Górnośląski Okręg Przemysłowy, GOP) and others in Rybnik Coal Area (Polish: Rybnicki Okręg Węglowy, ROW) [19, 20], (Fig. 2). Their scope and depth were at their greatest at this point. A considerable degree of destruction of the rock mass caused meant that the rock mass could be considered as drained of free water to a large degree.

Dewatering of the rock mass improved water conditions in running exploitations and strengthened the rock mass, simultaneously the frequency of geomechanical threat occurrence increased. In geomechanical testing, especially in the 80s, the utilization of the so called stiff testing machine began in Poland. That gave the possibility of the assessment of the mechanical properties of rocks full scope of straining, including post-damage, which in a rough approximation reflects the post-critical load capacity of the rock mass after the formation of a fracture zone. Still, however, results of geomechanical testing applied in many calculation formulas, e.g. endurance of safety pillars, are assumed for pre-critical properties of rocks in an air-dry state and with a high a factor of safety [5, 18]. The acceptance of these test results, for the air-dry state was justified with the assumption of complete drainage of the rock mass free of water in the area of mines in the USCB — especially in the period of the 1980s and 1990s.

Since the 90s the process of mining restructuring has become intensified. It is manifested among others by the abandoning of almost half of the mines in the USCB and in 2010 the setting up of extensive water reservoirs accumulating considerable for amounts of water repeatedly under high pressure (Fig. 4).

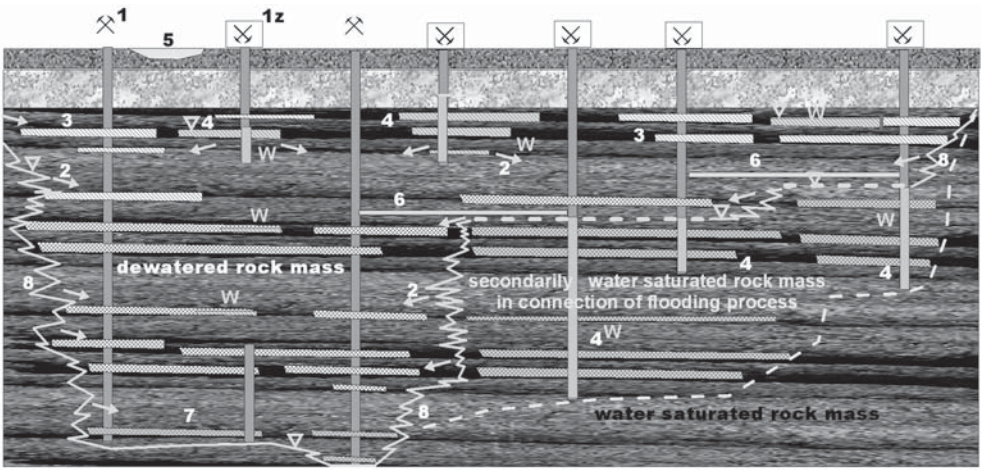

Fig. 4. Diagram of changes in spreading of cone of depression in the USCB with reference to changes in development of underground mining of hard coal — mining in the period of restructuring and abandoning of mines
1 — active mine, 1z — abandoned mine, 2 — directions of flow connected with drainage and mines flooding, 3 — goafs and not watered and not flooded mine workings, 4 — watered and flooded mine workings, 5 — postmining innundation, 6 — active levels of the mine, 7 — levels of mine under construction, 8 — schematic reach of regional cone of depression

The rock mass within reservoirs of underground waters and above water level can be characterized using the zones diagram for hydrogeological and geomechanical conditions according to [4]. The most difficult to assess, due to the occurrence of threats, are areas of rock mass located between flooded workings and active workings as well as located above free surface of water, especially in case of establishing of emergency reservoirs for submersible pumping stations and areas close to the surface of the ground. Rock mass in this region has been subjected to the process of the repeated saturation of rocks with water of various intensity [6, 7]. This process can change geomechanical properties to a considerable degree. The saturation of rocks with water most often causes a significant fall in the values of the strength parameters of rocks [2, 3]. Values of decrease factors of strength are determined empirically for some rocks of the USCB are juxtaposed in Table 3.

TABLE 3

Decrease factor of barren rocks strength in the USCB as a result of capillary saturation [2, 3]

Type of rock	Decrease factor of strength of rocks under the influence of capillary saturation*
Fine-grained sandstone	0.59–0.74
Sandstone interbedded with mudstone	0.46–0.84
mudstone	0.94–0.98
clay slate	0.5

* state of capillary saturation of rocks makes conditions of laboratory testing most similar to humidity conditions of rocks in natural environment changed by dewatering and impacts of mining exploitation [5]

Changes in geomechanical conditions have a decisive influence on the occurrence of water hazard and on rock mass movements, which can affect the surface infrastructure and conditions of dewatering [8]. Transformation of the cone of depression in the area of the USCB together with the increase of mining works depth heads in the direction of its deepening in the area of active mines. At the same time, it can affect the base level of drainage in areas of abandoned mines mainly in the NE part of Upper Silesian Basin increases.

In connection with the flooding of mines and the aiming of water rebound in them, with simultaneous lowering base level of drainage in active mines, one can talk about the constant increase of hydraulic gradient (Fig. 4) and the increase of water pressure in the rock mass as well as greater influence of the flooding process on the state of saturation of rock mass with water. Already in the 1950s it had been stated that the washing out of walls of fissures is conditioned by the compactness of rock, their compressive strength and intensity of water flow [13]. It remains connected with the value of hydraulic gradient and path of water flow. According to this Author [13], and on the basis of testing of formations of Laziska and Libiąż layers, a permissible hydraulic gradient I can be correlated with compressive strength of rocks. Strength of rocks R_c = 10 MPa corresponds to the admissible hydraulic gradient I = 5, and R_c = 35 MPa corresponds to a value of an

acceptable hydraulic gradient of about $I = 25$. It ought to be emphasized that these values have been calculated for the weak rock mass of the Cracow Sandstone Series (upper Westphalian).

As it appears from post-war history of mining in the USCB, mining works have been carried out in different hydrogeological conditions, diverse and changing state over time with the saturation of rocks with water. It has correlated with the forming of geomechanical conditions, which have been changing with the advance of destruction and drainage of rock mass. Since the start of underground mining until the present those changes differ significantly. They have lead to a verification of conditions of exploitation and natural hazards in underground mining. Moreover, these changes verify the need to carry out many research methods, classify necessitate and devise new methods which better represent current determinants of functioning of mining.

4. Summary

The construction of mine workings disturbs the primary state of stress existing in the rock mass. At that time, as a result of processes taking place in rock mass, the state of stress and strain changes, and also displacement of rocks to working occurs. The scale of this process depends on type of working, the properties of surrounding rocks and on the advancement of mining exploitation expressed with the surface area of the exploited deposit. Rock mass movements lead to formation of rock slide, falls of roof and falls of side walls as a result of convergence of underground workings, stratification and fissuring of rock mass. As a consequence it may lead to a decrease of the strength of the rock mass.

On the basis of comparing the results of testing the compressive strength of rocks and rock mass and the aspect of impacts caused by mining exploitation, it can be stated that regardless of the adopted research method, the strength of the rock decreases. The slightest difference in the compressive strength of rocks in comparison with results obtained before going through exploitation to the period after passing through was obtained by penetrometer test (4.1–17.7%). In this case a visible upward trend of this difference from weaker rocks to stronger rocks occurs. Changes in the compressive strength of rocks tested in the laboratory fluctuated from 12.7% in mudstones to 31% in sandstones. Testing of coals carried out with rebound hammer demonstrate a close to 30% decrease of its strength after passing through exploitation in the undermining seam. The biggest difference, however, was stated with laboratory testing for rocks surrounding the seam in conditions of its overmining, where in mudstone a decrease of strength reached almost 78% from the initial value. It has been found that these changes can increase as a result of the increase in rock mass watering, on average by 2% of the value of strength in mudstone, up to 50% in clay slate. However, the influence of fracture zone (e.g. in dislocation zone) can manifest itself with a 20–60% decrease in a rock mass strength in relation to a rock mass with low fracturing.

In the characteristics presented changes in the geomechanical properties, not all of the factors connected with influence of mining exploitation, e.g. mining-induced tremors were taken into account. Taking them into consideration in the assessment of quality of rock mass requires knowledge of the location of the tremor focus and its effects in the rock mass, which is not possible in every situation and can often be ambiguous.

The investigation into the changes of the geomechanical properties under the influence of various factors give views about accuracy of assessments referring to bump hazard, water hazard, falls of roof or methane hazard etc. Owing to testing carried out and the proper procedure during the estimation of the rock mass quality there is a possibility of selection of preventive means relevant to the state and expected scale of threats.

As can be seen from conducted research, throughout the history of hard coal mining in the USCB the general interdependence of the changes in geomechanical and hydrogeological conditions have occurred, which have been generated by the impact of mining exploitation. Changes in geomechanical conditions connected with the destruction, drainage and later flooding of the rock mass presented in the paper have had a significant influence on the state of mining safety and exploitation consequences.

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