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Assessment of Corrosion Phenomena of Hydromechanical Fittings and Elements of Excavation Support Under the Conditions of Active Mine Exploitation

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ABSTRACT

The paper presents the results of observations and research conducted in the Lublin Coal Basin (LCB), particularly during active coal mining. The mining technology is characterized by the extraction of usable minerals using underground methods. The safety of the mining operation, both for the people working there and the efficiency of the machinery, requires the use of excavation protection, as well as dewatering of geological layers lying above the zone of the mining operation. The quality of water and air as well as the materials used in the mine create the conditions conducive to corrosion. The duration of contact with the conditions conducive to corrosion and erosion is also important. While working under load, elements of the excavation lining and hydromechanical fittings are exposed to the formation of material defects, which can lead to the occurrence of emergency situations or even their destruction. The authors identify the phenomena conducive to corrosion and indicate the need for their further investigation.

Keywords: mine technology, water, corrosion, hydromechanical equipment.

INTRODUCTION

The Lublin Coal Basin, as an area of coal seams, is located in Eastern Poland, in the Lublin Province. It is divided into three main coal regions, namely: Northern Coal Region, Central Coal Region and Southern Coal Region. Active mining of Carboniferous strata containing hard coal takes place in the Central Region. Hard coal is mined here by a single mine: Lubelski Węgiel "Bogdanka" S.A., which consists of three mining fields, i.e. Bogdanka Field, Nadrybie Field and Stefanów Field (Fig. 1). The equipment needed to carry out the mining process works under various conditions, including dry, wet, completely submerged in water or with water distribution inside the equipment. Many pieces of equipment have been operating in the mine since its opening. The exposure to corrosive conditions of a chemical, electrochemical, mechanical or stress type creates the need for special care to maintain the continuity of operation of the components that directly affect operational safety. Damage, including that resulting from material degradation caused by corrosion, must be identified at an early stage. This allows timely replacement of corrosion-damaged components with new ones.

The paper contains a characterization of the phenomena conducive to corrosion observed at the Lubelski Węgiel "Bogdanka" S.A. mine, particularly in the Bogdanka Field and the Nadrybie Field. One of the main issues corresponds to the qualitative parameters of water occurring in the geological profile of the LCB and their stability over time, since the occurrence of corrosion largely depends on this. The second issue is the quality of materials coming into contact with moisture and mine gases.

The water quality parameters of the LCB area are described by the results of analyses conducted by an attested laboratory. Archived documentation from the initial period of the Lublin

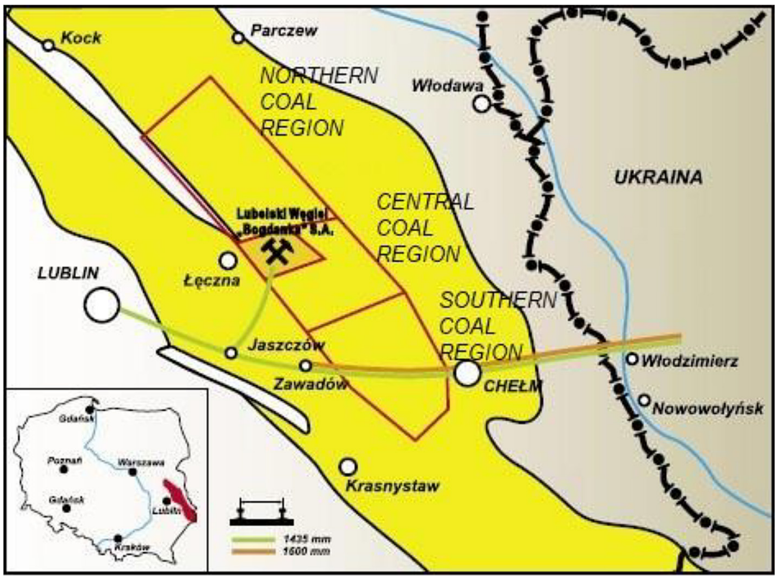

Fig. 1. Location of the Lublin Coal Basin (Source: LW "Bogdanka" S.A.)

Coal Basin contains full analyses of the waters. Subsequent ones, covering the years up to 2021, concern selected, most characteristic parameters. Due to the small resources of waters of the Carboniferous level accompanying the conducted exploitation, as well as their insignificant impact, they are omitted in the article. The main observations and considerations focus on the contact with waters of the Jurassic level, captured by the drainage system. Detailed and control analyses are also derived from own research. For the purpose of assessing the phenomena, archived records of water quality from 1983 to 2002 were analyzed.

The mining technology is described in detail, indicating the types of materials used in the construction of excavation protection. Elements of pipelines and hydromechanical fixtures in contact with the water captured by drainage, mainly of the Jurassic level, are described in terms of material science, which enables to assess the degree of sensitivity to corrosive phenomena.

The authors of this paper base their observations on the available scientific literature, as well as on site visits and in situ studies. The 2022 study is a control study to, i.a. confirm the stability of water quality parameters and assess the extent of corrosion.

The results of observations and conclusions resulting from the research will determine the types of phenomena that promote corrosion. They will also serve to deepen the research and develop protective procedures.

CHARACTERISTICS OF COAL MINING TECHNOLOGY USING THE UNDERGROUND METHOD

Hard coal, as one of Poland's natural resources, is used in the production of heat, electricity, cement, medicinal substances and other applications. Lubelski Węgiel "Bogdanka" Joint Stock Company is a mine that obtains coal in the Lublin region. The yellow box delimited by lines in Figure 1 represents the Lublin Coal Basin. The Bogdanka mine is located in the Central Coal District. The mining concession covers the seams marked in the diagrams with the numbers 382, 385, 389 and 391. The actual mining takes place at a depth between 920 and 1030 m bgl and is carried out in 3 mining fields, i.e. the Bogdanka, Nadrybie and Stefanów fields. In order to allow workers to stay underground, air is supplied to the work site via an intake shaft and discharged outside via an exhaust shaft. Both pairs of shafts are present for each of the mining fields. The intake air has a quality similar to that of the outside air, while the exhaust air additionally contains gases from the porosity and fissures opened during the extraction of the mineral. The Bogdanka mining field and the Stefanów field additionally have mine shafts equipped with hoisting (skip) equipment, by means of which the excavated material is transported to the surface, where it is then directed to the Mechanical Coal Processing Plant. Exploitation of coal seams is carried out using the retreating longwall system, with roof collapse and liquidation of roadways parallel to the progress of the longwall. After the passage of a coal-cutting device (longwall shearer or plough), the resulting voids behind the mechanized section support are not secured, resulting in the collapse of the rock required by the mining technology. Excavation support are discussed below. Mechanical equipment extracting excavated material, due to the risk of coal dust explosion, is equipped with sprinkler systems. The method of mining longwalls with a large runout (1500–7100 m), with an average longwall length of 305 m yielded a mass volume of extracted hard coal amounting to 9.9 million tons in 2021, which shows the intensity of mining and high efficiency of equipment.

HYDROGEOLOGICAL CONDITIONS OF THE AREA LUBLIN COAL BASIN

There are four main water-bearing complexes within the "Puchaczów V" mining area (Fig. 2):

1) Quaternary-Upper Cretaceous complex – associated with sandy Quaternary formations and carbonate formations of the Upper Cretaceous cracked as a result of erosion. The average thickness of the layers of this complex within the mining field is 150 m, the filtration coefficient is in the range of $1.1 \cdot 10^{-5} \div 1.1 \cdot 10^{-6}$ m/s. The zone of the so-called "impermeable chalk" is associated with carbonate formations of the Upper Chalk (limestone, marl, writing chalk). Its thickness is 400 to 450 m, and the filtration coefficient from $1.19 \cdot 10^{-9} \div 4.63 \cdot 10^{-9}$ m/s. The 1st aquifer complex consists of waters with a total mineralization of 0.36–0.51 d/dm^3 and bicarbonate-chloride-sodium water.
2) Albian-Upper Jurassic Complex – associated with sandy formations of the Albian, with a thickness of 1.5-8.0m and cracked carbonate formations of the Jurassic floor with a thickness of up to 10.0 m. The filtration coefficient is in the range of $5.0 \cdot 10^{-9} \div 4.96 \cdot 10^{-8}$ m/s. These waters occur at a pressure of 5.0 MPa. In the mining area, this complex is underlain by impermeable formations with a thickness of 50.0–70.0 m. The total mineralization of the waters of the 2nd complex is 0.5–1.8 g/dm^3, and the water type is defined as bicarbonate-chloride-sodium.
3) Middle-Lower Jurassic complex – associated with the sandy-dolomitic facies, occurring in the Jurassic floor, at the contact with the deposit series. This continuous aquifer complex has a thickness of 20–40 m. The filtration coefficient ranges from $12.0–8.0 \cdot 10^{-6}$ to $4.1–5.5 \cdot 10^{-7}$ m/s. The waters of this complex occur at a pressure of 0.2–5.8 MPa. Total mineralization is 1.0 ÷ 1.85 g/dm^3, and the type is chloride-hydrocarbonate-sodium. The waters found in the Jurassic strata have another characteristic, i.e. they contain fluoride ions that are higher than those most commonly found in Polish groundwater. The concentration of fluoride ranges from 5.0 to 10.6 mg/dm^3. This concentration value gives the waters a specific fluoride character. According to the ion product, elevated concentrations of fluoride ions, in parallel, correspond to low concentrations of calcium ions.
4) Carboniferous complex – this is a complex of Lublin strata with heterogeneous, discontinuous and highly variable character. There is a predominance of clay structures over sandstone. Ceiling layers have a thickness of 60 m on average, are highly eroded, so they have direct hydraulic contact with Jurassic formations. Their filtration coefficient is in the range of $1.3 \cdot 10^{-6}–4.2 \cdot 10^{-6}$ m/s. The middle part reaching the 397 deposit is characterized by weak waterlogging, with a filtration coefficient of $1.5 \cdot 10^{-8}$ m/s. The bottom part of the Lublin strata extends from deposit 397 to the ceiling of the Kumov strata containing discontinuous sandstones. According to the trend, the waters occurring deeper have higher mineralization, which in the case of the waters accompanying the mining layers is 6.4–8.4 g/dm^3. The waters of this level are of the chloride – bicarbonate – sodium type (Fig. 2).

MATERIAL CHARACTERISTICS OF HYDROMECHANICAL FITTINGS AND ELEMENTS OF LINING EXCAVATIONS

In order to ensure the safety of mining, there is a need to drain reservoir waters outside the mine area, the largest volume share of which is from Jurassic formations. Since the beginning of the mine, these waters have been captured by a special drainage. The drainage pipelines, depending on their technical condition, are replaced with those made of new materials, but the main pipes built into the shafts have been there since the start

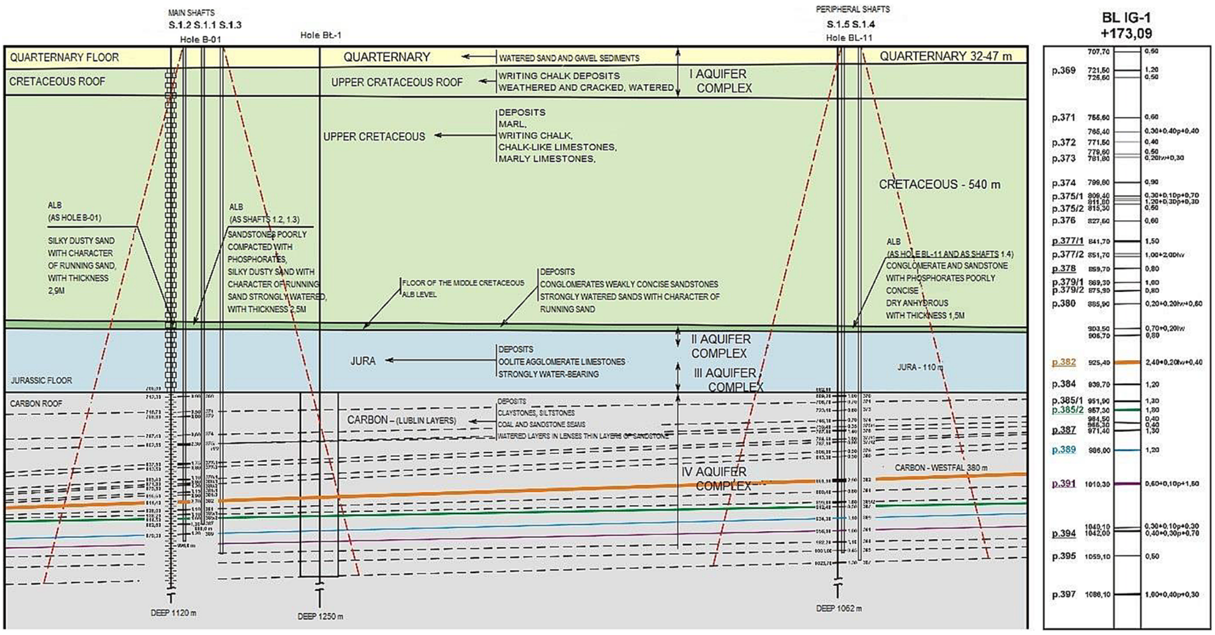

Fig. 2. Geological profile of the mining area (Source: LW "Bogdanka" S.A.)

of the drainage operation, which is about 40 years. Ensuring the continuity of drainage operation requires periodic inspections, including of the wall thickness, which is exposed to external and internal corrosion. Steel flanged pipes with loose or fixed flange adapted to a pressure of 4.0 MPa, are manufactured in accordance with PN-EN1092-1. Pipelines of the main drainage, installed vertically, with length of several hundred meters, must withstand pressures higher than 10 MPa. The materials used for drainage components (pipes and control fittings) are S235JRH, S355J2H, P265GH, P235TR1, P235TR2, P355TR1, P355TR2, L235, L275,L355, E235+N, St370, St44.0,St52.0. Both pipes and fittings (dewatering pumps) have anticorrosion protection by galvanization of factory-made components, as well as special paint, and in the case of pipelines with flanged connections, PE polyethylene inserts. As a general rule, water-guiding pipelines and control fittings are manufactured in a double-sided galvanized version.

Underground mining of minerals requires the use of appropriate elements to protect the cross-section of the excavation. The shape of these elements and the type of material is important, i.a. from the mechanical point of view. At present, the support of the corridor excavations in the Lublin mine is a curved yielding steel support made of V36 section (Fig. 3). In the case of capital excavations, the support elements are made of S550W steel, and in the near-pit excavations they are made of S480W steel. In addition to metal elements, the technology of spraying the inner contour of the excavation bounded by the steel support with concrete is also used. Most often, the shell support of this type (so-called shotcrete) contains reinforcing plastic threads. Treatments of this type are used to reduce the vulnerability of V36 steel support elements and simultaneously increase the load bearing capacity. This type of protection makes it impossible to monitor the condition of metal elements on an ongoing basis, both in terms of mechanical deformation and the extent of corrosion, in case of water outflows from the rock mass. The moisture in the space above the shotcrete layer is evidenced by stalactite threads hanging from the ceiling of the workings, and their appearance indicates locally occurring porosity or cracking of the sprayed concrete and infiltration of water from the rock mass into the concrete layers (Fig. 4). Forging of the sprayed layer in close proximity to the metal elements of the excavation support is inspected. The areas altered by active corrosion are noted.

HUMIDITY CONDITIONS AND THEIR INFLUENCE ON EXPOSED SURFACES OF MATERIALS

In the excavations of the LW "Bogdanka" mine there are spaces that are permanently dry, periodically dry and permanently wet. The elements located in a dry environment are covered

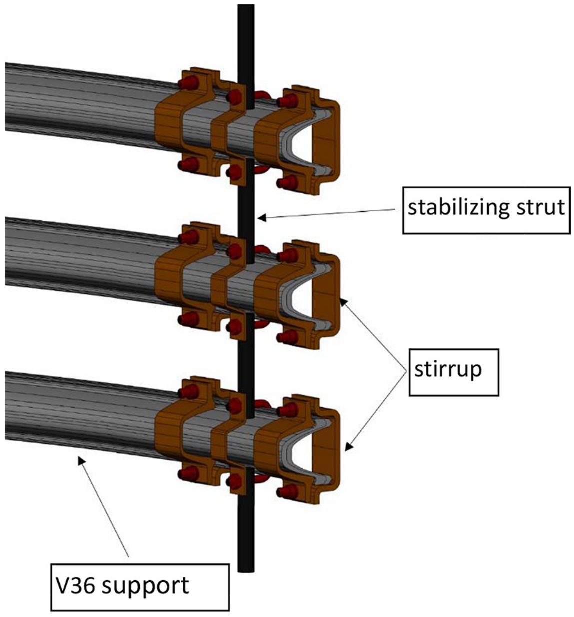

Fig. 3. Elements of the V36 type excavation support

only by a thin layer of rust evenly distributed over the entire surface. This is due to both atmospheric moisture from the mine air and a low concentration of corrosive gases from the intersection of the continuity of geological layers containing natural gas. One of the main components of natural gas is carbon dioxide. As it dissolves in water, it forms carbonic acid that lowers the pH, which promotes corrosion. This phenomenon can be described by the equation $H_2O + CO_2 \rightarrow H_2CO_3$. Moreover, hydrogen sulfide is also present, although in small concentrations; its high chemical activity causes corrosion. There is a similar condition of the surface of the materials of fittings, ducts and excavation supports when they are constantly wetted with water, without contact with air. Only the mine gases dissolved in water as natural components, including the afore-mentioned CO_2 and H_2S, give rise to the occurrence of surface corrosion. The condition of materials also depends largely on the duration of exposure to corrosive conditions. Both hydromechanical fittings and elements of the excavation support, some with unobserved corrosion have been in the mine since its inception. This is the case in dry places, while in periodically wet and completely waterlogged environments, many elements have already been replaced several times with new ones, after being found destroyed by active corrosion phenomena. Corrosion crusts are formed, which fall off after some time, exposing the raw material. The presence of oxygen in the air is important in this case. Especially at the water-air interface, corrosion is then more intense.

Fig. 4. DN400 main drainage pipelines and mine excavations with visible sprayed concrete

An additional stimulus for the replacement of elements is the phenomenon of convergence, involving the tightening of the support associated with changes in the state of deformation in the rock mass (Fig. 5). It should be added that the rock mass surrounding the excavations of the Lublin mine is characterized by poor strength parameters and has plastic mechanical properties. The effects of electrochemical corrosion may be intensified by stresses generated in the support.

BIOLOGICAL CONDITIONS AND THEIR IMPACT ON MATERIALS IN THE LINING EXCAVATIONS OF LCB

The existence of biological factors is important when extracting water from the rock mass, transporting it for various uses and periodically

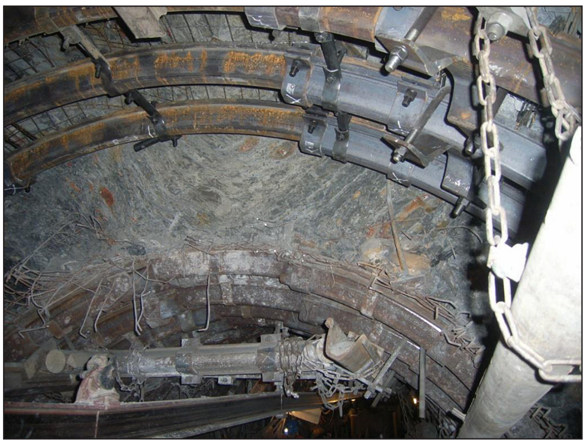

Fig. 5. Replacement of support due to tightening (convergence) as a result of the impact of the rock mass surrounding the excavation (Source: Wiadomości Górnicze Nr 3/2016)

staying in the open. Samples of green-colored sediment taken from the walkway, when examined under a microscope, confirmed the existence of live bacterial cultures and photosynthesizing organisms. They form microspheres with low pH or high concentrations of aggressive ions, the result of metabolic transformations. As a result of these factors, even the protective anti-corrosion layer can be destroyed. The greatest contributors to these processes are sulfate-reducing bacteria and ferrous bacteria. The bacteria that produce methane and nitrate-reducing bacteria are of lesser importance (Olańczuk-Neyman 1993). In the mine space, they can come from the outside air or may be brought along with mining components and equipment from the surface. The green color of the sediment indicates the presence of active chlorophyll, which is associated with the constant illumination of the excavations with white light. There is a clear boundary between the unlit surface and the lit surface, where the green sediment is present.

On elements of drainage pipelines from the drainage of Jurassic strata (Shaft 1.5, depth 640 m), mosses develop in places with a high accumulation of corrosion products. (Fig. 6) Their presence may indicate a decreasing pH value, which intensifies the corrosion phenomenon when in contact with bare material. The water conducted in the drainage pipeline has a pH = 8.1–8.3. The existence of moss on the outer surfaces indicates a pH <7.0. In addition, the constant presence of white light allows these plants to thrive and reproduce.

QUALITY OF MINE AIR AND DRAINAGE WATERS

The air in the workings of the mine LW "Bogdanka" is a mixture of external air subject to seasonal changes and gases from porosity and fissures opened in the rock mass during active coal mining. The corrosive factor may be the content of atmospheric oxygen, which easily dissolves in water when in contact with it, similarly to carbon dioxide as a component of natural gas, as well as H_2S. Under the conditions of increased temperature, coming from the surrounding rock mass, this can cause active corrosion of hydromechanical fittings and elements of the excavation support. The corrosion caused by such factors progresses very slowly if the surfaces are dry. Therefore, is the atmospheric moisture introduced with the outside air which, in view of the temperature of the surrounding rock mass, does not condense on the external air-washed surfaces, is of negligible importance.

The environment which is most aggressive to corrosion-sensitive materials corresponds to water and its parameters. These range from pH, chlorides, sulfates, and in many cases dissolved gases, to aquatic organisms whose metabolic products can intensify corrosion. In Table 1, the authors show two representative analyses of the quality of water from drainage draining Jurassic strata, to illustrate the conditions that can promote corrosion.

Fig. 6. Flora developing on corrosion products under 24h white light illumination. Level 640, drainage of Jurassic formations. (Photo: M. Ciosmak)

Table 1. Selected water quality parameters from Jurassic formations

Results sheets of analyses No. 610.59/2021		No. 610.39/2021
Item 990. South walkway I,		Item 990. Field walkway 2/VII
Inflow from new Jurassic boreholes		Inflow from decommissioned Jurassic boreholes
B-3/20, B-4/20, B-5/20, B-7/20		
Taken on 7th June 2021		Taken on 6th June 2021
pH	8.5 ± 0.2	7.4 ± 0.2
Specific conductivity, μS/cm	2300 ±100	3620 ± 180
Color, mg Pt/dm^3	10 ± 2	< 2.0
Odor, TON	2	< 1.0
Ammonium nitrogen, mg/dm^3 N	0.93 ± 0.09	0.085 ± 0.009
Nitrate nitrogen	0.059 ± 0.06	0.18 ± 0.02
Nitrite nitrogen	< 2000	< 0.002
Permanganate index	2.0 ± 0.4	1.6 ± 0.3
“p” alkalinity, mmol/dm^3	0.25 ± 0.04	< 0.1
”m” alkalinity	8.28 ± 0.83	9.86 ± 0.99
Free CO_2, mg/dm^3	2.2	42.0 ± 8.0
Dry residue, mg/dm^3	1270 ± 130	2350 ± 240
Total suspended solids, mg/dm^3	3.2 ± 0.5	21 ± 2
Temperature, °C	22.3	21.5
Total hardness, mg $CaCO_3$/dm^3	65.4	133.0
Carbonate hardness	65.4	133.0
Non-carbonate hardness	0.0	0.0
Anions, mg/dm^3:		
Chloride, Cl^-	482 ± 48	851 ± 85
Sulfate, SO_4^{2-}	25 ± 3	325 ± 32
Carbonate, CO_3^{2-}	15 ± 1.5	< 0.3
Bicarbonate, HCO_3^-	475 ± 48	602 ± 60
Nitrate, NO_3^-	0.26 ± 0.03	0.78 ± 0.08
Nitrite, NO_2^-	< 0.006	< 0.006
Fluoride, F^-	7.6 ± 0.08	3.2 ± 0.3
Phosphate, PO_4^{3-}	0.026 ± 0.003	< 0.010
Cations, mg/dm^3:		
Calcium, Ca^{2+}	15.9 ± 1.6	26.3 ± 2.6
Magnesium, Mg^{2+}	6.28 ± 0.63	16.5 ± 1.7
Sodium, Na^+	489 ± 49	855.0 ± 86
Potassium, K^+	12.2 ± 1.2	22.1 ± 2.2
Barium, Ba^{2+}	0.61 ± 0.06	0.083 ± 0.021
Ferrous, Fe^{3+}	0.60 ± 0.06	0.017 ± 0.004
Ammonium, NH_4^+	1.2 ± 0.1	0.11 ± 0.01

The most common characteristics of groundwater aggressiveness in Poland include leaching aggression at $CaCO_3$ concentration of less than 90 mg/dm^3. In addition, there is also carbonate aggressiveness, when the concentration of CO_2 is more than 4 mg/dm^3. Magnesium aggressiveness occurs when the concentration of magnesium ions reaches 1000 mg Mg/dm^3. Sulfate aggressiveness can occur at concentrations of more than 250 mg SO_4/dm^3. Ammonium aggressiveness results from coming into contact with water containing over 15 mg N-NH_4/dm^3. Chloride aggressiveness occurs at concentrations exceeding 100 mgCl/dm^3 (Table 2) (Macioszczyk, Dobrzynski, 2002).

KINDS OF CORROSION IDENTIFIED IN LCB MINE

In most underground spaces of mine excavations there are conditions conducive to corrosion and erosion. Electrochemical corrosion is noted, especially in the areas with low pH (occurring locally, associated with the presence of CO_2

Table 2. Comparison of selected physicochemical parameters with determinants of aggressiveness

No.	Determinants of aggressiveness	No. 610.59/2021	No. 610.39/2021	Corrosion
1	pH>7	8.5	7.4	Absent
2	Below 90 mg $CaCO_3/dm^3$	15.9	26.3	Present
3	Over 4 mg CO_2/dm^3	2.2	42	Present
4	1000 mg Mg/dm^3	6.28	16.5	Absent
5	Over 250 mg SO_4/dm^3	25	325	Present
6	15 mg $N\text{-}NH_4/dm^3$	1.2	0.11	Absent
7	Over 100 mg Cl/dm^3	482	851	Present
8	O_2	–	–	Present
9	Temperature	–	–	Present
10	Stresses	–	–	Present
11	Organisms + white light	–	–	Present

dissolved in water). There is corrosion associated with low concentrations of calcium carbonates (carbonate corrosion) at points of contact with drainage waters of Jurassic strata. At points of contact with waters with high concentrations of sulfate ions, as well as some low concentrations of hydrogen sulfide, corrosion is superficial. The same is true for high concentrations of chloride ions. At the water-air interface, in the presence of atmospheric oxygen introduced with the outside air, corrosion develops initially on the surface, followed by pitting or intergranular corrosion. This condition, in view of the stresses resulting from the total weight of the vertical pipelines in the shafts, occurring in parallel with the stresses transmitted by the elements stabilizing the structures (Fig. 7), is the cause of stress corrosion. Biological corrosion, arising as a result of the metabolic products of plant organisms (mosses and algae) deposited on the crusts of corrosion products, is rarely found in the mine. Corrosion of this type is intensified by constant illumination of the site with white light. It occurs mainly in the areas of high humidity or on leaks from fittings and drainage pipe connections of Jurassic strata. In addition to corrosion, erosion is also observed, mechanically removing the resulting corrosion products. This exposes the base material to the aggressive conditions of the surrounding environment. The corrosion resulting from unstable moisture conditions is also of interest. Alternating wet and dry conditions are the cause of first localized corrosion, and then the detachment of its products, thus creating the conditions for the corrosion of a given site to continue.

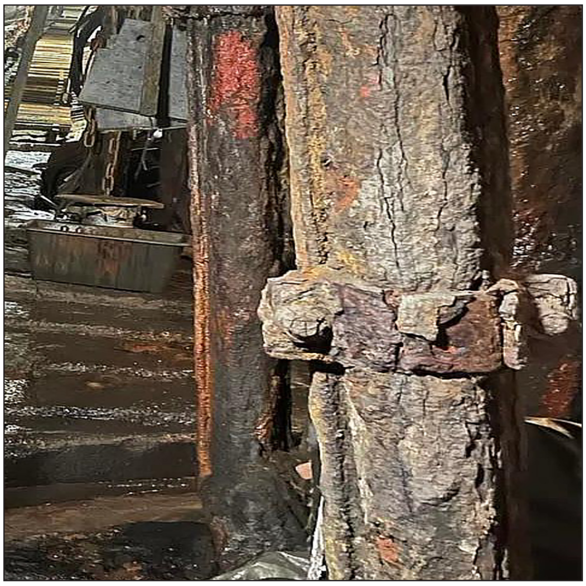

Fig. 7. Corrosion cracking in a moist environment, accelerated by stresses in the material. The vicinity of the shaft's riser 1.3 (Photo: M. Ciosmak)

CONCLUSIONS

In underground mine excavations of the Lubelski Węgiel "Bogdanka" S. A. mine, there are conditions conducive to various types of corrosion. These favorable phenomena have different intensities, depending on the type of material subject to change, humidity conditions, function of equipment, quality of mine air, temperature, presence of biological agents, lighting and time of exposure to corrosive phenomena.

In the spaces corresponding to the level of the Jurassic strata, hydromechanical fittings that are part of the drainage system of the strata above the level of active coal mining carried out, deserve particular attention. The water present both inside the pipes and fittings and on their external surfaces creates the conditions for intense corrosion. The water taken directly from the rock mass has a weakly alkaline pH, but after contact with carbon dioxide from the air, it creates the conditions for intensification of corrosion caused by a drop in pH below 7.0.

The moisture resulting from water outflows from the rock mass into the excavations, coming into contact with elements of the support, may – after prolonged exposure – cause deterioration of strength characteristics as a result of, i.a. stress corrosion. In the shaft space, pipes transporting water to the surface are exposed to compressive stresses due to the weight of the pipes and water pressure.

The methods of strengthening the support of corridor excavations by spraying concrete (shotcrete), which are favorable due to strength parameters, require developing an effective method of revising the space under the concrete layer due to the possibility of hidden corrosion phenomena.

In areas of high humidity, such as water walkways, flora develops on corrosion products in the presence of white light, including bacteria, algae and moss. These are isolated cases, but the metabolic products of these organisms strongly contribute to the destruction of materials, including corrosion protection.

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