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MONITORING OF THE ROCK MASS MOISTURE IN THE CRYSTAL CAVES NATURE RESERVE

The paper presents the results of works related to the analysis of microclimate hazards in the Crystal Caves of the Wieliczka Salt Mine. The paper focused on the development of a device for monitoring, testing and preliminary measurements of the gravimetric water content of rock in the Crystal Caves. The multisensory measurement system equipped with capacitive soil moisture sensors has been developed, calibrated and optimised. The system was used for monitoring moisture content in the sidewall and thill of the Crystal Caves.

Keywords: rock mass moisture; halite; underground nature reserve; measurement system

1. Introduction

In the Wieliczka salt mine there is an inanimate nature reserve – the Crystal Caves. Its uniqueness can be ascribed to the clusters of halite crystals, the size of which could reach even several dozen centimetres. These Caves are located in the Miocene geological layers, which makes them the only such reserve in the world [1] The discovery of the Crystal Caves took place gradually from the end of the 18th century (intensive mining works in the north-eastern area of the mine) until the 1930s (intensive exploration of the system of fissures and caverns in the area). During the first period following the discovery, the area of the Crystal Caves was used as a site for sourcing halite crystals, the size and purity of which had not been recorded before. The latter were used both for promotional and decorative purposes, as well as in the souvenir industry. The

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reserve consists of: the Vestibule, the Lower Crystal Cave, the Middle Chamber and the Upper Crystal Cave which is located higher (Fig. 1).

Not until the discovery of the Lower Crystal Cave in 1898 did the first conservation activities take place. It was then that the decision that the area was not going to be used for sourcing crystals was made. The first attempts to legally sanction the conservation activities in the area were made in 1928. However, until 2000 the Caves had not acquired a clear legal status and the area itself had been supervised by the Provincial Nature Conservator. In the first half of the 1990s extensive scientific research was carried out in the area of the Caves. Based on the latter detailed documentation was devised, which enabled the Caves to achieve the status of a nature reserve in 2000.

Nowadays, the aim of the research carried out in the Caves is to protect them by analysing the temperature and humidity of the ventilation air that flows through the area [2]. This requires proper supervision and management of the underground nature reserve [3-5].

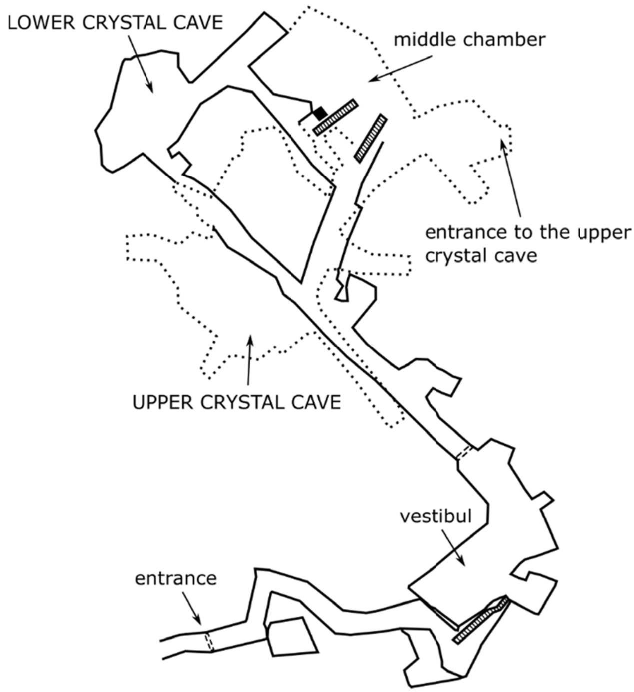

Fig. 1. Plan of Crystal Caves zone [6]

2. Microclimate hazards

So far the main purpose of the research carried out in the nature reserve has been to monitor environmental conditions, precisely the temperature and humidity of the atmosphere in the Caves. The data from such monitoring activity constitutes a clear indication for the mining services to take measures which will protect the site in situations when unfavourable conditions, may have a direct impact on the degradation of the halite cover. The latter is a result of karstic corrosion caused by water condensation on the surface of the crystals. This leads to rounding of their edges and the formation of pitting. Unfavourable thermal and humidity conditions may also lead to the detachment of the cover from the silt-rock substrate. Halite degradation occurs as a result of the air humidity inside the Caves. Due to the strong hygroscopicity of halite, when the concentration of water vapour exceeds a certain value, it gets absorbed by salt deposit. The moisture from the ventilation air is also absorbed by salt-laden gangue as well as argillaceous and arenaceous substrate creating a natural condenser of moisture which is then released into the air.

As part of the recent research, the boundary conditions under which the air in the Caves should be maintained have been defined. Aa a result of the conducted analysis [7], it was shown that in order to prevent the absorption of water vapour by salt surfaces the relative air humidity (when air temperature is equal to rock temperature) needs to be limited to the maximum equilibrium value of 75% RH. On the basis of the latter it is possible to accurately determine the boundary specific humidity, taking into account the current values of rock surface temperature, atmospheric pressure, height above sea level or barometric degree, and to compare it with the current specific humidity for the currently registered value of relative humidity. For this purpose formulas (1) to (4) apply [8]:

$$x = 622\, e/(b - e) \tag{1}$$

$$e = f\, E/100 \tag{2}$$

$$E = 6.108 \exp[(17.27T/(T + 237.3)] \tag{3}$$

$$b = 1013.25 - (h/s) \tag{4}$$

where:

- x — specific air humidity (g H_20 / kg dry air),
- e — pressure of unsaturated water vapour at a given temperature (hPa),
- b — average atmospheric pressure at h height above sea level (hPa),
- f — relative air humidity (%),
- E — pressure of saturated water vapour at a given temperature (hPa),
- T — air temperature (°C),
- h — height above sea level (m),
- s — barometric degree (m/hPa), which for the height of 0-500 m a.s.l. is on average 7.9 (m/hPa).

The current assessment of thermal as well as humidity conditions allows for taking measures, the purpose of which is to limit the humidity of the air in the Crystal Caves. Nowadays, there are two methods of reducing the level of air humidity in the workings of the reserve, i.e.:

- continuous ventilation of the reserve workings using air current (with a low flow rate), generated by the main fan,
- use of moisture absorbent in the workings of the reserve.

The regulation of the ventilation air volume flow is limited in terms of range and possibilities. Due to the fact that it is not possible to control the parameters of that air, methods of isolating the chosen zones of the Caves depending on the ventilation air parameters as well as activity done in the reserve are applied.

The use of moisture absorbent in the form of magnesium chloride ($MgCl_2$) has turned out to be the most effective method of drying the air. It is regularly poured in specially prepared troughs (Fig. 2), and the accumulated water is channelled by gravitation to specially prepared containers, which are then removed from the Caves.

By analysing the microclimate found in the Caves, 3 main sources of humidity which pose a threat to the state of halite cover, can be distinguished:

- ventilation air,
- damp rock environment,
- anthropogenic factor.

Fig. 2. Upper Cave – trough for the absorbent

2.1. Ventilation air

As part of the research carried out so far by various teams of scientists [6,9], recommendations were made on how to ventilate the area of the Caves, taking into consideration factors such as: distance from the inspiratory shaft, the amount and velocity of the air flow, rock temperature, as well as weather conditions of a given season (precipitation of moisture from the atmospheric air in the period between May and October as well as drying of the workings between November and April) [8]. Additional variable factors are works carried out on the ventilation route in the workings, with an increased number of people engaged and additional sources of moisture. The ultimate goal was to extend the ventilation routes as well as reduce the amount and velocity of the air flow so as to minimize the impact of external weather conditions.

Due to the spatial layout of individual chambers in the Crystal Caves, the mass exchange within them takes place in the inlet route, through the workings connecting with the Vestibule, Lower Chamber up to the shaft. The Upper Cave is diffusion-ventilated.

It is impossible to take a direct measurement of the velocity of the ventilation air flowing through the Crystal Caves using standard methods, as the value of the velocity in the workings of the area in question is too low. The estimated velocity of the air that flows on the way entrance-shaft has not exceeded 0.1 m/s. To estimate the volumetric air flow in the Caves, the velocity was measured with the use of a µAS4 vane anemometer in a ventilation window with dimensions of 0.2×0.126 m, placed in the entrance door. On the basis of the measurement, the value of the volumetric air flow does not exceed 12 m^3/min.

2.2. Anthropogenic factor

During the monitoring and protection works in the Crystal Caves it is vital that there are people present in the reserve area. Each time a person enters the area of the Caves, it results in a sharp increase in heat and humidity levels. Its sources are: heat given off by convection as well as moisture released through the process of sweating and breathing [10]. The amount of heat and moisture emitted by individual people is inextricably related to the kind of work done in the caves, as well as to individual physiological characteristics of a particular person. Based on the data available as part of the research, recommendations regarding the number of people and the amount of time they can spend in the Crystal Caves have been made.

2.3. Damp rock environment

The Wieliczka rock deposit is made up of clay-marl sediments and fragments of flysch rocks. Such a structure of rock fosters the accumulation of moisture. As a result of the latter, the largest amount of subsurface layer moisture can be found on salt argillaceous rocks in the Vestibule and Middle Chamber.

Damp rock environment is a factor that has been researched and described the least so far. It is known that accumulated moisture in argillaceous rocks exerts an influence on air humidity in the Caves. One of listed sources of that moisture is the absorption of water vapour by silt. There also exist hypotheses regarding the capillary rise of the water accumulated in the deeper layers of gangue or the water which comes from previously unidentified leaks.

In order to understand the phenomena concerning damp rock environment, it was necessary to create a measurement system which would enable continuous monitoring of the amount of water in the rock layer.

3. Measurement system

The problem of rock moisture detection is closely related to the methods of measuring soil moisture. Research on these methods suggests that they can be used in case of moisture detection in the Cristal Caves. These methods include [11,12]:

- Gravimetric method consisting in taking and weighing soil samples soaked in water and after evaporation. In this way, the water content of the soil is directly determined
- Tensiometers, measuring the water potential of the soil, and more precisely the soil moisture tension. For this purpose, a tube filled with water is used, terminated with a ceramic element through which the water is filtered. The whole is connected with a pressure gauge. When it is dry the soil draws water out of the tensiometer creating a negative pressure which is measured by the vacuum gauge. This negative pressure corresponds to the suction force of the soil. Resistance measurement method, also known as a gypsum block method, which uses two electrodes in a block of porous material (usually gypsum).

Such a probe is placed in the soil, and its resistance value depends on the water content in the porous block which changes with the water content in the soil.

- The method of measuring the electric permeability (capacitive) using the change of the dielectric constant of the medium in which the probe is placed, depending on the water content. The method is characterized by good accuracy. It works well in measurement systems. This method requires calibration depending on the type of medium.
- One of the more accurate devices available for measuring the amount of moisture in the soil is the neutron moisture meter. It uses the phenomenon of slowing down neutrons by the collision with the atoms of low atomic weight, mainly hydrogen. Depending on the soil moisture content, the neutron slowing down process varies and the number of neutrons counted varies. This method requires the use of measuring probes that are also a source of radiation, which is associated with the use of radioactive elements, e.g. caesium, Cs-137.
- Cosmic-Ray Neutron Sensing method is based on the discovery of the dependence of the intensity of low-energy cosmic neutrons on the hydrogen content in the environment. The use of this phenomenon made it possible to create a moisture monitoring network mapping significant areas.

3.1. Measurement system

The measurement system developed was dedicated to studying the moisture content in the Crystal Caves reserve. The Caves is an area with a limited access, where additional sources of energy are scarce (such as: mains supply or the possibility of using renewable energy sources). Therefore, the main assumptions made when devising the system for studying the moisture content in the Crystal Caves were: the possibility of using numerous sensors simultaneously as well as maximum limitation of the need to use electricity. In order to do so, a dedicated programmable electronics system, equipped with the most energy-efficient ARM series SAMD21 Cortex M0+ 32bit microcontroller, was implemented. The system is capable of handling 5 moisture sensors. It ensures continuous operation for the period of 220 days.

3.2. Sensor

The moisture sensor used for measurement is a capacitive sensor. The way it works is it detects changes in the electromagnetic field between two electrodes placed in the sensor. Then it works like a condenser, in which a pair of conductors (plates) are separated by a dielectric. The output voltage in this type of sensors depends on the change in capacity, which in turn is dependent on the surface area of the condenser plates, the distance between them, as well as the kind of medium placed between the conductors [13]:

$$C = \varepsilon_r \varepsilon_0 \frac{S}{d} \tag{5}$$

where:

C — condenser capacity,
S — surface area of condenser plates,
d — distance between condenser plates,

ε_r — relative permeability of the medium between conductors,
ε_0 — electric permittivity of the vacuum $8.854187 \cdot 10^{-12}$.

Capacitive soil moisture sensors may be used for measurement in various types of substrate. The producer of the SoilWatch 10 sensor, used in the measurement, suggests determining the static characteristics at two measurement points: for dry air and for the sensor completely immersed in water. Due to the sensor's fixed structure (both the surface area as well as the distance between condenser plates do not change), it is only the dielectric constant ε_r change (equation 5) that affects the change in capacity value. When it comes to rock mass, the latter depends on: the chemical composition of the mass, the crystallographic structure of minerals and components that make up the rock, the chemical composition and concentration of solutions saturating the rock, the frequency of the polarization field, as well as the temperature of the dielectric [14-16].

4. Measurement system research

The presented measurement system is to be used to measure the moisture content in the thill of the Crystal Caves. It is a specific medium, characterized by constant thermal conditions, a diverse composition of rocks and sediments, and various petrographic compositions, together with various forms of halite crystals embedded in them. The saturating solution is brine with a significant concentration of salt. Therefore, it was necessary to calibrate the sensor in the material coming from this place.

As a set of arguments for the determined characteristic, the gravimetric water content W was adopted, defined as a ratio of the mass of the NaCl solution M_w contained in the rock medium to the mass of the solid phase of the medium M_s expressed as a percentage:

$$W = \frac{M_w}{M_s} * 100\% \tag{6}$$

4.1. Characteristics of the medium

The Crystal Caves are situated in a lump deposit. The latter is made up of gangue, inside which lumps of rock salt are embedded. Gangue can be characterised by a variable composition. There are argillaceous and arenaceous rocks, which contain dispersed fragments of salt crystals. The following can be listed here [6]:

- silt-argillaceous sediment,
- rocks with various arenaceous and argillaceous components, containing salt crumbs and small clusters of silt,
- rocks consisting of coarse grains of salt joint by arenaceous-argillaceous medium,
- arenaceous-argillaceous.

All these types of rock may be found in the thill of the Crystal Caves. As a result of the protection works conducted in the Caves, it was possible to obtain a small amount of spoil from the thill of the Vestibule leading to the Caves. It is possible to find there both fragments of gangue as well as salt crystals of various sizes of fractions (Fig. 3). The largest pieces of gangue may reach the size of 12 cm, whereas the smallest ones are like several millimetres of dust. Secondary salt crystals can be observed in them. These are hard, grey rocks, however, they can crumble under pressure. When wet, they become less compact and turn dark grey. By contrast, the size of the salt crystals in the collected material ranges from 4-5 cm to a few millimetre particles. The latter indicates the possibility of strong anisotropy of the medium in terms of sorption properties, as well as it may cause different dielectric permittivity of the medium depending on the direction.

Fig. 3. Characteristics of the thill in the Crystal Caves – rocks

4.2. Research

The aim of the research carried out was to determine the static characteristic of the soil moisture sensor using the spoil from the Crystal Caves. Such an experiment was supposed to result in obtaining a function, on the basis of which it would be possible to describe it and make use of in the future.

Before starting the research, the material was dried in an oven at 110°C (Fig. 4a). Then, using the medium prepared in such a way, samples containing various amounts of 20% NaCl solution were prepared. In order to minimise the influence of material porosity on the obtained results, each prepared sample underwent mechanical densification (Fig. 4b). During the research, along with the gradual saturation of gangue with NaCl solution, the smallest fraction of the medium was dissolved, resulting in a homogeneous compact mixture.

In each sample 11 measurements were taken, by placing a sensor in various areas of the analysed sample (Fig. 4c). The average value and standard deviation were determined for each series of measurements. The results are shown in Fig. 5.

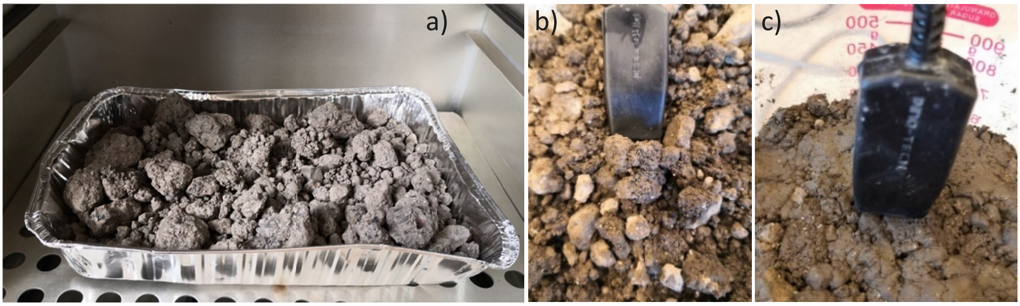

Fig. 4. The measurement system research on the target site; a) dry rock material, b) and c) taking moisture samples of rocks with different moisture content

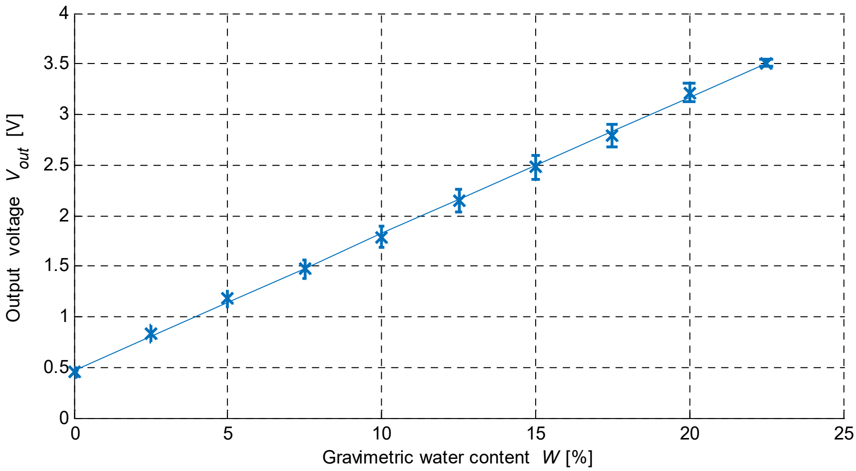

Fig. 5. Results of the measurement system research on the target site (20% NaCl solution)

The static characteristic of the moisture sensor obtained for thill material differs from the characteristics obtained in unsalted media [17]. The main changes were observed in its shape and offset. In that case, it can be approximated by a linear function with coefficients $a = 0.13$ and $b = 0.47$. For such a match, R^2 coefficient of determination of 0.992 was obtained.

5. Test measurements in the crystal caves

As part of the experiment, in-situ test measurements were performed. For this purpose the presented measurement system equipped with one measuring sensor was used (Fig. 6).

Fig. 6. Measurement system – test version

In the first stage, measurements were done in control sites, where there is no suspicion regarding the sources of moisture coming from damp rock environment (Fig. 7). The measurements included randomly selected points in the thill of the Upper Cave and Lower Cave.

Fig. 7. Measurements in places not influenced by rock environment moisture

The measurements were recorded with a frequency of 1 Hz. The results are shown in Fig. 8. They represent series at the time of the recording, in which the sensor was repositioned within the area identified as 'dry'. By contrast, Fig. 9 shows standard deviation for individual series of measurement.

Based on the recorded data average, maximum and minimum values were determined. These data are presented in Table 1.

As a result of the conducted analysis, it has been found that in sites where weather conditions (relative humidity) are closest to the values defined as recommended for maintaining the condition of halite cover, gravimetric water content remains within the range of 0.3 to 4.2%.

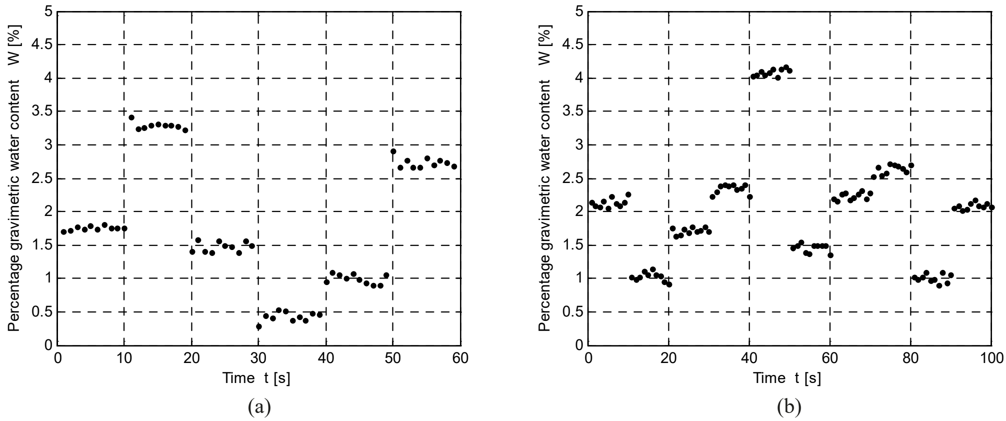

Fig. 8. Results of measurements in ‘dry’ areas taken in the thill of (a) Upper Cave and (b) Lower Cave

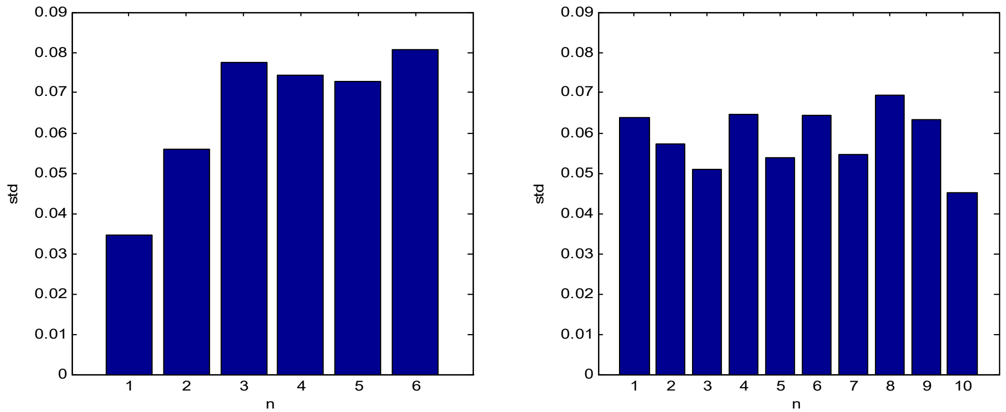

Fig. 9. Standard deviation for individual series of measurement shown in Fig. 8

TABLE 1

Quantitative results of measurements in ‘dry’ areas

Measurement site	**Average gravimetric water content [%]**	**Maximum gravimetric water content[%]**	**Minimum gravimetric water content [%]**
Upper Cave	1.76	3.42	0.29
Lower Cave	2.08	4.17	0.89

In the second stage, measurements were done in sites where the earlier measurements of relative air humidity indicated an increased proportion of water vapour. Two locations were selected to do the experiments. The first of them is called ‘Oven’, located in the entrance to the Upper Cave (Fig. 10). For testing the developed measurement system, an area including fragments of sidewall and ceiling was chosen, where periodic level of moisture is observed. For a long time periodically increased values of relative air humidity were recorded in this place.

Fig. 10. Measurement of rock moisture – 'Oven'

The second site where an increased level of air humidity was recorded is the Vestibule area (Fig. 11). In this place singular roof areas were located, where the halite cover is damp. The seeping brine then accumulates on the thill, causing areas of increased water content in the thill. As part of the test, measurements were taken in one point of the thill, directly under the damp halite cover.

Fig. 11. Measurement of rock moisture – Vestibule

In both cases the measurements were taken in one point characterised by observable moisture. The recorded measurement series are shown in Fig. 12.

Based on the recorded data, average values of the percentage of gravimetric water content for each of the measurement series were determined. These data are presented in Table 2.

The obtained results have shown a significant increase in the gravimetric water content measured, compared with the sites described as 'dry' (more than twofold). However, the difference in gravimetric water content between each of the analysed points is over 5%. The measurement result recorded on the thill of the vestibule is related to the visible condensation or seepage of

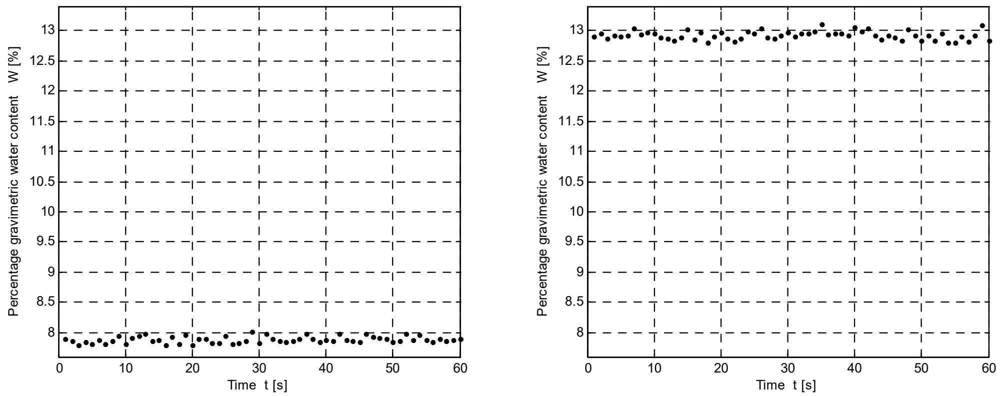

Fig. 12. Measurement results in 'Oven' (a) and Vestibule (b)

TABLE 2

Quantitative results of measurements in 'wet' areas

Measurement site	Average gravimetric water content [%]	Standard deviation [%]
'Oven' – sidewall	7.88	0.06
Vestibule – thill	12.92	0.07

brine through the rock mass. The brine then accumulates on the thill and forms a muddy area. Gravimetric water content recorded in damp areas of the sidewall, located in the so called 'Oven', has lower values. During the on-site observation no seepage of brine through the rock mass was noticed there.

6. Conclusions and plans for the future

The paper presents a measurement system dedicated to the detection of moisture content in the rock environment of the Crystal Caves nature reserve, located in the Wieliczka Salt Mine. The analysis of the sensor performance has been done, taking into account its static characteristic in a highly mineralised environment. The sensor The test measurements have demonstrated the ability of the devised system to detect gravimetric water content in various locations of the Crystal Caves, with different levels of moisture content. Additionally, ranges of gravimetric water content for sites identified as 'dry', as well as examples of measurements of moisture in the rock environment, have also been determined.

The research conducted, using the presented measurement system, requires long-term observations as well as correlation with the measurements of the relative humidity of the mine atmosphere. The latter will help to create an early warning system for excessive accumulation of moisture in the rock medium. It will also make it possible to determine the source of moisture in the gangue. In order to do so, the system has been permanently installed in the Crystal Caves nature reserve.

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