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Article

A new method of regulation of loads acting on the shaft lining in sections located in the salt rock mass

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Abstract: Rock salt is characterized by specific geomechanical and rheological properties. Layers of rock salt on depth over 900 m cause problems with shaft lining deformation. Methods of shaft lining protection used so far (e.g. in Sieroszowice mine) have not been effective enough. The research presents a patented and copyright protected concept of a shaft lining construction that can be used in rock masses with strong rheological properties and susceptible to leaching. In the case of salt layers, especially at significant depths the relative convergence of the heading contour may be about 40 ‰/year. That results in the fact that any other method of securing the shaft lining, e.g. by making it flexible, is not sufficient to ensure the stability of the shaft guidance geometry. In the new shaft lining concept, the excessive rock creep into the outbreak inside the shaft diameter is removed by local and controlled leaching of the shaft cheeks by means of fresh water through a porous medium at the contact layer behind the watertight tubing lining. The article presents the methodology of performing tests on a special device and the test results.

Keywords: mine shaft; salt rock; leaching

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1. Introduction

Convergence of the salt rock sidewall generates very strong pressure inserted onto shaft lining (Lotze, 1957; Schuppe, 1966; Höfer i Thoma, 1968; Serata, 1968; Ślizowski, 2001). Convergence rate is an indicator that gives an information what action should be undertaken in order to reduce its destructive influence on the shaft lining.

As was proved by expert calculations and observations conducted on a section of the salt rock sidewall, salt rock rheological deformations can cause excessive load on the final shaft lining in relatively short time (Flisiak 2005, Fabich 2016). Modification of the shaft lining in working shaft is rather impossible, with respect to necessity of the shaft operation stoppage for long time period. Thus, designing of the shaft lining assuring removal of the creeping salt rock from the shaft, is necessary.

As the salt is easily dissolved in freshwater, contact of salt rock on the whole surface of shaft cheek with water introduced into space between lining and shaft wall should be assured in the new construction of the shaft lining. Saturated brine resulting from the dissolution process should be removed from the space of shaft lining. As was proved by the experiments, stagnant water should be periodically replaced or thinned with freshwater, or recycled by laminar or turbulent water flow. Thus, the space between the shaft lining and shaft sidewall should be designed in such manner to serve two functions:

a) enabling load transfer from the rock body onto shaft lining,

b) enabling controlled freshwater flow behind shaft lining.

New construction of the shaft lining, called “tubing-aggregate lining” consist of the following elements:

1. Preliminary sidewall bolting protecting shaft pipe during its sinking through the layer of salt.

2. Tubing lining installed from the bottom to the top, which is supported by shaft set (special technological ring) localized right under the bottom of the salt rock layer.

3. Tubing of special construction, playing role of technological rings (shaft sets) for individual sections of the shaft lining, of the length determined by examinations made on testing section in one of the shafts sank in this region.

4. Filling with porous material – coarse grained aggregate of high compression strength, allowing temporal washing of the salt rock sidewalls with freshwater or salt brine of suitably selected concentration.

5. Pipe-line systems, pumps and containers for leaching medium and salt brine inflow and outflow.

The aggregate used in the described solution has a key task, as it must assure contact between salt rock body and shaft lining. Moreover, it should form a porous structure, which could be freely penetrated by leaching medium. In addition, it plays a role of the deformable and equalizing layer for point loads.

2. Device for salt rock leaching

A number of tests and analyses were planned in order to prove assumed thesis. The first examination series additionally aimed at verification of the device operation and calibration.

Differentiation of executed tests can be described by the following factors:

a) water temperature and salinity,

b) area of the sample’s cross-section and sample preparation procedure,

c) contact between the salt and aggregate,

d) character of the acting load,

e) volume of the leaching medium and flow characteristics.

Thirty of the most representative samples have been selected and registered results were exposed to further analysis. Cube-shaped and rectangular-shaped samples were cut from the salt material. Sample’s cross-section dimensions were: 150×150, 100×100 and 50×50 mm. Frontal wall exposed to leaching process was prepared to form a salt face, whereas the other surfaces were coated with water-proof paint or were left in original state (Fig. 1).

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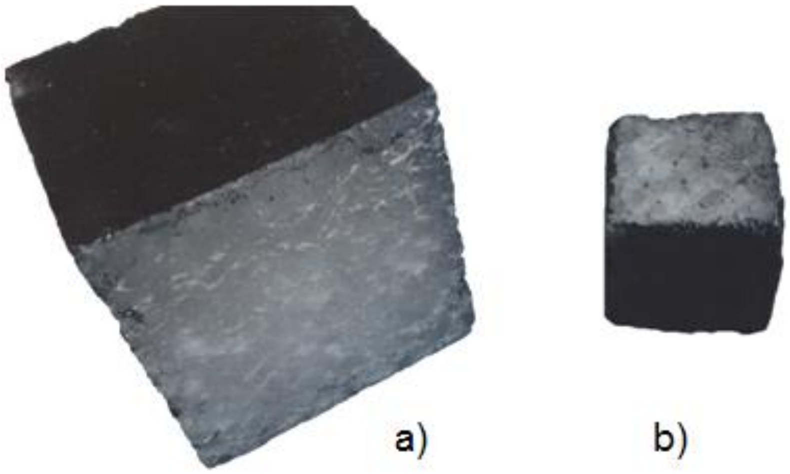

Figure 1. Example of cube-shaped samples a) – 100x100 mm, b) – 50x50 mm

The examinations were conducted in the device described in details in the studies (Kamiński, Cyran 2014) and (Kamiński 2018). Mechanism of work of the device for salt rock leaching, as well as information showing flow between individual components, is shown in Fig. 2. Water flow forced by pump is marked with red colour. Temperature was controlled via heater installed in the container, whereas flow discharge was registered by suitable sensor. System for loading (pump with servomotor) and main chamber filled with salt and aggregate, are shown in the central part of the Figure 2. Data from individual module was registered by notebook via suitable connectors. Beside of data acquisition image recording with use of time-lapse camera has been conducted.

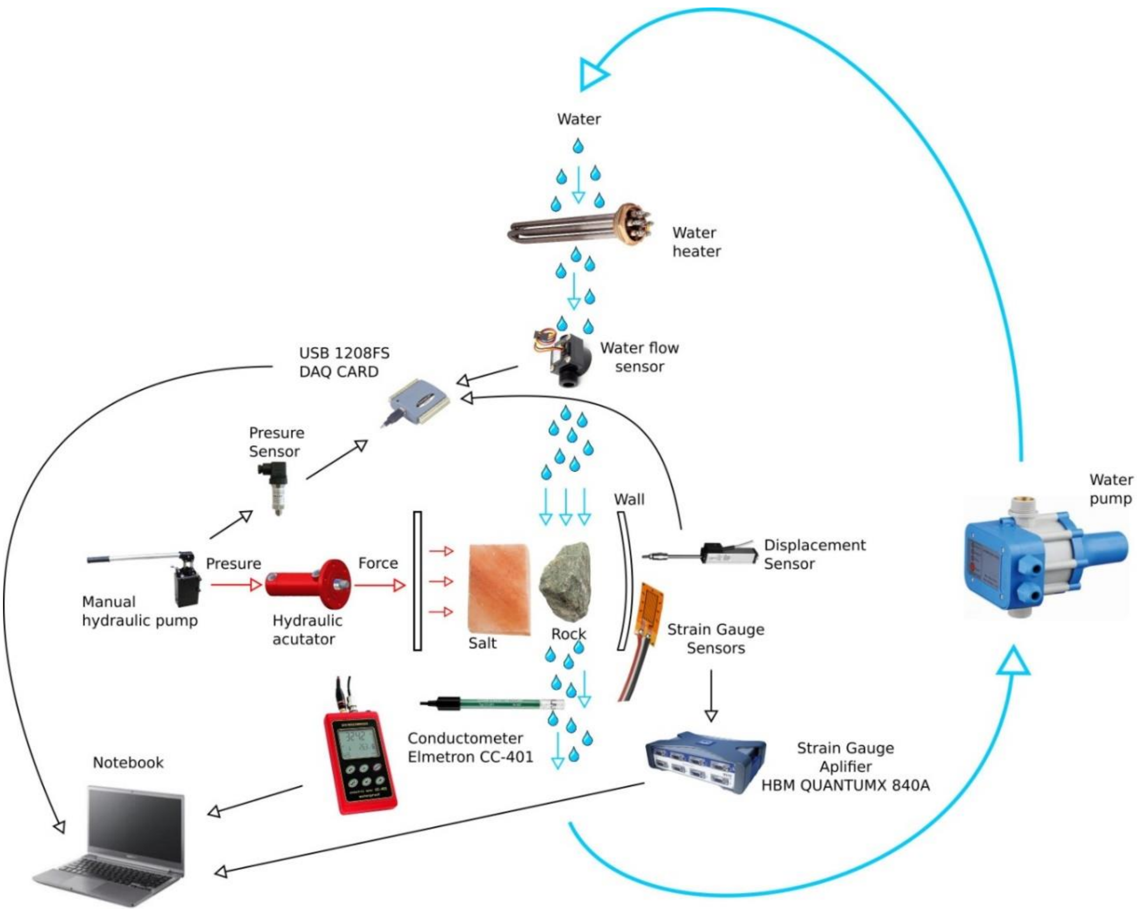

Figure 2. Operation scheme of the measurement test device

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Testing compartment was made of 12 mm thick steel sheet S355, and it was divided into open and closed part. Closed part of the testing chamber is a sealed system equipped in sleeve for hydraulic cylinder mounting. Hydraulic cylinder piston with pressing plate puts pressure on the salt sample. Load is transmitted via salt sample and aggregate onto testing plate, where stresses and deformations are generated. Suitable values are measured by extensometric converter and relocation transducer mounted at the measuring side of the testing chamber. Inflow and outflow valves allow control of the water flow direction and water discharge in the container. Overflow container with capacity of 70l allows water recirculation through the chamber – pumping unit – chamber system.

Figure 3. 3D model of final version of the test facility and photography of components before assembling

Pumping system consist of plastic filter, membrane pump of maximal discharge of 11,3 l/min, flow meter and set of valves: suction valve, inflow valve and outflow valve. Membrane pump construction ensures safe operation in salt environment (internal part of the head is made of EPDM and santropen®, and the internal part – of polypropylene) with maximum pressure head up to 10 m. Depending on connection, pumping system allows flow from the top or from the side of testing chamber.

Hydraulic system comprises manual hydraulic pump (max 250 bar), hydraulic pipes, hydraulic cylinder and hydraulic fluid pressure sensor. The system was designed to assure pressure of 80 kN for maximum operation pressure (180 bar) of the pump.

To realize designed experiment, test facility had to be equipped with electromechanical accessories such as: pump and water heater. Application of additional electrical subsets was necessary to assure safety of the operator and the test facility.

2. Examinations

Conducted examinations aimed at:

a) Confirmation that periodical leaching of salt rock sidewalls supported by coarse-grained aggregate stack is possible, and it allows effective control (reduction) of the shaft lining load.

b) Preliminary recognition of the processes related with the salt rock walls leaching and influence of the offloading process dynamics on deformational pressure of the shaft lining.

Experiments proved that in result of dissolving process on the contact between salt and aggregate, a salt bridge is formed (Fig. 4), which shape, dependently on the experiment characteristics, is similar to truncated cone or pyramid. Tests were conducted to determine the cone development mechanism and its geometrical parameters.

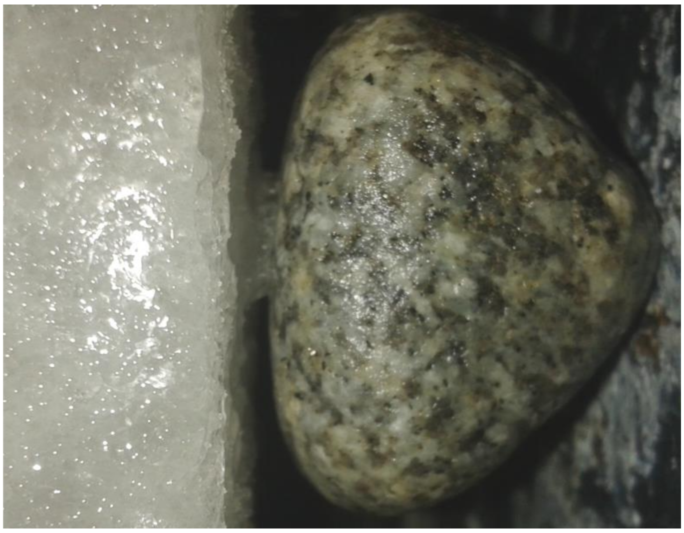

Figure 4. Salt bridge on the contact between salt sample and individual aggregate grain

Moreover, influence of the contact area between the sample and aggregate, onto development of the salt bridge was observed. Thus an attempt to simulate various contact characteristics of the salt wall with single grain was undertaken.

In the next stage, on the basis of collected data, rate of salt tenon (salt bridge) development was modelled. Experiments were conducted for three different-sized samples. In the initial moment T = 0 surface was equal to 1 (100%) and during washing process it was reduced until its destruction. Linear regression model of numerous variables was used in modelling, where percentage of the surface occupied by salt tenon was an explained variable and explanatory variables were: water temperature, water discharge per hour and time of the analysis. Square root of time was taken because it improved model tailoring and better described examined phenomenon. The effect is visualized in graphical form in Fig. 5.

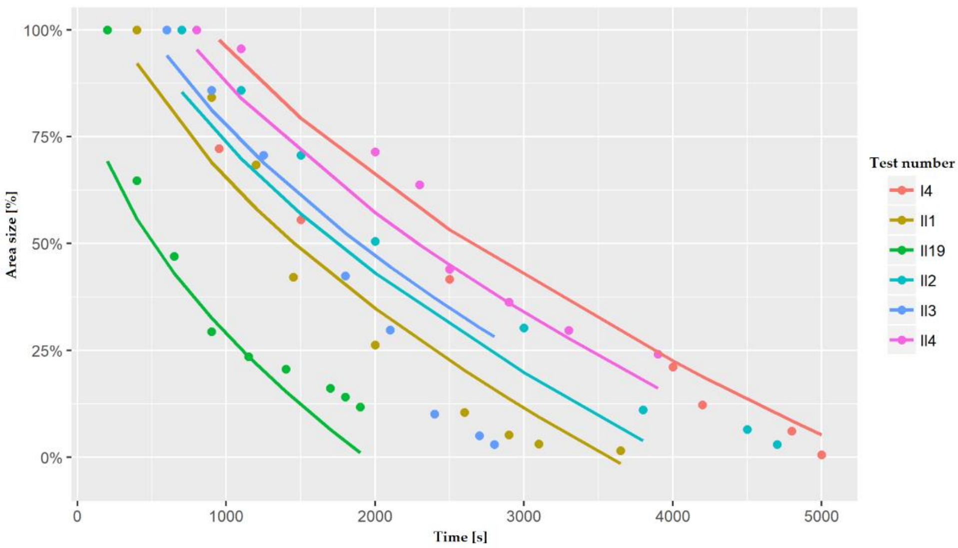

Figure 5. Salt tenon surface in time for targeted parameters

Salt rock wall dissolving model acting on some contact points where salt bridges are formed, has been developed according to preceding experiments' results.

Empirical formulas, shown below in descriptive and mathematical notation, were obtained:

$$\textbf{Percentage salt tenon surface} = (-0.0232 \cdot \sqrt{\text{time}} + 0.0376 \cdot temperature + 0.0456 \cdot flow\ discharge)$$

Preceding formula was adapted to measurements, thus in time T=0, 100% is not always obtained. This relationship presents general tendencies with respect to temperature and flow discharge, and it indicates approximate time of growth of the salt tenon of a specifized area.

In result of this formula transformation, leching time to achieve critical surface $A_{critical}$ was obtained:

$$\textbf{Time} = \left(\frac{0.0376 \cdot Temperature + 0.0456 \cdot Flow\ discharge - percentage\ salt\ tenon\ surface}{0{,}0232}\right)^2$$

Where:

$$\textbf{Percentage of salt tenon surface} = \frac{\text{Critical surface}}{\text{Salt wall surface}}$$

The ultimate relationship is as follows:

$$\boldsymbol{P} = \frac{Salt\ tenon\ height}{Side\ wall\ advance\ rate}$$

Factor P informs about the time (in days) needed to create salt tenons of critical surface, which are then destroyed with rate adapted to the side wall relocation. Leaching time is calculated from former equation.

On a basis of the salt tenon height, block wall flushing rate was determined. Similary to the previous case, linear regression was applied. Salt rock leaching rate was assumed as constant and it was expressed as a ratio of the flushed salt height and its leaching time. Explanatory variables comprised flow discharge in litres per minute and temperature. It was observed that salt is also flushed out from the frontal tenon surface on the salt block contact with the obstacle. Height of the leached salt was is about 20%. Data obtained in experiment are shown below.

Accordingly empirical formula for the salt wall leaching rate was combined with leaching time formula, which allows to determine dissolved salt height H [mm]:

$$\boldsymbol{H} = V_{leaching} \cdot t$$

Where:

$$V_{leaching} = 0{,}66 \cdot t + 2{,}15 \cdot U + 89{,}42$$

Fig. 6 illustrates the effects in graphical form.

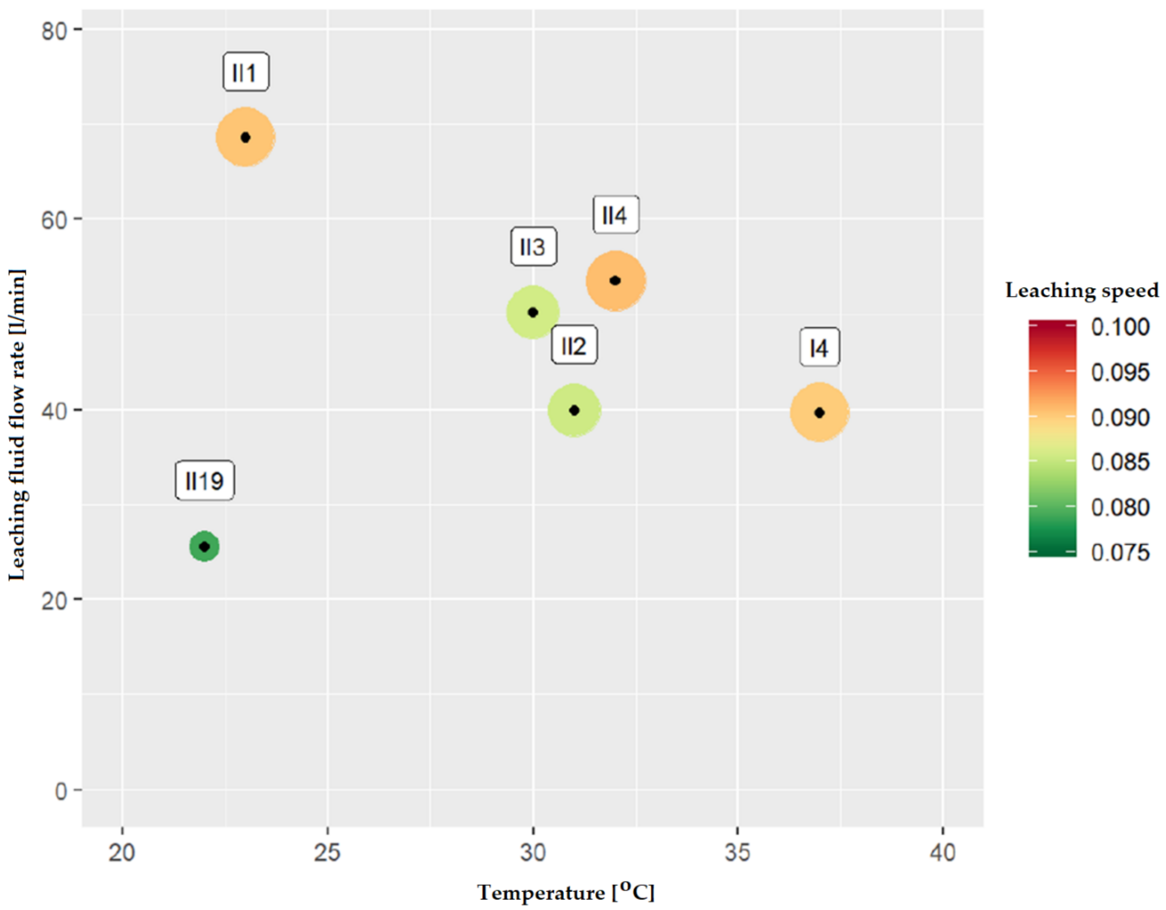

Figure 6. Salt wall leaching rate with targeted parameters

Analysis of characteristic fragments of single sample

The first scenario of the analysis of obtained results is composed of comparison of characteristic courses of single test sample. Drop of the force from the same initial value in specified time range in sequent simulation cycles of the rock body creeping was examined.

- **Analysis of test marked with symbol II.12**

Basic informations about experiment's procedure:

a) Pressing force of the salt block to the shaft lining via cylinder.

b) Leaching during measurments – process of the salt block washing with water in order to reduce the load.

c) Sample protection – salt block was covered with paint in order to allow dissolving of only one (unprotected) wall, which was in direct contact with shaft lining.

d) Only measurements lasting 600 s with initial value of the aggregate pile load of about 18 kN were chosen for the analysis.

Based on the functionality of the application developed for needs of the analysis of drop of the force loading the salt lump, specified fragments of the data were removed from the full set of results and then put on the diagram in order to compare data. The result is shown in diagram presented in Fig. 7.

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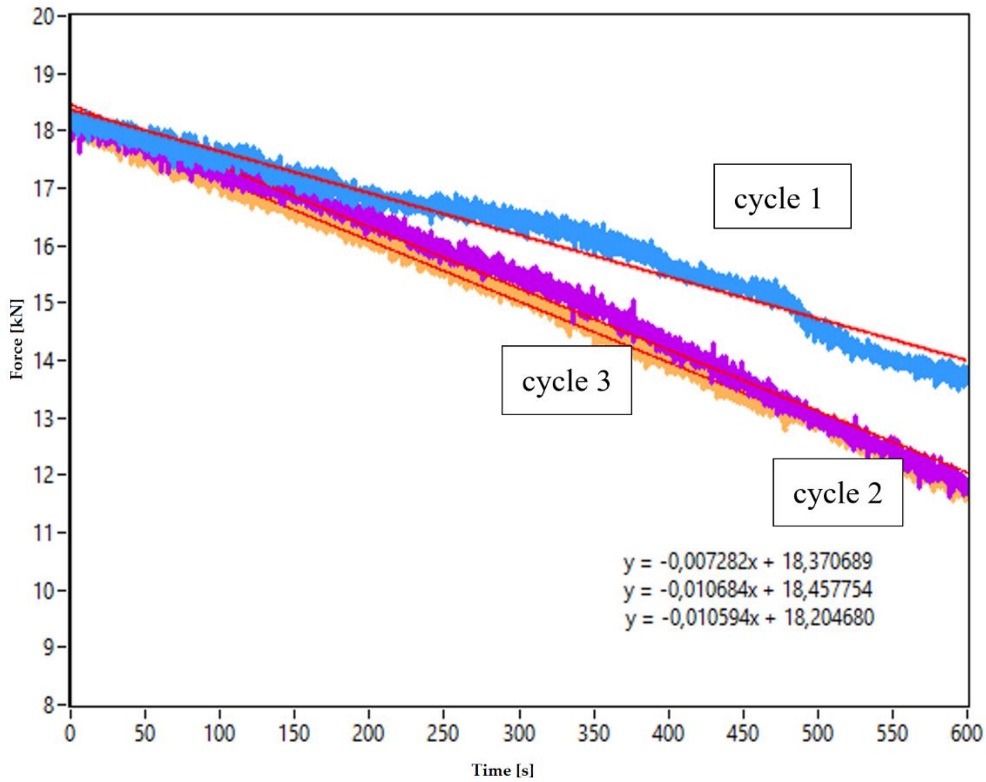

Figure 7. Comparison of individual loading cycles

Similar inclination angles of the straight line approximating formation of the force loading the shaft lining in time in subsequent leaching cycles can be observed in diagram. Leaching rate, expressed with tangent of inclination angle of approximation line, is low, which is the direct result of the initial water salinity (result of the previous test), despite of continuous dissolving process and constant water temperature amounting for about 36 Celsius degree.

- **Analysis of the test marked with symbol I.5**

Basic informations about experiment's procedure:

a) Pressing force of the salt block to the shaft lining via cylinder.

b) Leaching during measurments – process of the salt block washing with water in order to reduce the load.

c) Sample protection – salt block was covered with paint in order to allow dissolving of only one (unprotected) wall, which was in direct contact with shaft lining.

d) Only measurements lasting 120 s with initial value of the aggregate pile load of about 30 kN, were chosen for the analysis.

Similary to previous case, fragments of the data were removed from full data set and then shown in one diagram for comparison.

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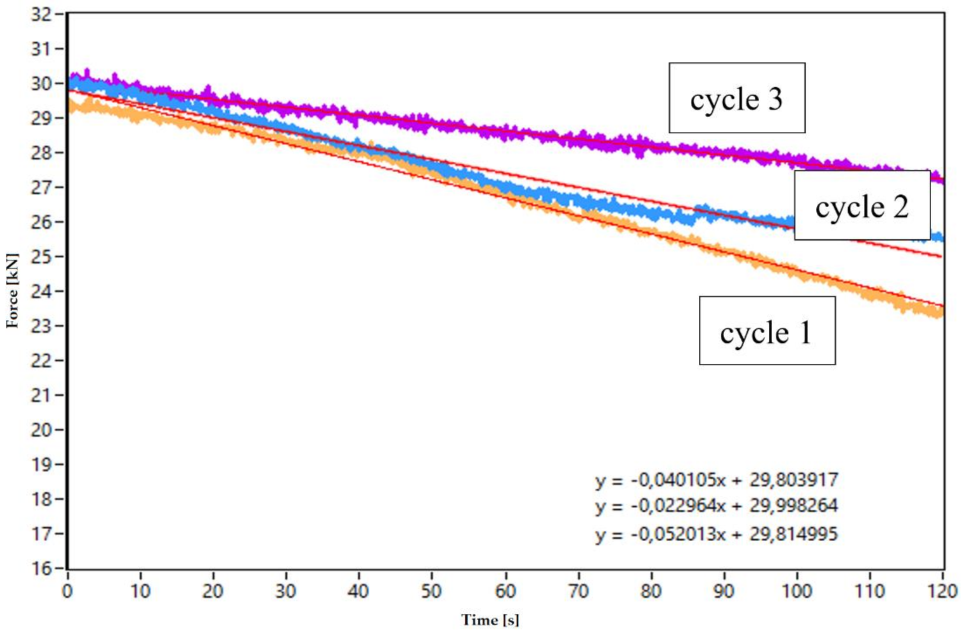

Figure 8. Comparison of subsequent loading cycles

Variable angle of line force approximation lines in time can be observed in the diagram above. Leaching rate is very high despite high brine salinity, which is the result of previous tests. High rate also results from salt sample protection on sample's sides, which was done in order to force leaching of the area simulating rock mass which is in contact with lining.

It was also observed, that despite of cyclic leaching process and constant brine temperature about 38°C, the leaching rate was reduced in each sequent cycle.

- **Analysis of test marked with symbol II.8**

Basic informations about experiment's procedure:

a) Pressing force of the salt block to the shaft lining via cylinder.

b) Leaching during measurments – process of the salt block washing with water in order to reduce the load.

c) Sample protection – salt block was covered with paint in order to allow dissolving of only one (unprotected) wall, which was in direct contact with shaft lining.

d) Only measurements lasting 375 s with initial value of the aggregate pile load of about 20 kN, were chosen for the analysis.

In the diagram (Fig.9), variable angle of inclination of the approximation line of the force in time was observed. Leaching rate is low (tangent of the inclination angle) despite low level of the brine salinity – water was replaced before measurement.

It was also noted, that despite cyclic leaching process, the leaching rate is reduced in each sequent cycle (cycle 1, 2 ,3) until the moment in which leaching rate is almost equal for all cycles (cycle 4, 5, 6) It is caused by increasing level of the leaching water salinity, as well as low temperature of the leaching water (~20 Celsius degree).

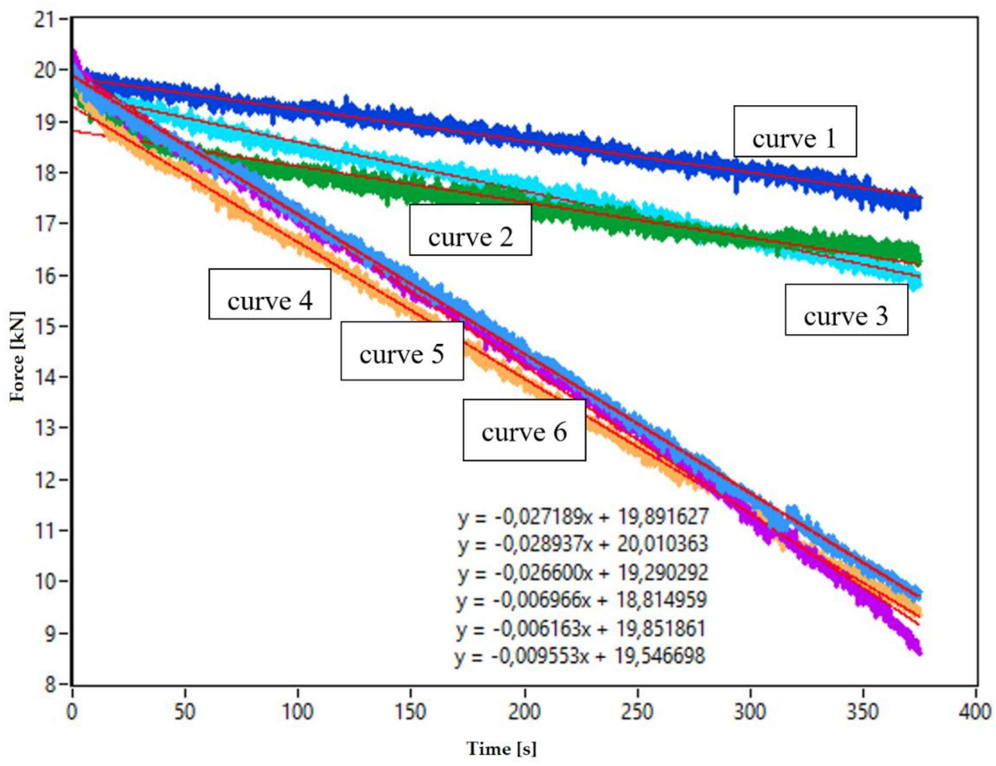

Figure 9. Comparison of subsequent load cycles

Analysis of various tests' characteristic cycles

Next scenario of the results' analysis comprises comparison of the characteristic fragment of the research process beginning. The analysis aimed at the load drop in the first phase of relaxation, directly after the load application. The following samples were considered:

1) II.5 pressing force applied to plate, fresh stagnant water,
2) II.7 pressing force applied to cylinder, leaching with salted water,
3) II.8 pressing force applied to cylinder, leaching with salted water,
4) II.9 pressing force applied to cylinder, leaching with salted water.

Measurements of the first load relaxation phase were chosen to the analysis, with initial value within range 16 - 20 kN.

Test results from of measurements are shown in Fig. 10. All samples were made from salt from the same localization. Leaching water temperature was constant during all measurements (22°C). It is observed in diagram related with test II.5, that small force value (about. 16 kN) resulting from stoppage of water flow and clamping force, caused development of large number of salt tenons and caused (threefold) elongation of the load relaxation time. Thus we can conclude that clamping force of the salt rock (directly and tightly) inserted to the shaft lining may cause retardation of the leaching process. Results of other samples' tests confirm rightness of the application of aggregate, used as intermediate layer between the shaft lining and salt rock body.

Another tests II.7 and II.8 are similar. However, higher rate was observed in the first case, where relaxation has similar rate despite the fact that in test II.7 brine was replaced with fresh water. Thus we can conclude, that water salinity has no considerable influence onto leaching rate.

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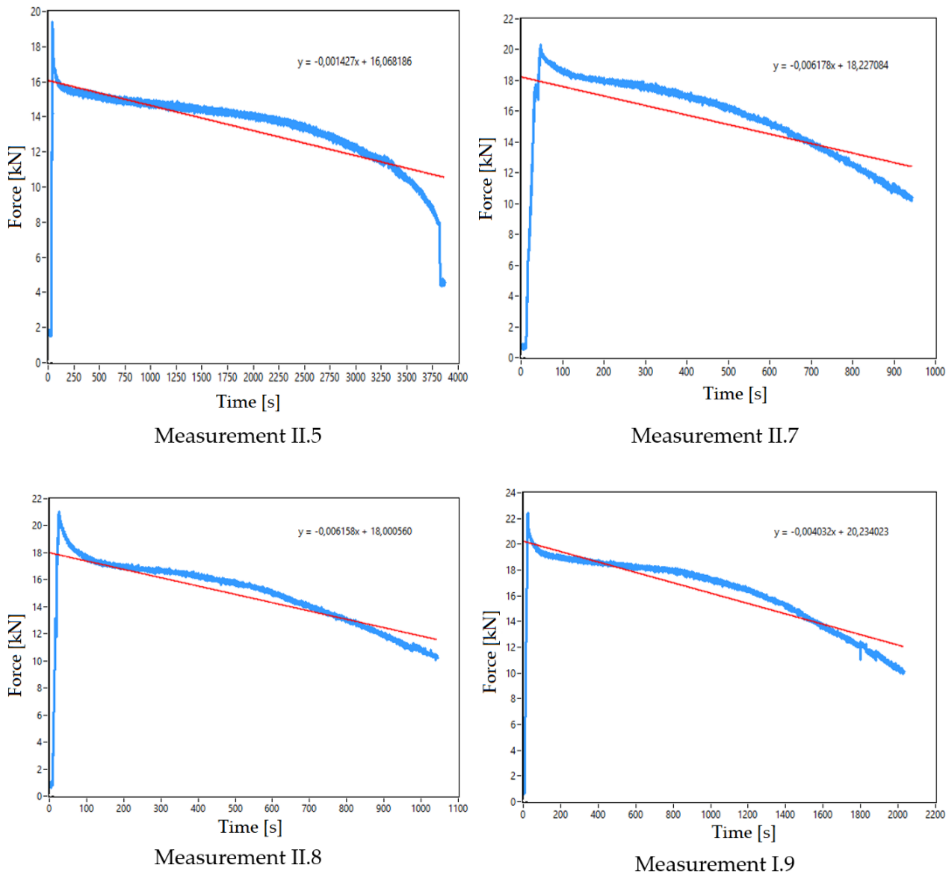

Figure 10. Comparison of individual loading cycles

In the test II.9 elongation of the time of the first relaxation was observed. It resulted from increasing of the water salinity during tests II.7 and II.8. In case of the test II.9, leaching time was elongated, despite of active water circulation

Another phenomenon analysed was related with destruction of the salt tenons in subsequent cycles of the rock body moves.

Graphical illustration of the process of salt tenons destruction are shown in Fig. 11 and Fig. 12. Fragments of results, in which load causing rock body relocation after leaching process, were selected from measurement data. Curve 1 illustrates course of the first cycle of sample loading, noticable fluctuations result from sample settlement in the test facility. Curves 2, 3, 4 and 5 (in case of tests II.8 and II.9) comprise data from subsequent relaxation processes, in which destructive processes were observed.

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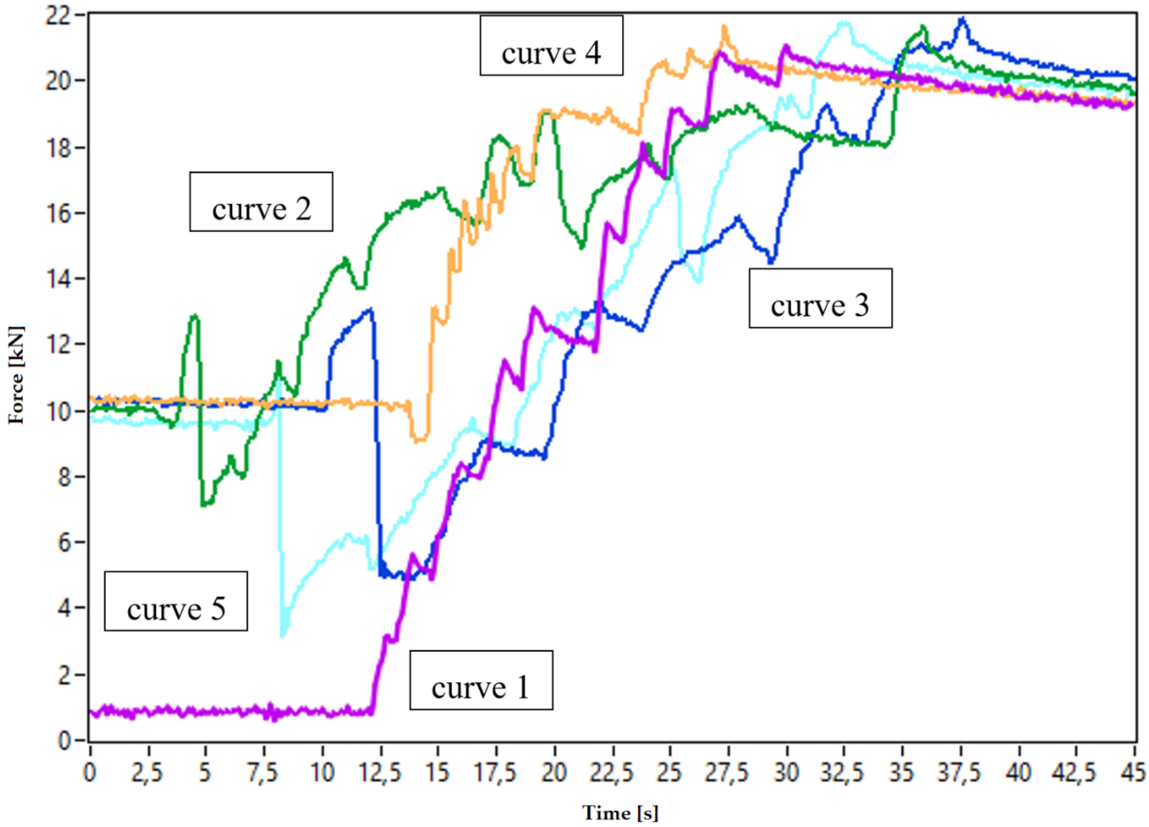

Figure 11. Comparison Courses of the salt tenon destruction in test II.8 of individual loading cycles

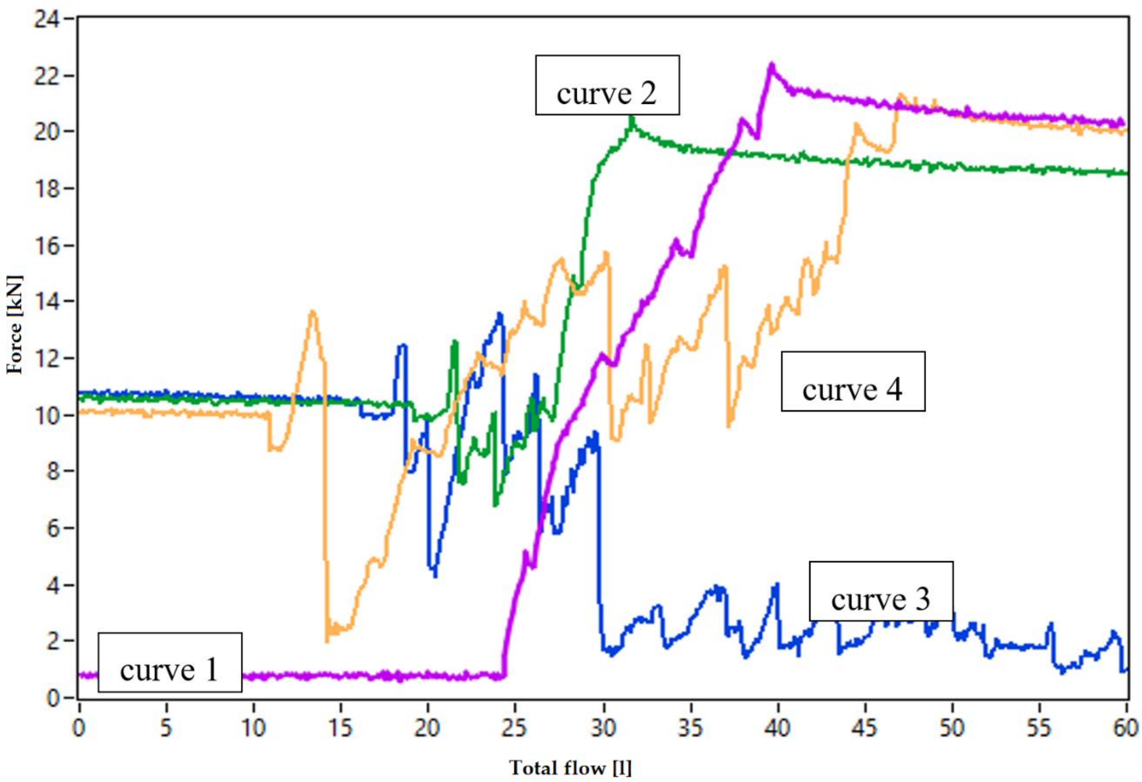

Figure 12. Courses of the salt tenon destruction in test II.9

Phenomenon of the salt tenon destruction can be observed in the diagram, in which force course was replaced with its derivative. Local maxima and minima reflect dynamic changes occurring in the time when the rock body press onto shaft lining and, salt tenons developed during leaching process, are not able to bear compressive force and they are exposed to dynamic destruction. Maxima/minima of the beginning and the end of measurement range result from errors of the numerical differentiation.

3. Conclusions

The issue of the stability of mine working in the salt rock mass is neither new nor not analyzed. The problem was discussed in thousands of research studies and publications.

Perspective of further development of copper mining in Pre-Sudetic Monocline, as well as advance of exploitation front to the north is related with necessity of development of new workings in the salt rock mass. These headings, as long-lasting ones, must guarantee rock body stability for decades. Shafts equipped with lifts must also provide consistent shaft structural members geometry, especially conveyance guidance, which provides high speed of the lifts' movement. Before works related with salt formations start, we should realize that issues of salt rock geo-mechanical behavior are very complicated and they differ from most other rocks. Each examined case should be based on parameters of given deposit.

Analysis of literature and available data from research works allowed following conclusions:

a. Shafts built for needs of KGHM Polska Miedź S.A. will penetrate salt rock body on sections of different length on the depth about 1000 m.

b. The shafts sections located in salt rock mass will be exposed to convergence of relatively high rate and relatively big relocation of the shaft sidewalls. After 4 years of sinking of the SW-4 shaft, convergence of the shaft sidewalls noted is about 0,5 mm/day, so yearly dislocation of the shaft sidewall is about 18 cm.

c. Yielding lining used in the SW-4 shaft can be used only because of the fact that the shaft has no lift and gradual dislocations of the shaft sidewalls play no considerable role, despite decrease of shaft cross section used for ventilation.

d. Periodic reconstruction of the shaft section located in the salt rock mass is coast-bearing, and requires stoppage of regular shaft operations, what generates very high cost and is a very complicated process.

e. Application of similar solution of the shaft lining is not possible in shaft equipped with lift, because precise operation of the conveyances is required, both in case of fixed and rope guidance.

Method of the control of shaft lining load via suitable construction and operations procedure, described in this work, utilizes biggest disadvantage of the salt rock mass, which is high solubility in fresh water. In this case, this rock property is considered as its great advantage.

Preliminary examinations conducted and documented in the present study proved that process of controlled leaching of the salt sidewalls of shaft opening is possible. Application of this process in practice should be a new tool used for elimination of the deformation pressure inserted onto shaft lining.

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Designed test facility for salt rock leaching gave only basic answers for questions related with described problem, whereas solutions for numerous technological questions require application of large-scale models in situ.

The solution of such complex problem proposed in this work requires further examinations related both with leached salt properties and forecasting and measuring rates of salt rock mass creeping into the shaft, as well as its effective and uniform leaching.

It should be emphasized that results of the executed examinations indicate that after periodic leaching, grained filling of the contact layer can and should be voided from fluid (and brine). Thanks to that the shaft tubing lining will not be additionally loaded with hydrostatic pressure coming from the brine, which is aggressive to construction materials.

Application of new construction solutions allows to eliminate planned periodic reconstruction works. It results in avoidance of shaft operations stoppage, which is crucial for effectiveness of mining shaft.

References

Lotze F. (1957). Steinsalz und Kalisalz. Berlin: Gebrüder Berntraeger.

Schuppe F. (1966). Untersuchungen über rheologische Eigenschaften von Salzgestein.

Höfer K.H., Thoma K. (1968). Triaxial tests on salt rocks. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, t. 5(2), 195–196.

Serata S. (1968). Application of continuum mechanics to design of deep Potash mines in Canada. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, t. 5(4), pp. 293–314.

Ślizowski J. (2001). Badania własności reologicznych soli kamiennej przy projektowaniu komór magazynowych gazu ziemnego w górotworze solnym. Przegląd Górniczy, t. 5, pp. 9–15.

Flisiak D. (2005). Badania procesów reologicznych w górotworze solnym wywołanych użytkowaniem podziemnych magazynów gazu. Projekt badawczy KBN Nr 5T12A 01722 (praca niepublikowana).

Fabich S., Morawiec P., Soroko K., Szlązak M. (2016). Problems with maintenance of shaft lining in the salt interval of SW-4 shaft in "Polkowice-Sieroszowice" copper mine. Przegląd Górniczy, t. 72(3), pp. 65–74.

Kamiński P., Cyran K. (2014). Research device for lining effort measurements located on the large depth in rock salt layers. Salt Review : yearbook of Polish Salt Mining Association ; ISSN 2300-9349. t. 10, pp. 75–84.

Kamiński P. (2018). New structure of shafts lining and load adjustment method on sections passing through a salt rock mass. Dissertation AGH.