AGH Journal of Mining and Geoengineering • Vol. 36 • No. 2 • 2012

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RESEARCH ON GEO-MECHANICAL PROPERTIES OF ROCK SALT IN KŁODAWA DIAPIR

1. Introduction

Forecasting the geo-mechanical phenomena in a salt rock mass surrounded by underground headings, the basic strength parameters and strain parameters for elastic rocks are used. Laboratory tests are the basic source of information regarding the mechanical properties of rock mass, i.e.: single-axial compression tests (compression strength, modulus of elasticity, Poisson ratio), single-axial tension tests or tests with Brazilian method, and creep tests with a single-axial constant load (salt viscosity). Tests *in situ* are mainly limited to convergence of headings [7].

The calculation results of rock mass displacement, in which were used parameters obtained in the laboratory, are often significantly different from the values recorded in nature. That fact can be related to the choice of material for testing (e.g., non-representative sampling place in a non-homogeneous deposit), the imperfections of laboratory research methodology as well as simplified mathematical formulas imposed on by professional computer programs [4, 6]. Therefore, more often the determination of rock parameters is done by means of direct observations of rock mass behaviour and the verification of numerical modeling results under conditions of measurements *in situ*.

The research undertaken in the Department of Geomechanics, Civil Engineering and Geotechnics in order to develop effective research methodology, and construct an appropriate constitutive model for salt rock mass, showed that despite the general opinion regarding rock salt homogeneity, on the grounds of fragmentary sampling deposit, quantitative conclusions of the behaviour of designing underground objects cannot be formulated [2, 3].

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2. Description of material under investigation

Taking into consideration its lithological structure the material under investigation, was classified as light rock salt and grey rock salt. As a result of macroscopic assessment, a great variety of salt structures were identified: from completely chaotic to those clearly oriented with single pile-ups of large salt crystals in a fine-crystalline and medium-crystalline mass.

From drawn cube sampling, 49 cylindrical samples were made by means of the dry turning method of a size which is in accordance with the ISRM (International Society for Rock Mechanics) recommendations [8], with the control of basis' parallelism. The samples produced underwent macroscopic assessment, and the sutability of their performance was checked by measuring them accurately within 0.1 mm. Next, all of the samples were weighed, and on the grounds of their weight, unit weight was determined, which was in intervals between 20.64–21.36 kN/m^3 (average value 21.11 kN/m^3).

The samples produced were used to carry out the following tests: single-axial compression test, triple-axial compression test, creep test with constant and variable load and tensile test by means of transverse compression (Brazilian method).

3. Strength and deformation properties in immediate tests

Compression strength, in the uniaxial tests as well as in triaxial tests, were determined as a maximum strength ratio, with which there was damage to the sample or abrupt acceleration of axial deformation with a partial coherence.

In the uniaxial and triaxial tests, with lower radial stress, the samples underwent dynamic, brittle damage with a maximum load value, or after reaching post-critical phase. The damage was in the form of a slip along the face of cut, or total disintegration of the sample. In the triaxial tests with higher pressure values, the samples underwent a significant deformation with a partial coherence.

The recorded characteristics of: axial strain, transverse strain and volume strain show non-linearity in all range of stress (Fig. 1). The threshold of macro-dilation appears with axial stress of 11.29–19.28 MPa, which on average constitutes 55% of the strength limit R_c. A further growth of stress is accompanied by an intensive growth of volumetric strain, which attests the development of inner cracks. The samples under research show an anisotropy of strain properties, which is indicated by a course of most of the characteristics of transverse strain and different values of Poisson ratio, which are determined in two reciprocal perpendicular directions. The factor of transverse strain, calculated in the stress interval 0.2–0.8 R_c, is higher than 0.5 and loses its physical sense as a parameter for the Hooke's law.

The analysis of numerical values of the parameters obtained during the uniaxial compression trials (Tab. 1) shows a relatively slight diversification of the mechanical properties for the samples under research: ±10.97% of an average strength value $R_{cśr}$ = 27.33 MPa and ±14.44% of an average value of macro-dilatation limit (15.17 MPa). Whereas, as it is presented in the figure, the stress-strain parameters show a significantly bigger diversification.

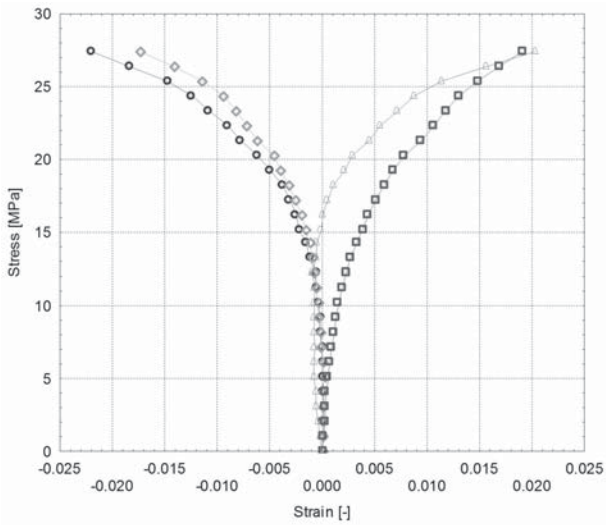

Fig. 1. The exemplary stress-strain characteristics of rock salt in the Kłodawa diapir (sample 4/1)

TABLE 1
Results of uniaxial compression tests

Value	Strength R_c [MPa]	Macrodylatation threshold from, [MPa]	Coefficient of longitudinal, E [MPa]		Coefficient of transverse strain υ,[—]		
			in linear interval	according to ISRM	in linear interval, υ 1	in linear interval, υ 1	Average value
Average	27.33	15.17	6 886	2 221	0.29	0.32	0.30
Minimal	22.41	11.29	4 113	1 414	0.11	0.10	0.17
Maximal	32.47	19.28	10 320	3 978	0.48	0.46	0.42

The research results by means of the transverse compression method showed the tensile strength changes in interval 1.14–2.52 MPa, with an average value $R_{rśr}$ = 1.75 MPa. It is difficult to estimate statistically the obtained results because of too few tests, being carried out.

The results of the triaxial compression tests show a linear dependence of the destructive stresses on the values of radial stresses in the whole pressure interval in which the particular tests were carried out (from 0 to 24 MPa), (Fig. 2). The minimal number of the tests carried out does not enable a reliable numerical description of this dependence.

The analysis in deviation stresses (Fig. 3) also shows that during the interval of radial stresses applied, the growth process of the maximal tangential stresses, during destruction, proceeds linearly. The confirmation of this appears while observing the way a sample destruction behaves during testing: with all pressures applied the brittle destruction of soil occurred with little plasticity deformation.

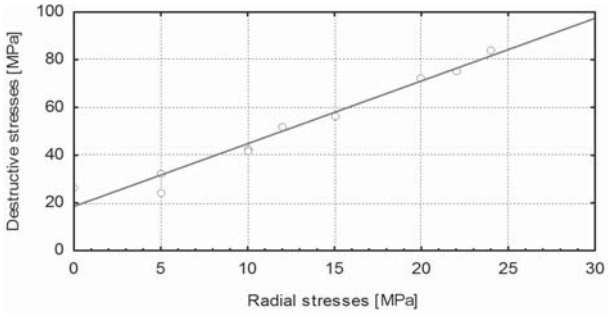

Fig. 2. Dependence of destructive stresses in triaxial compression on values of radial stresses

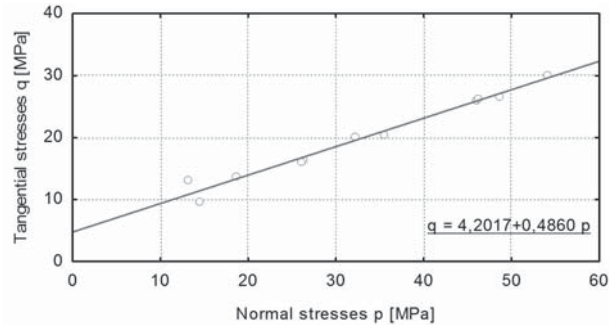

Fig. 3. Dependence of maximal tangential stresses on values of average normal stresses, during destruction

It is also reflected in the image of the Mohr's circles for particular samples (Fig. 4). On the grounds of that, for the tested samples during the whole interval of radial stresses, the equation of the equilibrium limit can be formulated in the form of the classical Coulomb's condition with rectilinear envelope and the following parameters:

— cohesion: 4.20 MPa,
— internal friction angle: 29.08°.

This equation, with sufficient accuracy, describes the strength condition for rock-salt in the depth interval, from which the tested samples were taken.

The specification of the numerical values of the Coulomb's condition's parameters and their exploitation in the area of diaper, where further exploitation activity has been planned, requires an appropriate numerous series of testing with different radial stresses and a statistical evaluation of the results obtained.

4. Rheological characteristics

One of the premises necessary when choosing a rheological model for tested rock--salt was a relatively simple form of mathematical formula, which easily enables one to make use of it in the numerical modelling of the deformation phenomena, which

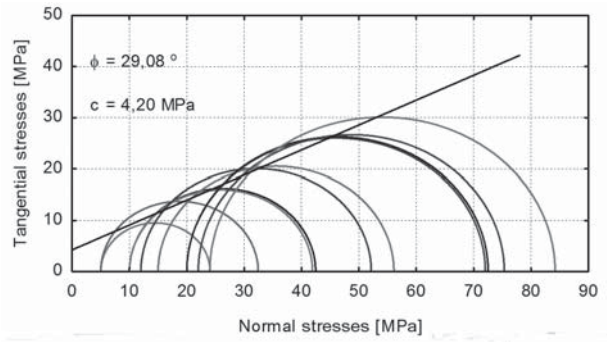

Fig. 4. Diagrams of Mohr's circle and coefficients of rectilinear envelope for tested rock-salt

with the passage of time, occur in the surrounding of the heading located in the diapir. The run of creep curves under different loads (Fig. 5–7) univocally shows non-linear relation of rheological deformations with stresses that occur, and the fact that stresses with a value of 75–80% of immediate strength, cause brittle sample destruction over a short period of time. However, taking into consideration, the values of stresses which exist in rock mass at depths, from which the testing samples were taken, the deformation processes of salt can be described with a certain approximation by means of the Burger's rheological model, which comply with the requirements resulting from conducted creep tests, which means unlimited creep under each load and partially reversible deformations:

$$\sigma + \left(\frac{\eta_M}{E_M} + \frac{\eta_M}{E_K} + \frac{\eta_K}{E_K}\right)\frac{\partial\sigma}{\partial t} + \frac{\eta_M \cdot \eta_K}{E_M \cdot E_K} \cdot \frac{\partial^2\sigma}{\partial t^2} = \eta_M \cdot \frac{\partial\varepsilon}{\partial t} + \frac{\eta_M \cdot \eta_K}{E_K} \cdot \frac{\partial^2\varepsilon}{\partial t^2} \quad (1)$$

which after integrating with steady stress σ_0 for $0 < t < t_0$ (creep phase) and after unloading to $\sigma = 0$ for $t > t_0$ gives dependences:

$$\varepsilon(t) = \begin{cases} \dfrac{\sigma_0}{E_M} + \dfrac{\sigma_0}{\eta_M} \cdot t + \dfrac{\sigma_0}{E_K} \cdot \left[1 - \exp\left(-\dfrac{E_K}{\eta_K} \cdot t\right)\right] & (t < t_0) \\ \dfrac{\sigma_0}{\eta_M} \cdot t_0 - \dfrac{\sigma_0}{E_K} \cdot \exp\left(-\dfrac{E_K}{\eta_K} \cdot t\right) \cdot \left[1 - \exp\left(-\dfrac{E_K}{\eta_K} \cdot t_0\right)\right] & (t > t_0) \end{cases} \quad (2)$$

where:

E_M, η_M — parameters of Maxwell's body,
E_K, η_K — parameters of Kelvin's,
t_0 — time of unloading pulse occurrence.

Non-linear approximation of the results of rock salt testing by means of the relations above gives, for particular creep curves, a very good fitting in a statistical respect (correlation above j 0.98 in estimation method of the Newton-Gauss, conducted by means of the Statistica

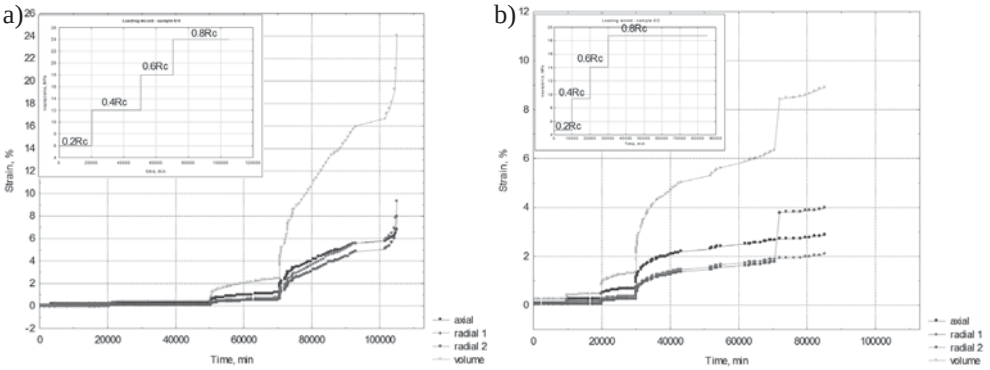

Fig. 5. Run of salt creep test for diapir in Kłodawa with variable stress and with loading record: a — sample 6/4, b — sample 8/2

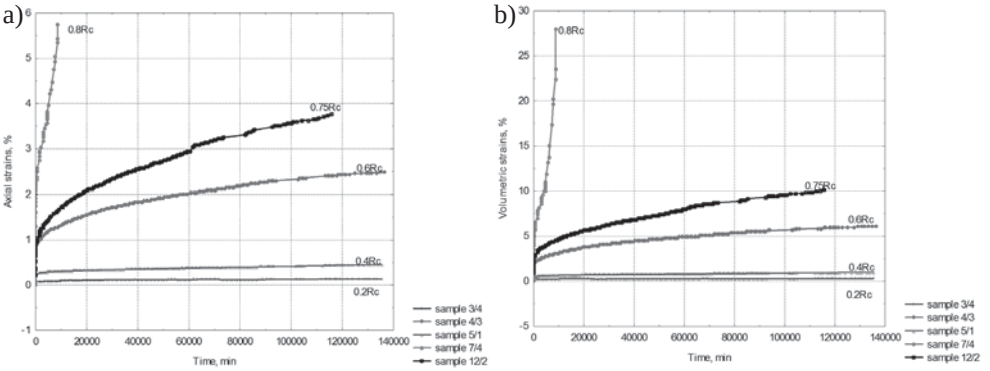

Fig. 6. Results of short-duration creep tests with steady stress: a — axial strains, b — volumetric-strains

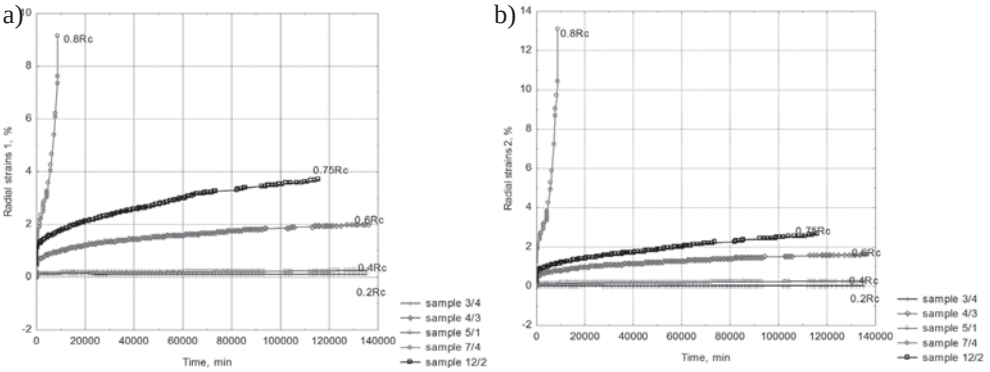

Fig. 7. Results of short-term creep tests with steady stress: a — radial strains 1, b — radial strains 2

v.8. program. However, the calculated parameters depend on applied loading in a different way, which significantly limits the use of equation 2 for practical calculations.

Creep phase established with sufficient accuracy can be described with the equation:

$$\varepsilon(t) = \frac{\sigma_0}{\eta} \cdot t + \varepsilon_0 \tag{3}$$

where ε_0 is the initial strain at the moment $t = 0$, which forms as a result of sample loading up to strain σ_0, and η — viscosity of the tested salt.

As a result of the approximation of the creep curves, slopes of asymptotes were calculated in function of applied stress, which can be interpreted as creep speed at the final stage of the test duration, and on that basis the value of the viscosity coefficient for the tested salt can be calculated. It should be emphasized that because of the short duration of the tests, that speed can be treated only with a certain approximation as creep speed in the phase of steady-rate creep.

The dependence of the both parameters on the applied stresses, are illustrated by the following diagrams (Fig. 8–9). The analysis of these parameters shows their strong dependence on applied load as well as a significant diversification among particular samples.

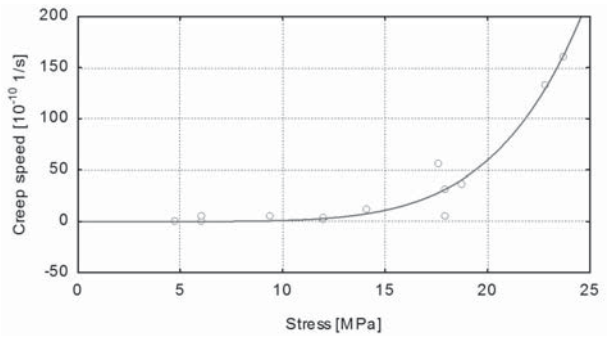

Fig. 8. Diagram of creep speed of tested rock salt in function of acting stresses

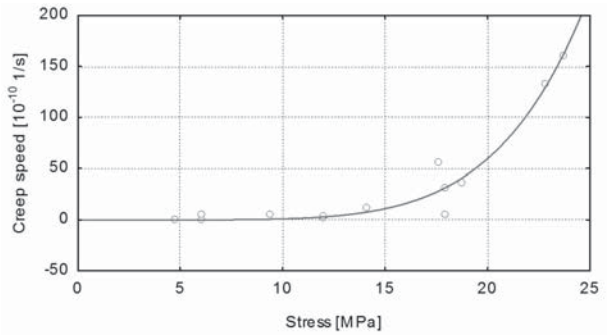

Fig. 9. Diagram of rock salt viscosity in function of acting stresses

Due to a small number of determinations, it is difficult to obtain a statistical estimation of these values and their generalization for the whole diapir.

5. Summary

A strong dependence of creep speed on the acting strains univocally shows, that in the case of the rock mass described, behaviour in the field shows a significant diversification of values (e.g., in big interval of depths or in the headings' surrounding of complicated geometry), therefore it advisable to use the rheological equation, which gives consideration to non-linear dependence between strains and stresses. With the assumption that creep occurs during the phase of steady-rate creep, for this purpose, many authors make use of Norton's law as follows:

$$\frac{d\varepsilon}{dt} = A \cdot \sigma^n \cdot \exp\left(-\frac{Q}{R \cdot T}\right) \tag{4}$$

where R determines the universal gas constant (1.987 cal/mol K), T means the temperature in Kelvin's grades, and Q the so-called activation energy, which value can be determined on the grounds of laboratory creep tests at different temperatures. On the grounds of literature data accepting, Q = 12 000 cal/mol [1, 5], the other parameters of creep law for testing rock salt are determined by means of a non-linear estimation with the usage of the Statistica v.8 package, they amount to:

$n = 4.77$

$A = 9.0916 \cdot 10^{-35}\ \mathrm{Pa}^{-4.77} \cdot \mathrm{s}^{-1}$

These parameters are contained in the interval of values quoted in the literature, but attention should be paid to the fact that they were determined on the grounds of only a few tests and the speed measurements in the phase of creep development was worked out on the same basis. Therefore, their verification requires long-term laboratory tests applying different loads, with a transition in the phase of steady-rate creep determined with a stable speed, or a comparison using the measurement results of the convergence of the headings in actual conditions.

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