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ŁUKASZ GRZYBOWSKI*, PAWEŁ WILKOSZ**, DANUTA FLISIAK***

Mechanical properties of rock salt from Mogilno salt dome

Introduction

Increasing interest in properties of salt rocks has been observed for a number of years now. It is connected with the possibility to locate different strategic objects, such as e.g. landfill sites or storage facilities for useful substances in salt orogens. For this purpose Zechstein salt domes in the Polish Lowland are especially suitable. Considerable thickness of salt masses, their cohesion and chemical inertness facilitate underground tankless storage of oil derivatives and gases.

From the point of view of long-term stability of the storage facility it is necessary to conduct geomechanical assessment of the orogen to know its actual behaviour. Usually such an assessment is performed using numerical modelling based on results of laboratory testing, averaged for the entire bed. Complex tectonics and diverse lithology within the salt dome result in the necessary bed generalization, i.e. also recorded mechanical parameters. In reality rocks contained in the salt orogen differ markedly, especially in terms of geomechanical properties.

The study presents results of laboratory testing of geomechanical properties for different rock types from the Mogilno salt bed, focusing on the determination of a dependence between the state of stress and the state of strain and on the description of the course of rheological processes. To realize this objective it was decided to study uniaxial compression and creep, constituting the basis for the determination of geomechanical properties. Recorded parameters were also used for comparison with those of salts in other bed

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* IKS „SOLINO” S.A. Inowrocław; e-mail: lukasz.grzybowski@yahoo.pl

** Instytut Geologii, Uniwesytet im. A. Mickiewicza, Poznań; e-mail: wilkosz@amu.edu.pl

*** Katedra Geomechaniki, Budownictwa i Geotechniki, AGH Kraków; e-mail: danutafl@agh.edu.pl

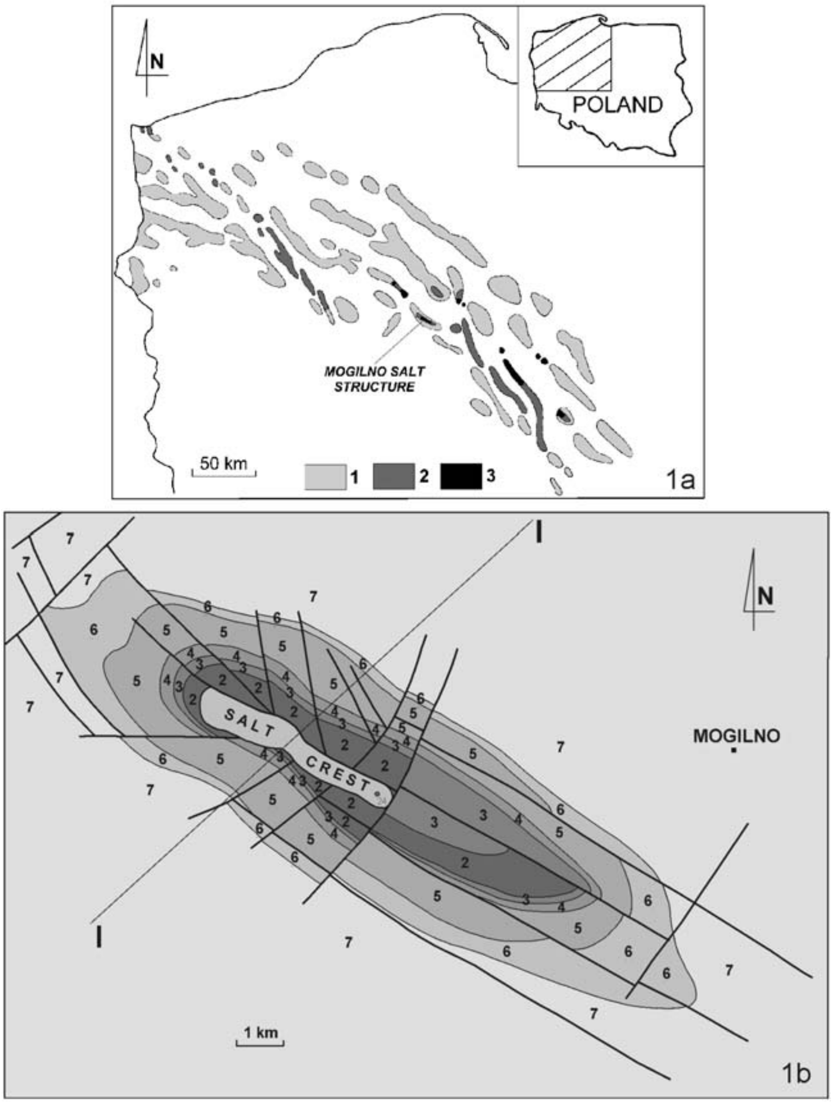

Fig. 1. Location of the Mogilno salt dome (1a) and geological subcrop map (1b) (without Cenozoic cover) with location borhole M-24
1a: Salt structures not piercing, salt pillows (1), partly piercing (2) and completely piercing (3) the Mesozoic cover rocks
1b: 1 – Zechstein salt, 2 – Upper Trissic, 3 – Lower Jurassic, 4 – Middle Jurassic, 5 – Upper Jurassic, 6 – Lower Cretaceous, 7 – Upper Cretaceous, 8 – Cenozoic, 9 – cap rock

Rys. 1. Lokalizacja wysadu solnego Mogilno (1a) i szkic geologiczny (1b) (bez pokrywy kenozoicznej) z lokalizacją otworu M-24
1a: struktury solne nieprzebijające, poduszki solne (1), częściowo przebijające (2) i całkowicie przebijające (3) mezozoiczną pokrywę wysadową
1b: 1 – sole cechsztyńskie, 2 – Trias górny, 3 – Jura dolna, 4 – Jura środkowa, 5 – Jura górna, 6 – Kreda dolna, 7 – Kreda górna, 8 – Kenozoik, 9 – czapa gipsowa

structures. The Mogilno I rock salt bed, constituting the south-eastern part of the structure, had never been investigated in laboratory testing of geomechanical properties, in spite of the 20-year history of mining works in that area. Such studies were performed for the Mogilno II bed, where the Mogilno Underground Cavern Gas Storage Facility is located (Kłeczek et al. 1986).

1. Geological setting

Salt domes are one of the most characteristic structural elements of Zechstein – Mesosoic of the mid-Polish basin (Marek, Dadlez 1997). Their linear dimensions and levels of piercement of Mesosoic cover rocks are various (Fig. 1). Among them 10 pierce the denudational-structural surface of Mesosoic deposits, and intrude into the cover of Caenosoic rocks, and one reaches the contemporary topographic surface (Wapno salt dome). The Mogilno salt structure is the one that completely pierces diapirs.

The Mogilno salt structure is about 30 km long, and up to 7 km wide (Fig. 1) and is the NW-SE directed elongated structure. The longitudinal axis of the structure runs from the NW towards the SE, at the angle of about 300°. In the central zone a small salt crest rises up. The salt crest is about 8 km long, and up to 1 km wide and consists of a sequence of PZ2 (stassfurt rock salt formations) and, on the flanks, PZ3 (leine) and PZ4 (aller) salt rock formations. The main feature of this salt crest is the vertical arrangement of the layers of the three Zechstein salt cycles. The internal structure of the salt body is very complex, including vertical or steeply inclined and overturned fold axes.

At the present time different parts of this structure are used for gas storage (NW part of the salt crest) and salt mining (SE part of the salt crest). The investigated core material comes from the borhole number 24 which is located in SE part of the salt crest.

2. Material and methodology of laboratory analyses

Laboratory testing of salts from the Mogilno bed were conducted at the Department of Geomechanics, Building Engineering and Geotechnics, the University of Science and Technology in Kraków in February 2007. Rheological testing lasted longer and it was completed in May 2007. Material for analyses came from the M-24 exploratory borehole drilled in 2006, reaching the depth of 1 923 m. It is over 500 m deeper than boreholes drilled previously in the Mogilno I bed. Several tests were conducted on collected core material and in the borehole in order to determine the geological structure in the immediate vicinity of the borehole (Fig. 2), including:

- — description of lithology, performed by the Dział Mierniczo-Geologiczny IKS SOLINO,
- — profiling, performed by Geofizyka Toruń,

— analyses to determine detailed stratigraphy, performed by the German Institute of Geology (BGR),

— analyses performed at the IKS SOLINO laboratory.

In the course of sampling for the purpose of laboratory analyses, at the turn of 2006 and 2007, a total of 28 sections were selected (NNS), exhibiting diverse lithology from depths ranging from 353.8 to 1 905.8 m. They included twenty rock samples of cyclothem PZ2, represented by grey and light grey rock salt, with varied grain size composition including crystal salts as well as twenty two samples of upper and top surface salt rocks, with varying contents of impurities, including also zubers (clayey salts) and anhydrites. Such a vast variation of rocks is especially evident when analyzing results of weight by volume tests. The values for rock salt ranged from 20.96 to 22.36 kN/m^3, while for anhydrites they were from 28.8 to 29.4 kN/m^3.

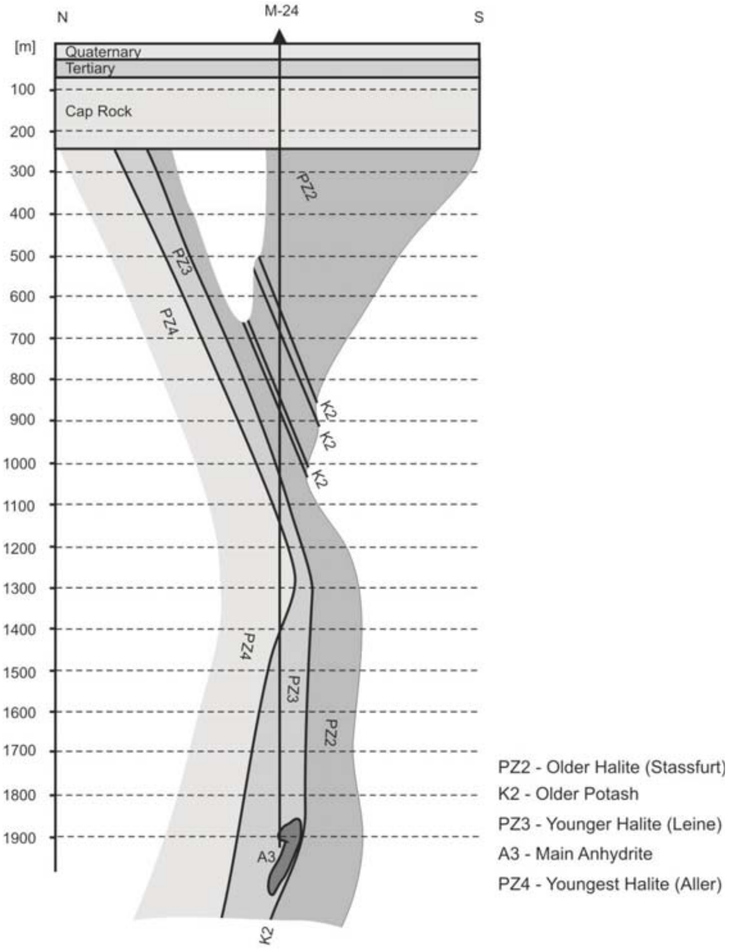

Fig. 2. Geological structure in the area surrounding borehole M-24 (after Bornemann et al. 2006)

Rys. 2. Budowa geologiczna w otoczeniu otworu M-24 (za Bornemann i in. 2006)

Following the method developed at the University of Science and Technology of Kraków 34 test samples with a diameter of 55.0 ± 0.1 mm and height of 110.0 ± 0.1 mm were dry-rolled from the collected core material, preserving bottom parallelism, to be used in uniaxial compression and short-term creep testing.

Material remaining from core cutting was dissolved in deionized water and quantitative and qualitative analyses were performed for insoluble fractions. For all samples percentages of the insoluble fractions were determined, next X-ray examinations were conducted for 6 different lithotypes in order to determine their mineralogical composition. X-ray examinations were performed at the Institute of Geology, the Adam Mickiewicz University of Poznań.

2.1. Uniaxial compression samples

Tests were performed using a universal testing machine with a hydraulic drive, recording axial and radial strain of the sample in the function of applied load, required for the determination of strain parameters of the rock (Grzybowski 2007). In relation with expected anisotropy of radial strain, sensors measuring horizontal strains were mounted in two perpendicular directions, at 1/2 sample height, with the position of sensors selected on the basis of assessed rock structure. Compressive strength was defined as a ratio of maximum force, at which the sample was destroyed or at which axial deformations to the sample cross-section surface were rapidly accelerated.

The effect of these tests was the determination of strain and stress characteristics for each sample, consisting of curves of vertical strain ε_z, horizontal strain ε_r and volumetric strain ε_v in the function of vertical strain. On the basis of their analyses strain parameters were determined following ISRM recommendations:

— Young’s modulus [GPa]: as a mean at strain range of 20–80% R_C

— The Poisson ratio [–]: within a range of transverse strain linearity.

2.2. Short-term creep tests

Creep was tested in an MTS 815 rigid testing machine in the static load control mode. The MTS measuring system facilitates digital recording of strain using extensiometers, e.g. in the form a chain, which measure circumferential strain, i.e. averaged for the entire sample. In this case, in view of anisotropy of radial strain, mechanical displacement indicators were used for measuring purposes, analogously as for uniaxial compression samples. Identical loads were applied for all samples: 8, 16, 24, 32, 40 and 48 kN. Depending on loaded surface, strain values differed slightly for individual samples. Tests lasted for two hours at each load level.

It results from research conducted so far on salt that for pure science purposes the rheological model of salt may be roughly described using the Maxwell creep model, which at steady stress takes the form (Kłeczek 1994):

$$\varepsilon(t)=\frac{\sigma_o}{\lambda}t+\varepsilon_o$$

where:

ε_o – initial strain at $t = 0$, resulting from loading the sample with stress σ_o [Pa],

λ – coefficient of linear viscosity [Pas].

Thus, approximating the creep curve with a straight line, its slope may be interpreted as creep velocity. It also needs to be stressed that numerical values of creep velocity and coefficients of viscosity calculated on their basis, determined in short-term tests, are not actual values found at the phase of steady-rate creep, which may be recorded only in long-term tests (Flisiak 2004). However, they may be fully used to compare the behaviour of individual lithotypes in the time function.

3. Assessment of geomechanical properties of salt rocks from the Mogilno salt dome

3.1. Properties of salt rocks in temporary tests

Analysis of data collected from uniaxial compression testing showed considerable scatter of strength values, which needs to be connected with the lithological facies of the rock (Fig. 3). The biggest effect on the structure of a given rock was found for its strength and dislocation properties and it may generally be assumed that the more fine-grained a given salt is, the stronger it is. It also seems that the content of single fine anhydrite grains has a positive effect on salt strength.

The group of strong rocks is opened by grey, medium- and coarse-grained salts of the PZ2 cycle. Their mean strength is 27.9 MPa. Maximum strength of 37.06 MPa was recorded for a sample collected from the depth of 677 m and it was the highest value for all the tested samples. This was coarse-grained salt with a rather marked content of single anhydrite grains. According to geophysical data, in this interval there was also an elevated content of kieserite. Younger salts collected from the depth of 1 078 and 1 111 m, with anhydrite and clayey impurities, were also strong. Moreover, in the sample from the depth of 1 111 m quartz was also detected in X-ray tests. Strength of these rocks was approx. 35 MPa, i.e. a value comparable with those for both tested anhydrite samples. Salt rocks of the type used in salt lamps, representing the youngest salts (Na4), were weakest. Despite considerable anhydrite contents, especially in sample no. 1283/1, their mean ultimate compressive strength was 25.7 MPa.

Crystal salts, belonging to older salts, yielded inferior results in strength tests. Only one in four tested samples exceeded the limit of 20 MPa, raising their mean strength to 19.7 MPa. Those salts were destroyed very fast due to the formation of fissures at the grain boundary.

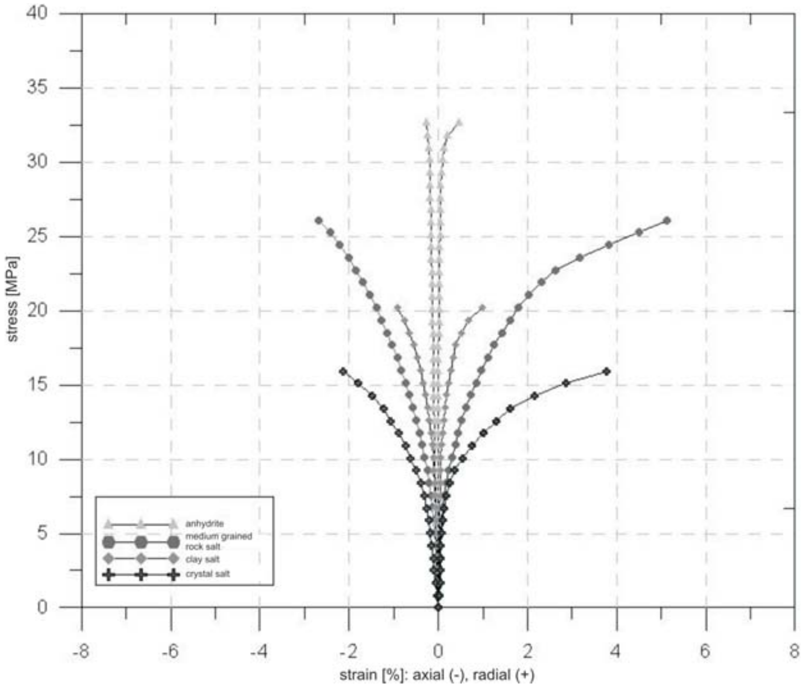

Fig. 3. Stress and strain curves for rocks with different mechanical properties

Rys. 3. Krzywe naprężenie–odkształcenie dla skał o różnych cechach mechanicznych

Such a failure model was also observed in a separately analyzed sample no. 735/1, as a result of one large crystal with a height of 8 cm being found in the mass of coarse-grained salt. The sample failed due to creep embrittlement at a stress of 22 MPa, with smaller grains being scattered and the large crystal remaining intact. This shows clearly that the failure resulted first of all from conditions found at the grain level.

Rocks, also contained in the salt orogen, but exhibiting different geomechanical properties than rock salt, i.e. anhydrite and zuber (clayey salt), were strength tested as well. A primary anhydrite sample (A3) collected at a depth of 1904–1905 m, as it has already been mentioned, exhibited considerable strength in contrast to clayey salt (sample no. 1459/1), which failed at a low stress level of 21 MPa. Much bigger differences between properties of these rocks and rock salt was observed during analysis of strain testing results.

In case of anhydrite, the stress and strain characteristic is generally a straight line, showing its elastic-brittle character. This rock is destroyed at high stress values and relatively low strain values, with sample failure occurring suddenly, with no apparent acceleration, as it is the case with rock salt. Concentration of stress in anhydrite results in the formation of fissures and as a result of layers being cut into individual blocks (Spies et al. 1998). In mining practice this means the risk of collapse in mining workings exploited under layers of anhydrite. It also results from salt mining practice and from the analysis of geomechanical models that the formation of a working in the vicinity of anhydrite rocks may result in the

TABLE 1

Results of uniaxial compression tests

TABELA 1

Wyniki prób jednoosiowego ściskania

Sample	Strati-graphy	R_c [MPa]	Dilatancy boundary R_D [MPa]	R_D/R_c [%]	E [GPa]	$\nu 1$ [–]	$\nu 2$ [–]	$\varepsilon_{z\ \max}$ [%]	$\varepsilon_{r1\ \max}$ [%]	$\varepsilon_{r2\ \max}$ [%]	$\varepsilon_{\mathrm{vol}\ \max}$ [%]
353/1	Na2	16,36	0.84	5.13	1.03	0.38	0.38	2.13	6.66	3.77	8.30
462/1	Na2	23.58	7.58	32.15	1.25	0.17	0.31	2.27	3.04	2.58	3.35
467/1	Na2	26.95	2.53	9.39	1.01	0.27	0.41	2.69	3.55	5.13	5.98
610/1	Na2	17.22	6.03	35.02	1.39	0.33	0.19	1.47	3.33	3.08	4.94
677/1	Na2	37.06	9.26	24.99	1.20	0.14	0.23	4.12	5.09	6.82	7.79
680/1	Na2	33.69	3.37	10.00	1.04	0.39	0.36	3.82	5.55	6.73	8.45
735/1	Na2	22.66	1.68	7.41	1.18	0.45	0.45	2.05	3.41	3.67	5.02
748/1	Na2	17.50	5.83	33.31	1.00	0.43	0.29	2.32	3.83	3.09	4.61
821/1	Na2	27.79	8.42	30.30	1.50	0.25	0.30	2.00	1.81	3.24	3.05
859/2	Na2	26.11	5.90	22.60	1.22	0.50	0.14	2.25	3.64	3.25	4.63
860/1	Na2	29.27	3.34	11.41	1.05	0.48	0.31	3.19	6.05	4.47	7.33
1009/1	Na2k	31.16	5.05	16.21	1.52	0.49	0.49	2.94	5.09	4.00	6.15
1078/1	Na3b3	35.37	5.90	16.68	1.24	0.35	0.37	3.45	4.11	5.78	6.43
1111/1	Na3b5	32.85	2.53	7.70	1.41	0.50	0.50	2.70	3.38	4.84	0.53
1170/1	Na4a1	31.16	6.74	21.63	1.99	0.40	0.31	2.38	5.47	4.67	7.76
1198/1	Na4a2	27.79	4.21	15.15	1.33	0.36	0.46	2.29	2.94	3.90	4.57
1255/1	Na4a3	23.58	3.37	14.29	2.77	0.40	0.32	1.53	4.31	3.82	6.59
1263/1	Na4a3	27.79	6.74	24.25	2.19	0.22	0.44	1.92	2.44	3.95	4.56
1283/1	Na4a3	26.11	6.74	25.81	2.23	0.40	0.21	1.46	3.22	1.71	3.46
1373/2	Na4a2	22.74	4.21	18.51	1.25	0.34	0.48	2.27	4.60	5.44	7.78
1408/1	Na4a1	26.95	5.05	18.74	1.54	0.14	0.42	2.03	2.45	3.73	4.15
1459/1	Na3t	21.06	9.26	43.97	2.93	0.39	0.50	0.91	0.89	0.98	0.95
1721/1	Na3b	21.90	2.53	11.55	1.77	0.29	0.44	1.69	2.78	3.56	4.65
1904/1	A3	35.25	16.72	47.43	16.26	0.44	0.50	0.31	0.83	0.91	1.42
1905/1	A3	32.61	22.58	69.24	17.78	0.50	0.31	0.26	0.43	0.47	0.64

generation of fissures, which in consequence leads to an increase in rock mass permeability (Kamlot in: Spies et al. 1998), which is precisely what engineers designing underground storage facility are especially anxious to avoid.

In contrast to anhydrite, in situ rock salt does not have fissures, which is a consequence of its plastic properties. In temporary tests it undergoes non-linear deformation throughout the entire range of stress values and uniaxial compression load tests showed a practically negligible share of elastic strain. Following the methodology given above, the following parameters: Young's E modulus and the coefficient of transverse strain, were applied in the description of strain properties. Values of modulus of longitudinal strain are quite similar for rock salts, being relatively low, below 2 GPa. Rocks with higher values of the moduli contain larger amounts of impurities, such as zuber, anhydrites as well as salt rock type used to produce salt lamps (1283/1). Due to the fact that rock salt exhibits relatively high anisotropy of radial strain, the Poisson ratio was determined in two perpendicular directions. Anisotropy of strain was probably connected with textural properties of rocks, as measured by the difference between established values of the Poisson ratio. However, this problem should be considered on the basis of a larger number of tested samples.

Deformation properties, similarly as in case of strength properties, exhibit considerable scatter of values. The strongest salts were deformed most, and thus for sample no. 677/1 radial strain was 6.82%, which was recorded as the highest value. It needs to be stressed that all salt samples exhibited larger horizontal than vertical strain Considerable strain was also observed in crystal salt samples, in spite of slight strength. It is connected with the potential of large crystals to be easily loosened and next ejected from sensor mounting sites. The phenomenon of ejection of larger crystals from the surrounding salt mass was also observed in medium-grained salts.

Rocks containing large amounts of anhydrite yielded to low values of strain. An example in this respect may be a sample of rock salt of the salt lamp type, collected from a depth of 1283 m, where radial strain was slightly over 3%, while axial strain was respectively lower, i.e. approx 1.5%. Obviously, an extreme example may be primary anhydrite with the $CaSO_4$ content of approx. 85% (sample no. 1904/1), where strain values did not exceed 1% initial diameter or height.

The recorded fact that – starting from a certain stress value – horizontal deformations are larger than vertical ones means that the process of deformation in tested samples is accompanied by an increment in volume. This effect, known as dilatancy, in tested rock salt illustrates effectively the fissuring deformation model by Nur (Nur, in: Kwaśniewski 1986). It assumes that initially closed microfissures become open again as a result of slip with friction, e.g. at grain boundaries. With an increase in stress frictional resistance is overcome in an increasing number of microfissures and thus increasing numbers of slips are initiated. It results in an increase in rock volume, being the larger, the larger stress it is subjected to. The opinion, expressed by Kwaśniewski (1986) that dilatancy appears at limits close to yield point and precedes the failure of the rock medium, is not confirmed in the tested rock salt samples. In this case dilatancy occurs both at values of 0.05 R_c (sample no. 353/1) (Fig. 4)

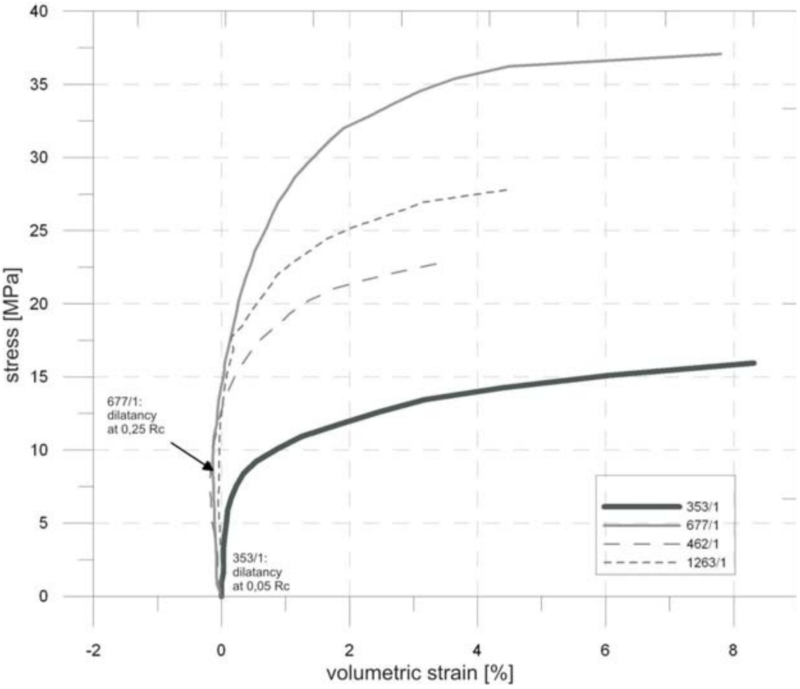

Fig. 4. Curves of volumetric strain for different salts

Rys. 4. Krzywe odkształceń objętościowych dla różnych soli

and 0.35 R_c (610/1). It needs to be stressed that this variation is manifested not only within the same stratigraphic group, but even in rocks with a similar structure. However, in most cases the absolute increase in volume occurs at stress of approx. 0.2 R_c, whereas for zuber and anhydrites it is much higher and thus for sample no. 1905/1 (anhydrite) it is as much as 0.7 R_c.

3.2. Properties of salt rocks in rheological tests

Following the methodology presented above seven short-term creep tests were conducted. Testing was carried out on rock salts representing three cyclothems found in the Mogilno salt dome. Additionally samples differed in terms of their lithological facies, including colour, grain size as well as the amount and distribution of impurities. As a result creep curves were plotted with a large degree of variation, for which several common objections may be formulated. An increment in stress was accompanied by a disproportionate increment in strain, indicating non-linearity of the rheological model of rock salt. Analysis of obtained results shows that even at lowest stress values creep does not disappear.

Creep velocity as well as the level of abrupt strain after loading strongly depend on the lithological facies of a given rock. Variation includes both salts from different cyclothems and the analyzed group of older salts. Figure 5 presents creep curves for seven salt samples with information on their stratigraphy. The biggest value of initial strain was recorded for

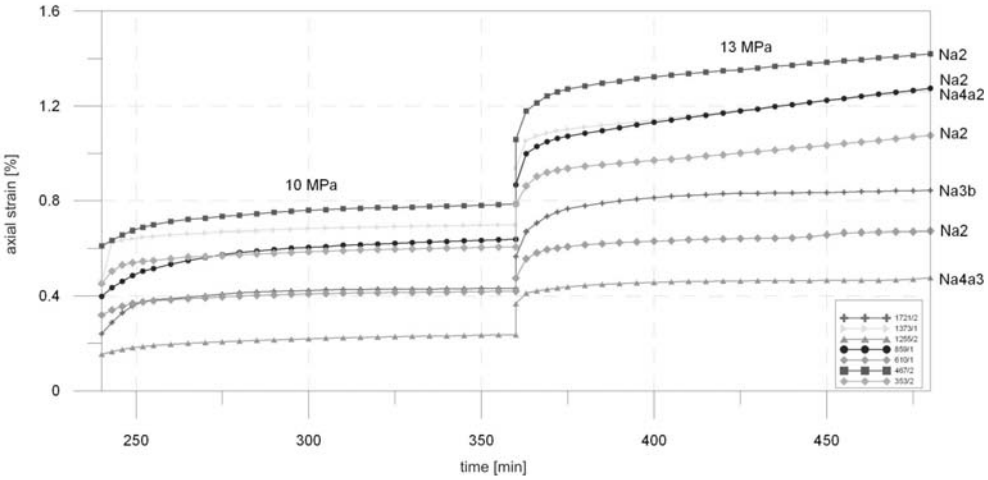

Fig. 5. Creep curves for salt samples with their stratigraphy

Rys. 5. Krzywe pełzania próbek soli z zaznaczeniem ich stratygrafii

sample 467/2 belonging to the group of older salts. The smallest deformability in the analyzed set was found for salt type used to produce salt lamps (1255/2), belonging to the youngest salts, which may be connected with elevated contents of impurities. It should be emphasized here that curves representing older salts (Na2) had higher values of initial strain and bigger creep velocity, except for the curve plotted for sample 610/2, exhibiting a similar slope as the above mentioned sample 1255/2. Samples of the core collected from a depth of 610 m contained rather high amounts of impurities (approx. 5%) in the form of streaks, which may explain the course of this curve on the graph.

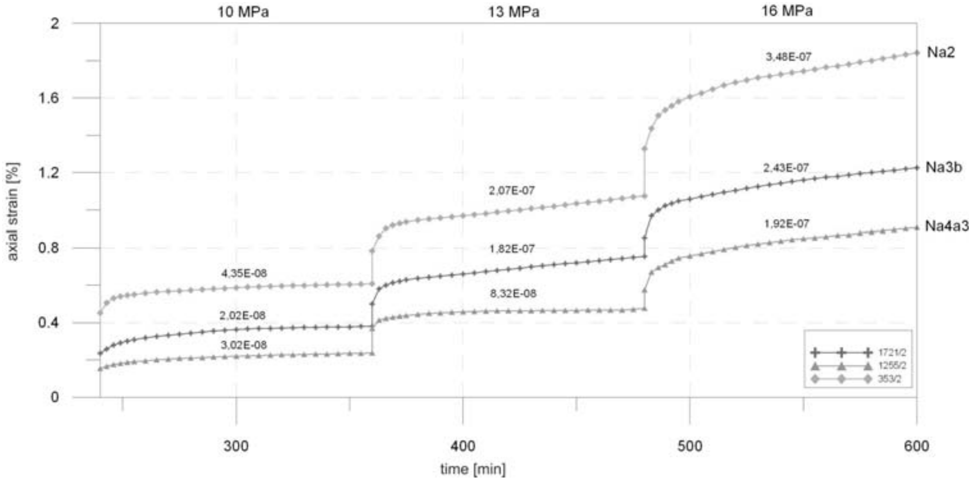

Fig. 6. Creep curves for three samples with creep velocity [1/s]

Rys. 6. Krzywe pełzania trzech próbek z zaznaczeniem prędkości pełzania [1/s]

The next graph (Fig. 6) shows differences in rheological characteristics of individual samples with different stratigraphy in the context of a wider stress range. Additionally, calculated creep velocities were also plotted here. The number and form in which impurities may be found may have a decisive effect on the character of salt creep, thus older salts as the "purest" exhibit different properties than the other salts.

4. A comparison of recorded results with properties of salts from other facies

Available archive data were used to compare results of this study with parameters of other investigated salt beds. Geomechanical properties of described facies presented there are based mainly on studies of grey rock salt, i.e. apparently older. Unfortunately, the fact that detailed descriptions of lithology and stratigraphy are not included in archive materials makes it impossible to conduct direct comparisons of identical lithotypes. Another problem is connected with diverse research methodologies adopted by authors of individual studies (e.g. different sample sizes), which affects collected results.

Among all salt beds the biggest number of geomechanical studies was conducted on the Góra diapir. Intensive mining works carried out in the Góra salt bed for many years as well as the operation of the underground fuel storage facility resulted in the preparation of around fifteen geomechanical studies. On their basis strength properties of salt from this bed are considered advantageous, even more so than salts from the underground gas storage in Mogilno (Brańka et al. 2006).

The first immediate tests of rock salt from Góra were conducted in 1972. They included white and pink rock salts from five boreholes. The research method applied at that time assumed the application of uniaxial compression tests on samples with slenderness ratio $\lambda = 1$, whereas present standards recommend, especially for salt, slenderness ratio $\lambda = 2$. As a result recorded results are most probably inflated.

For the purpose of geomechanical evaluation of storage chambers in the Góra salt bed laboratory analyses of salts from two boreholes were conducted in 1998 (Kortas et al. 1999) and it was found that their properties do not differ markedly from those of salts from other beds. Uniaxial compressive strength ranged from 24.4 MPa to 39.1 MPa, on average 29.7 MPa from thirty tested samples, while final strain ranged from 1.8 to 3.3%.

Further drillings in the Góra bed provided more research material to assess geomechanical properties of rocks from that bed. Results of tests conducted in 2002 were presented in the geological and engineering documentation for the underground fuel storage facility in Góra (Brańka et al. 2006). Considerable uniaxial compressive strength of pink salt needs to be stressed (over 40 MPa). It may be assumed that it is a younger or the youngest salt. Geophysical data and chemical analyses from the interval of the occurrence of this salt in borehole G-23 do not suggest any unusual mineral or chemical composition. For comparison, the youngest lamp-type salt in the course of tests performed in this study exhibited much lower strength.

The adopted research methodology, developed at the Department of Geomechanics, Building Engineering and Geotechnics, the University of Science and Technology in Kraków (Kłeczek et al. 1986), made it possible to compare the results with those from this medium (Table 2). Analyzed rock salt did not differ much from salts from other beds. The biggest differences in deformation properties were manifested when comparing Young's modulus E. It may be assumed that salts from the Góra and Dębina beds (E < 1 GPa) are more susceptible to plastic strain than salt from Mogilno, which was also recorded by other authors (Brańka et al. 2006; Flisiak 2004).

TABLE 2

Physical and mechanical parameters of rock salts from different beds

TABELA 2

Fizyczne i mechaniczne parametry soli kamiennej z różnych złóż

Salt bed	Unit weight [kN/m^3]	R_c [MPa]	E [GPa]	Poisson's ratio
Mogilno II	21,60	19,30–35,90	2,2–3,5	0,17–0,49
Sieroszowice	21,20	34,00	5,90	0,21
Góra:				
white fine-grained salt	22,00	33,70	1,14	0,15
white coarse-grained salt	21,50	28,20	0,88	0,22
pink salt	22,00	41,40	12,26	0,22
Lubień Kujawski	21,20	–	1,92	0,45
Dębina	21,49	37,30	0,65	0,48
Mogilno I:				
grey medium- and coarse-grained salt	21,60–21,74	23,50–37,10	1,01–1,52	0,14–0,49
lamp-type sal	21,79–22,36	23,60–27,80	2,19–3,20	0,21–0,44

6. Concluding remarks

Geomechanical properties of salt rocks are an interesting and at the same time highly complicated issue, analyzed in this paper. The primary research problem was to determine numerical parameters defining physical properties of specific types of salt rocks, especially to generate their stress and strain characteristics. Individual lithotypes were compared and then results were referred to parameters from other analyzed salt beds.

Laboratory analyses of rock salt in Poland are rare. This results from their being time-consuming, laborious and requiring unique equipment. Results presented here have considerable value for pure science, although they may not be used in case of engineering calculations. It takes up to several months to obtain results which may be used in practical applications.

A detailed recapitulation of this study is contained in the following conclusions:

1. The behaviour of analyzed rocks in conducted tests did not differ from that of rock salts from other beds. A large scatter of values between individual lithotypes needs to be stressed, which is probably connected with rock texture.
2. The most advantageous strength properties were found for older rock salts. The youngest salts yielded worst results in uniaxial compression tests. Highly disadvantageous properties were recorded for older crystal salts, where slacking of the crystal structure occurred at low stress values.
3. Compression of samples is accompanied by considerable strain, with radial strain being bigger than vertical strain already at slight stress values. The participation of elastic strain in total strain was very small.
4. Anhydrite and silty salts need to be classified to rocks with completely different mechanical properties. Their characteristics over almost the entire load range may be approximated with a straight line.
5. Rock salts exhibit rather considerable strain anisotropy. This might be the effect of crystal anisotropy. In crystal salts it was additionally enhanced by easy loosening of individual crystals.
6. Dylatancy occurs at stress from 5 to 30% strength. In this respect the scatter of numerical values is large even for rocks with similar lithological facies. In anhydrite and silty salt an increase in volume occurs at higher stress. This effect is connected with an increase in rock permeability, which is especially important when using salt beds for storage facilities.
7. Calculated creep velocities showed a non-linear dependence on the applied load. Moreover, they probably depend on rock lithology, where pure salts had the highest strain increments. The dependence of creep on rock stratigraphy, described in literature sources, is also connected with lithology, with the decisive effect of the share and distribution of impurities.
8. A comparison of strength testing results with parameters of other beds did not show considerable differences. However, it seems that salts from Góra are on average stronger than those from Mogilno. In this context we have to emphasize different research methods used in laboratories, which have an effect on the recorded results.
9. Values of short-term creep velocity are much higher than those for long-term tests and may not be used in model calculations. Such calculations also have to include the current state of geological and engineering conditions. Thus, it is necessary to obtain the biggest possible amount of information on lithology and mechanical characteristics of all rocks contained in the salt orogen.

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WŁAŚCIWOŚCI MECHANICZNE CECHSZTYŃSKICH SKAŁ SOLNYCH Z WYSADU MOGILNO

Słowa kluczowe

Skały solne, testy laboratoryjne, wytrzymałość i odkształcalność, litologia, wysad Mogilno

Streszczenie

Właściwości soli kamiennej stanowią interesujący temat badawczy dla wielu naukowców na całym świecie, a od szeregu lat obserwuje się wzrost zainteresowania tą problematyką. Wiązać to należy z możliwością lokalizowania w górotworze solnym różnych obiektów strategicznych m.in. składowisk odpadów czy magazynów substancji użytecznych. Do tego celu szczególnie nadają się cechsztyńskie wysady solne występujące na Niżu Polskim. Duże miąższości mas solnych, ich zwięzłość oraz chemiczna obojętność umożliwiają bezzbiornikowe magazynowanie substancji ropopochodnych i gazów.

Z punktu widzenia długotrwałej stateczności magazynu, konieczna wydaje się geomechaniczna ocena górotworu dla znajomości jego zachowania się w warunkach rzeczywistych. Zwykle ocenę taką przeprowadza się za pomocą modelowania numerycznego opierając się na wynikach badań laboratoryjnych, uśrednionych na całe złoże. Skomplikowana tektonika oraz zróżnicowana litologia w obrębie wysadu solnego powoduje konieczność generalizacji złoża, a więc i otrzymanych parametrów mechanicznych. W rzeczywistości skały wchodzące w skład górotworu solnego znacznie różnią się od siebie, zwłaszcza właściwościami geomechanicznymi.

Artykuł przedstawia wyniki badań nad właściwościami geomechanicznymi skał z wysadu solnego Mogilno, na podstawie badań laboratoryjnych, w których skupiono się na wyznaczeniu zależności między stanem naprężenia i stanem odkształcenia oraz przebiegu procesów reologicznych dla różnych typów skał. Do realizacji takiego celu wybrano badania jednoosiowego ściskania i pełzania, ponieważ w różnych laboratoriach całego świata to najczęściej one stanowią podstawę do określenia właściwości geomechanicznych. Uzyskane parametry posłużyły także do porównania ich z solami innych, lepiej rozpoznanych struktur. Złoże soli kamiennej

„Mogilno I", stanowiące południowo-wschodnią część struktury, nigdy nie było rozpoznawane pod kątem laboratoryjnych badań geomechanicznych, pomimo ponad dwudziestoletniej historii robót górniczych na tym obszarze. Badania takie wykonywane były jedynie dla złoża „Mogilno II" (Kłeczek, Flisiak 1986), gdzie zlokalizowany jest podziemny magazyn gazu. Badania właściwości mechanicznych soli prowadzono również dla złoża Lubień Kujawski (Kłeczek i in. 1978) oraz wysadu Góra, dla którego zrealizowano największy zakres badań (Kortas, Brańka 1999; Branka i in. 2006).

Badania laboratoryjne właściwości mechanicznych soli zostały przeprowadzone w Katedrze Geomechaniki, Budownictwa i Geotechniki Akademii Górniczo–Hutniczej w Krakowie (Grzybowski 2007). Materiał do badań pochodził z odwierconego w 2006 roku otworu badawczo-eksploatacyjnego M-24 do głębokości 1923 m, czyli o ponad 500 m głębiej niż otwory odwiercone dotychczas w złożu Mogilno I. Ponadto wykonano inne badania rdzenia wiertniczego: makroskopowy opis litologii, analizy bromowe i analizy chemiczne, a także profilowanie geofizyczne w otworze, mające na celu rozpoznanie budowy geologicznej w bezpośrednim otoczeniu otworu (rys. 2).

Do badań laboratoryjnych wybrano 28 odcinków (NNS) o zróżnicowanej litologii z przedziału głębokości 353,8–1905,8 m. Wśród nich skały cyklotemu PZ2, reprezentowane przez sól kamienną szarą i jasnoszarą, różnoziarnistą z solami kryształowymi włącznie, skały soli młodszych i najmłodszych, w różnym stopniu zanieczyszczonych, także zubry (sole ilaste) oraz anhydryty. Tak duża różnorodność skał jest szczególnie widoczna podczas analizy wyników badań ciężaru objętościowego. Rozrzut wartości dla soli kamiennej wynosi od 20,96 do 22,36 kN/m^3, a dla anhydrytu od 28,8 do 29,4 kN/m^3.

Zgodnie z metodyką opracowaną w AGH, z rdzenia wykonano 34 próbki o średnicy 55,0 ± 0,1 mm i wysokości 110,0 ± 0,1 mm, metodą toczenia na sucho, z zachowaniem równoległości podstaw i przeznaczono do testów jednoosiowego ściskania i krótkotrwałego pełzania. Materiał, który pozostał z cięcia rdzenia, rozpuszczono w wodzie dejonizowanej i dla części nierozpuszczalnych wykonano analizę ilościową oraz jakościową. Dla wszystkich próbek określono procentowy udział frakcji nierozpuszczalnej, następnie dla 6 różnych litotypów wykonano badania rentgenowskie, dla ustalenia składu mineralnego. Badania RTG zostały wykonane w Instytucie Geologii UAM w Poznaniu.

Efektem prób jednoosiowego ściskania było określenie naprężeń niszczących R_c, granicy dylatancji oraz charakterystyki deformacyjno-naprężeniowej dla każdej próbki. Na podstawie analizy przebiegu krzywych odkształceń pionowych ε_z, poziomych ε_r i objętościowych ε_v określono parametry odkształceniowe zgodnie z wytycznymi ISRM: moduł Younga, jako średni w przedziale naprężeń 20–80% R_c oraz liczbę Poissona w zakresie liniowości odkształceń poprzecznych (tab. 1 i rys. 3).

Próby pełzania zrealizowano jako testy krótkotrwałe, ze stopniowym dociążaniem po każdym etapie dwugodzinnego pełzania. Mając na uwadze stwierdzoną w próbach jednoosiowego ściskania anizotropię odkształceń radialnych, ich pomiar wykonywano w dwóch wzajemnie prostopadłych kierunkach, ustalając je na drodze oceny makroskopowej ułożenia ziaren. Wszystkie próbki były obciążone jednakowymi siłami osiowymi: 8, 16, 24, 32, 40, 48 kN. W wyniku określono prędkości pełzania zależnie od stratygrafii i wielkości naprężeń (rys. 5 i 6).

Analiza wyników badań i ich odniesienie do właściwości mechanicznych soli kamiennej z innych złóż (tab. 2) pozwoliły na sformułowanie zarówno szczegółowych wniosków o związku wykształcenia litologicznego z zachowaniem się próbek, jak i wniosków o charakterze ogólnym. W szczególności stwierdzono, że zachowanie się badanych skał w przeprowadzonych próbach nie odbiega od zachowania soli kamiennych z innych złóż. Zwraca uwagę duży rozrzut wartości pomiędzy poszczególnymi litotypami, co zapewne ma związek ze strukturą skały. Największą wytrzymałość posiadają starsze sole kamienne, słabsze są sole najmłodsze. Bardzo niekorzystne właściwości wykazują sole starsze kryształowe, gdzie rozluźnienie struktury krystalicznej następuje przy niskich wartościach naprężeń. Ściskaniu próbek towarzyszą duże deformacje, przy czym udział odkształceń sprężystych w całkowitym odkształceniu jest bardzo mały. Sole kamienne wykazują znaczącą anizotropię odkształceń, co być może jest efektem ukierunkowania kryształów. W solach kryształowych dodatkowo potęgowane jest to poprzez łatwe odspajanie się od siebie pojedynczych kryształów. Dylatancja pojawia się przy naprężeniach od 5 do 30% wytrzymałości, przy czym rozproszenie wartości liczbowych jest duże nawet w przypadku skał o podobnej budowie litologicznej. Obliczone prędkości pełzania wykazują nieliniową zależność od przyłożonego obciążenia. Ponadto zależy ona od litologii skały, przy czym decydujący wpływ ma udział i rozkład zanieczyszczeń, a czyste sole osiągają największe przyrosty odkształceń.

Do skał o zupełnie innych właściwościach mechanicznych należy zaliczyć anhydryt i sole ilaste. Ich charakterystyki można prawie w całym zakresie obciążeń przybliżyć linią prostą, a wzrost objętości następuje przy wyższych naprężeniach.

Zróżnicowanie wartości liczbowych poszczególnych parametrów wskazuje, że do obliczeń modelowych należy także uwzględniać aktualny stan warunków geologiczno-inżynierskich. W związku z tym we wszystkich nowych otworach jest niezbędne uzyskiwanie jak największej ilości informacji odnośnie litologii oraz charakterystyki mechanicznej wszystkich skał wchodzących w skład górotworu solnego.

MECHANICAL PROPERTIES OF ROCK SALT FROM MOGILNO SALT DOME

Key words

Rock salt, laboratory tests, strength and deformability, lithology, Mogilno salt dome

Abstract

The study presents results of laboratory testing of geomechanical properties for different rock types from the Mogilno salt bed, focusing on the determination of a dependence between the state of stress and the state of strain and on the description of the course of rheological processes. To realize this objective it was decided to study uniaxial compression and creep, constituting the basis for the determination of geomechanical properties. Recorded parameters were also used for comparison with those of salts in other bed structures. The Mogilno I rock salt bed, constituting the south-eastern part of the structure, had never been investigated in laboratory testing of geomechanical properties, in spite of the 20-year history of mining works in that area. Such studies were performed for the Mogilno II bed, where the Mogilno Underground Cavern Gas Storage Facility is located.

The behaviour of analyzed rocks in conducted tests did not differ from that of rock salts from other beds. A large scatter of values between individual lithotypes needs to be stressed, which is probably connected with rock texture. Results presented here have considerable value for pure science, although they may not be used in case of engineering calculations. Such calculations also have to include the current state of geological and engineering conditions. Thus, it is necessary to obtain the biggest possible amount of information on lithology and mechanical characteristics of all rocks contained in the salt orogen.