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The Cutting Resistance of Rock Salt in Function of Temperature

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INTRODUCTION

Underground rock salt mining currently accounts for about a sixth of the global production of this resource. Depending on the form of deposition, geological and mining conditions and sediment purity, salt deposits can be exploited in several ways (Andrusikiewicz 2008, Poborska-Młynarska 2015), using both blasting and mechanical techniques. Salt rocks usually exhibit poor or average strength, depending on mineralogical and petrographic properties. In addition, their elastic-plastic behaviour in terms of strain-stress characteristics is not a typical rock behaviour, causing continuous strains as a function of time (Kolano & Flisiak 2013, Phatthaisong et al. 2018, Yintong et al. 2012).

During salt rock excavation using mechanical methods, the cutting tools come into contact with the rock mass, producing friction and, consequently, an increase in temperature (Powell, 1969). In many cases the rock salt deposits lie at great depths, where the temperature of the surrounding rocks sometimes reaches or even exceeds 50° C. Hence, before solid salt rock can be excavate by milling, the rock’s cuttability and strength must be investigated, including at increased temperatures (Andrusikiewicz 2008, Yetkin et al. 2016, Raghavan & Murthy 2018, Małkowski & Kotwica 2019).

In the literature can be find information on mechanical alterations in salt due to changes in temperature. For example, it was reported that compressive strength at temperatures up to 200°C increases logarithmically (Ostadhassan & Tamimi 2014). For the same temperature value was demonstrated that a considerable increase in temperature caused a linear decline in both the compressive and tensile strength of salt rock mass (Sriapai et al. 2012). In the same conditions the elasticity, expressed by the Young's modulus, might decline by half, whereas transverse strain, expressed by Poisson's ratio, usually increases by more than 10 percent (Iverson et al. 2012, Sartkaew & Fuenkajorn 2013, Phatthaisong et al. 2018).

Since the rise in temperature of the rock mass due to friction by cutter heads is short-lived and localized, no such significant increases in temperature are

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recorded. During the tests, the results of which are presented in the article, the measurements of the cuttability index and the side chipping angle for three different temperature values - 20, 50 and 80°C were carried out (Małkowski et al. 2019). Also, the same tests were performed after cooling of rock salt sample to room temperature. The tests were carried out on the special laboratory test stand. The selected mechanical parameters of rock salt – compressive, tensile and shear strength were also measured for the same temperature values and compared with results obtained in the first part of tests. The sample temperature measurements during the tests were also made using thermography camera. The tests were performed on the samples of Miocene salt from a Carpathian region. This salt is comparable to the salt deposed in the south region of Poland. The tested rock salt sample was not a pure salt sample. In the salt sample was included 99.7 percent halite. Other identified minerals included anhydrite and potassium and iron aluminosilicates – most likely clay minerals. It caused problems when collecting cylindrical samples from the salt block. When drilling with a Trepaner drill, these samples have cracked and split laterally into rings. This destroyed sample is shown in Figure 1. This caused that cubic and cuboid samples with a side of 50 mm at the base were cutted from the salt block.

Fig. 1 View of destroyed sample after drilling using a Trepaner drill

TESTS OF CUTTABILITY RESISTANCE

The tests for determination of cutting resistance were carried out on the special laboratory test stand presented in Figure 2. This stand allows the recording value of forces components of the rock salt sample's cutting resistance.

Fig. 2 View of special laboratory test stand for cutting resistance tests with a strain-gauge head

The cutting resistance laboratory test stand consists of a horizontal shaper, a strain-gauge head (test cutter handle) fitted with a standard test radial pick, and a rock-sample specimen holder on the shaper table. The signals from the gauge head are sent through conductors via the strain-gauge amplifier to the measurement computer for recording and further processing and analysis (Małkowski et al. 2019).
The laboratory test to determine the cuttability index A and the side chipping angle ψ involved making open cuts in the rock samples using a standard test cutter. The cutting depth was predefined. The tests were designed to measure the components of the cutting resistance (Ps – cutting force, Pd – pressure force, Pb – side force). The cuts after mining were measured to determine the actual cutting depth g_s and cutting width b_s. The resulting values Ps, Pd, Pb, g_s and b_s could then be used to determine the cuttability index A (the ratio of the resultant cuttability resistance and the cutting depth) and the side chipping angle ψ (the ratio of the opening-cut width difference arctangent and the double cutting depth).
The cutting tests were performed on the big dimension rock salt sample (350 x 200 x 200 mm) for the temperatures of 22°C and about 50°C and 80°C. The salt sample was heated into desired temperature in an oven. The sample temperature was controlled on the test stand directly before the measurement, after the sample's surface was even. The measurements were taken on cuts with a depth of g_s = 5 mm at the cutting speed v_s of about 1 m/s. Each consecutive cut was made at a scale interval t_s of at least 30 mm. Also, thermographic images were captured during the cutting tests. The views of obtained cuts for cutting depth of 5 mm, with temperature about 22°C and about 80°C are shown in Figure 3.

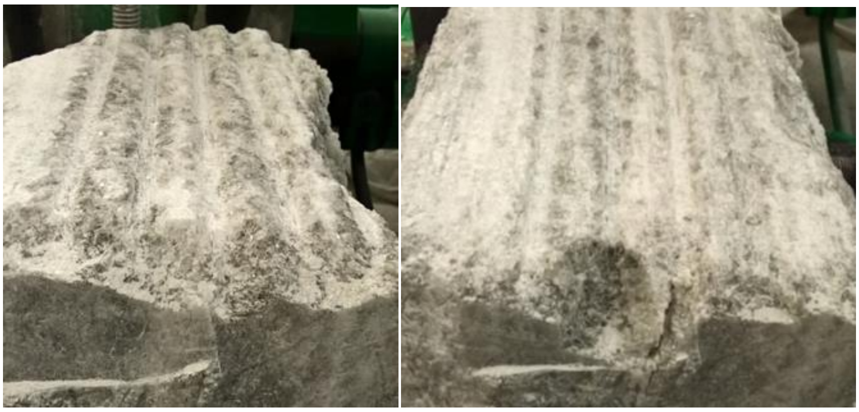

Fig. 3 View of obtained cuts for cutting depth of 5 mm, with temperature about 22°C (left) and about 80°C (right)

The Figure 4 thermograms of the salt sample after cutting in three different temperatures are presented. The real temperature value was about 22.5°, 55° i 72°C. On the thermographs can be observed that at 22°C the cut surface temperature rose to about 27.5°C along its entire length, at 55°C, the temperature rose only in the end section of the cut – by 4°C and at 72°C the cut surface temperature rose up to 82°C.

a) b) c)

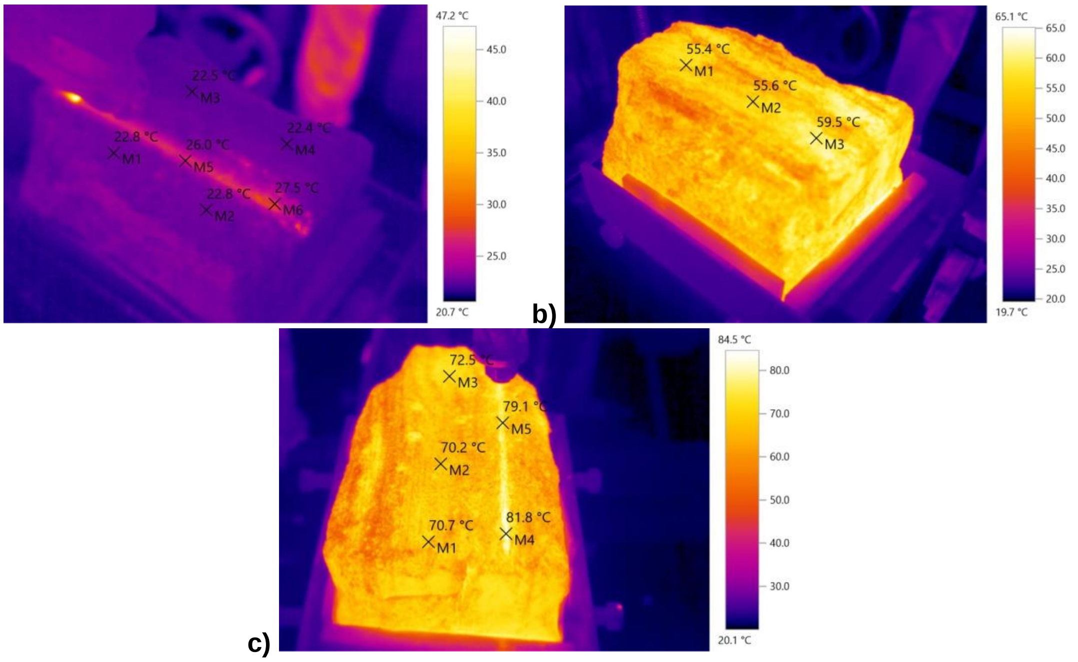

Fig. 4 Thermograms of a sample surface and performed cut during cutting with temperature: a) 22,5°C, b) 57°C and c) 72°C

After the salt sample has cooled to about 20°C, a cutting test was carried out for a cut depth g_S of approximately 5, 7 and 10 mm. The sample was cooled about 48 hours. The surface of the sample with these cuts (from the left in turn g_S 5, 10 and 7 mm) is shown in Figure 5. Further tests were not possible because on the sample crack along its entire height was observed, which caused the sample splitting into two parts.

Fig. 5 View of the sample with the cuts (depths in turn from the left g_S 5, 10 and 7 mm) made at a temperature of about 20°C, after cooling the sample

The graphs in Figure 6 show registered examples courses of Ps, Pd and Pb force values for cuts with a depth of 5 mm at temperatures 22.5°, 55° i 72°C and a cut with a depth of 10 mm for temperature 20°C after sample cooling.

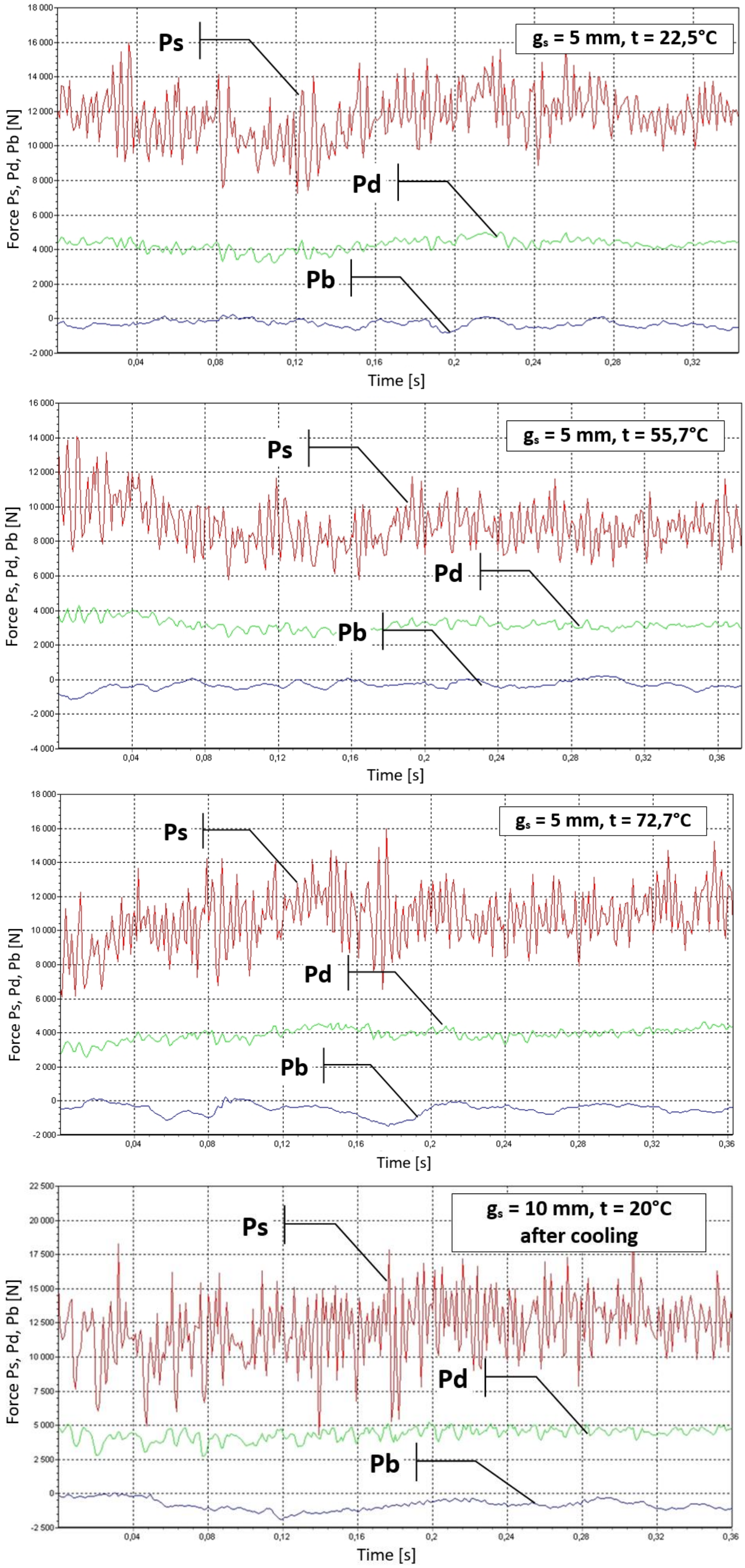

Fig. 6 The courses of Ps, Pd and Pb force values for cuts with a depth of 5 mm at temperatures 22.5°, 55° and 72°C and a cut with a depth of 10 mm for temperature 20°C after sample cooling

The charts show only sections during steady work, without starting and ending cutting. On Figure 7 the courses of Ps force value were compared for cutting depth 5 mm and three different sample temperature and for the same cutting depth after sample cooling. Based on recorded force courses and measurements of the obtained cuts the average values of cuttability index A and the side chipping angle ψ were estimated. These values are given below.

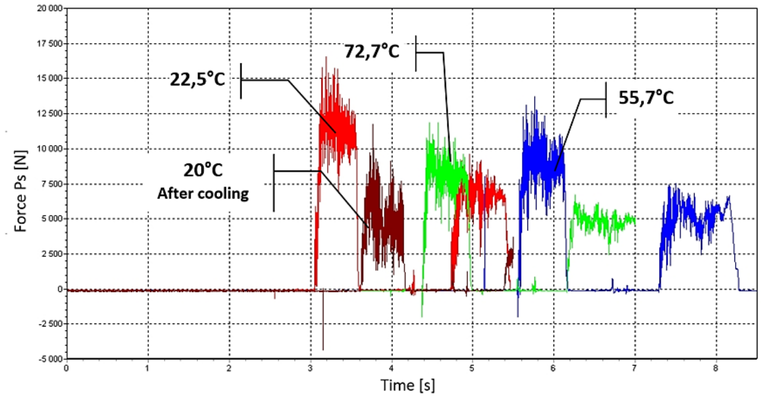

Fig. 7 Ps force value for cutting depth 5 mm for three different sample temperature and after sample cooling

The average value of cuttability index A and the side chipping angle ψ for three different sample temperature and cutting depth g_s = 5 mm:

- 22°C – A = 2192 kN/cm, ψ= 55.8°,
- 55°C – A = 1742 kN/cm, ψ= 51.2°,
- 72°C – A = 1653 kN/cm, ψ= 48.7°.

The average value of cuttability index A and the side chipping angle ψ for three different cutting depth after cooling the sample:

- 20°C (g_s = 5 mm) – A = 917 kN/cm, ψ = 48.7°,
- 20°C (g_s = 7 mm) – A = 1497 kN/cm, ψ = 51.2°,
- 20°C (g_s = 10 mm) – A = 1579 kN/cm, ψ = 53.4°.

Taking into consideration the data on the workability degree of a given material depending on the on the cuttability index A and the side chipping angle ψ, based on the coal cuttability index presented in Table 1 (Biały W, 2005, Biały W, 2009, Biały W, 2011) it can be stated that at room temperature, the tested salt sample qualifies for medium workable materials.

Table 1 The degree of workability depending on the cuttability index A and the side chipping angle ψ

Cuttability index A [kN/cm]	Side chipping angle ψ [°]			Degree of workability
	Ψ > 70°	40° < Ψ ≤ 70°	Ψ ≤ 40°	
A ≤ 1,8	I	-	-	easily workable
1,81 < A ≤ 3,0	-	II	-	medium workable
A > 3,01	-	-	III	hard to workable
	Brittle rock	Compact rock	Very compact rock	

After heating to 50°C it becomes an easily workable material, except that the value of the side chipping angle ψ instead of increasing decreases. After overheating and cooling the salt sample, its cutting resistance clearly decreases. Compared to the values obtained at 20°C, the cuttability index A decreases more than twice, with a side chipping angle ψ comparable to measurements performed at 72°C. On the other hand, the cuttability index A values obtained for a cutting depth of 7 and 10 mm are about 10% lower than for measurements for 5 mm deep cuts made at 72°C.

TESTS OF SELECTED MECHANICAL PARAMETERS

As was mentioned the additionally tests were carried out for determination of selected mechanical parameters – compressive σ_c, tensile σ_r and shear strengths σ_s. There tests were performed using cubic and cuboid samples with a side of 50 mm at the base (Małkowski et al. 2019). Four to eight determinations per parameter were made for each sample at pre-defined temperatures of 20, 50 and 80°C. Compressive strength σ_c was determined according to the PN-G 04303:1997 standard. The tensile strength σ_r was determined using the transverse compression method (the so-called Brazilian test) according to the PN-G 04302:1997 standard. Shear strength σ_s was tested using a method proposed by ISRM in 1975 involving an induced shear angle of 45°.
This involved compressing the sample in special moulds with one washer that adjusted the concentric alignment of the moulds to ensure equal shear area. View of the tested samples after the tests of compressive, tensile and shear strength is shown in Figure 8.

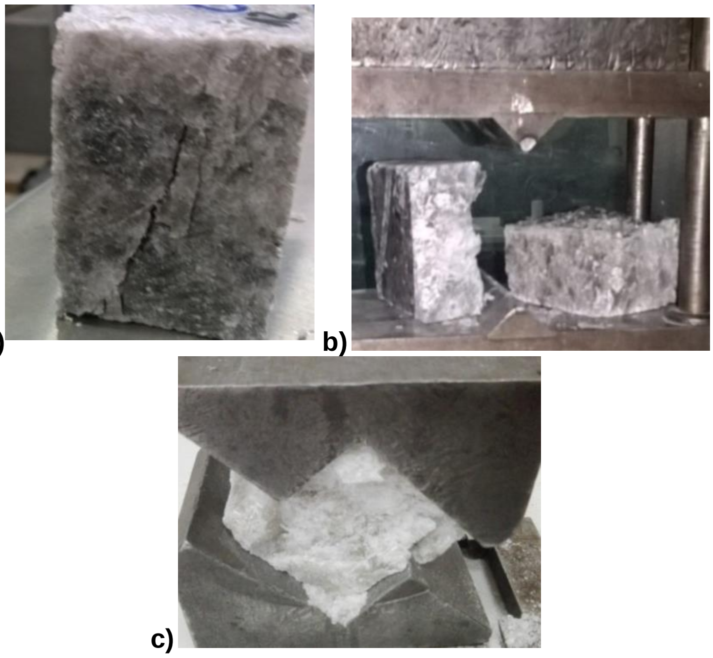
a) b) c)

Fig. 8 View of tested samples after the tests of:
a) compressive strength, b) tensile strength and c) shear strength

During the tests, the outer temperature, as well as the inner temperature were being monitored continuously with a thermographic camera. Thermograms of the samples after compressive σ_c and tensile strength σ_r test s performed in temperature 50°C are shown in Figure 9. It can be seen that the surface and inside temperature of the sample was comparable. The temperature drop was not greater than 1°C in 3-4 minutes.

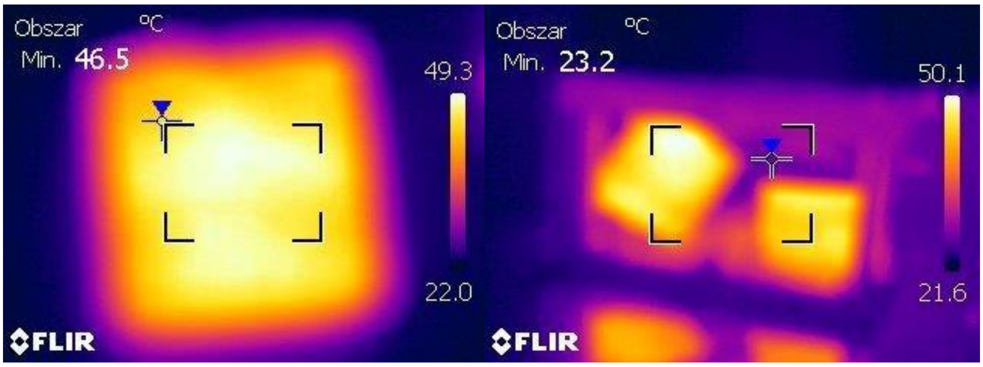

Fig. 9 Thermograms of the samples after compressive (left) and tensile strength (right) tests performed in temperature 50°C

Table 2 summarizes the average test results. It is evident that both compressive σ_c and tensile strength σ_r values increased along with temperature, from 24.2 MPa to 28.4 MPa, and from 1.8 MPa to 2.1 MPa, respectively. A reverse trend was observed for shear strength σ_s. As temperature increased, shear strength decreased from 22.1 MPa to 19.1 MPa. This can be considered an advantage especially for mechanical salt rock cutting. It should be noted, however, that the test methodology provided an induced shear angle of 45°, while the actual internal friction angle for salt is usually about 28-30° (Kolano & Flisiak 2013), although it can exceed 50°C as well (Ostadhassan & Tamimi 2014).

Table 2 Values of shear strength σ_s, compressive strength σ_c and tensile strength σ_r in temperature function

Parameter	Shear strength, σ_s			Compressive strength, σ_c			Tensile strength, σ_r		
Assumed temperature [°C]	20	50	80	20	50	80	20	50	80
Parametervalue [MPa]	22.12	21.04	19.07	24.17	25.18	28.44	1.81	1.92	2.06
Final temperature of the sample [°C]	23.16	48.76	71.81	23.05	50.26	79.17	23.08	49.69	75.91

Table 3 also shows the average values of the ratio of compressive strength σ_c to tensile strength σ_r. The higher the value of this ratio, the easier workable is the rock. In the case of the tested salt sample, only a small increase in this ratio could be observed.

Table 3 Values of compressive strength σ_c to tensile strength σ_r ratio in temperature function

Ratio σ_c/σ_r		
20°C	**50°C**	**80°C**
13.35	13.12	13.81

SUMMARY AND CONCLUSION

Analysis of the results obtained during tests allows to express the following conclusions.

The results of testing the mechanical parameters of the rock salt sample provided confirm that the salt is a springy-plastic rock material with characteristics that differ significantly from other rock centers.

The tested rock salt sample after heating was easier workable. In the rock salt sample heated to 80°C, the cuttability index A decreased by almost 25%, and the side chipping angle ψ by 13%. The shear strength σ_s value decreased almost 14%.

While compressive σ_c and tensile strength σ_r of salt sample, when heated from room temperature to 80°C can increase by as much as 28%. This is a considerable change in strength properties within a relatively small range of temperatures. So mechanical mining process by cutting can be compared to the mechanical parameter of shear strength σ_s. In all tests the increasing of temperature caused both the decrease of shear strength and cutting resistance value.

A very interesting observation is the fact that in the case of the rock salt sample heated to 80 C and then cooled to room temperature there was a significant decrease of cutting resistance. In the case of cuttability index A, for the same cutting parameters its value decreased more than twice.

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Abstract.
Currently over then 16 percent of the total worldwide salt production is excavated in underground mines. Salt deposits often lie at great depths up to 1000 m, where the temperature of the surrounding rocks reaches 50°C and even exceeds it. A large part of it is exploited using mechanical methods, mainly with the use of road headers and continuous miners. When excavating salt rock, the cutters of the road header mining head come into contact with the rock. This generate friction and in consequence a rise in temperature. In AGH University of Science and Technology the laboratory tests were carried out to determine the effect of temperature on cutting resistance and selected mechanical properties of rock salt. On the special laboratory test stand the rock salt sample was cutted at three different temperatures - 20, 50 and 80°C. The cuttability index and the side chipping angle were measured for each temperature. Additionally the same tests were performed in the case of salt sample after cooling to room temperature. The selected mechanical parameters of rock salt - compressive, tensile and shear strength were also measured for the same temperature values. The obtained results were compared and described in the paper.

Keywords: Rock salt, cuttability index, workability, laboratory tests, temperature change of salt