ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
DOI: 10.17559/TV-20150130152828

ESTIMATION OF UNIAXIAL COMPRESSIVE AND TENSILE STRENGTH OF ROCK MATERIAL FROM GYPSUM DEPOSITS IN THE KNIN AREA

Zlatko Briševac, Trpimir Kujundžić, Marija Macenić

Original scientific paper

In certain engineering tasks of preliminary nature there is a need for an estimation of important physical and mechanical properties such as uniaxial compressive and tensile strength. This paper analyzes the problems related to the assessment of uniaxial compressive and tensile strength of rock material in the deposit of gypsum in the Knin area. Its engineering characteristics strongly depend on the quantity of ground water and temperature and therefore it is difficult to conduct laboratory tests on this kind of material. The paper describes the comparison of estimates using equations published in the literature and equations that have been established on the basis of the research for the purpose of writing this paper.

Keywords: *estimation; natural gypsum; tensile strength; uniaxial compressive strength*

Procjena jednoosne tlačne i vlačne čvrstoće stijenskog materijala iz ležišta gipsa na području Knina

Izvorni znanstveni članak

U određenim inženjerskim poslovima preliminarnog karaktera javlja se potreba za procjenom važnijih fizikalno mehaničkih značajki kao što su jednoosna tlačna i vlačna čvrstoća. Ovaj rad bavi se problemima vezanim uz procjene jednoosne tlačne i vlačne čvrstoće stijenskog materijala u ležištu gipsa na području Knina. Njegove inženjerske karakteristike jako ovise o količini podzemne vode i temperaturi te je otežano provođenje laboratorijskih ispitivanja takve vrste materijala. U radu su opisane usporedbe procjene pomoću jednadžbi objavljenih u literaturi i onih koje su uspostavljene na temelju istraživanja u svrhu izrade ovog rada.

Ključne riječi: *gips; jednoosna tlačna čvrstoća; procjena; vlačna čvrstoća*

1 Introduction

In Croatia there are numerous deposits of gypsum. Gypsum was mined in the past in many places, and in the recent times exploitation is retained only in the area of Knin and Sinj (Fig. 1) [1].The contact of the softer gypsum and a stronger anhydrite in the deposits of gypsum in the Knin area is not sharp and the contact surface is highly uneven, and there are frequent occurrences of residual anhydrite in the gypsum, or initial and isolated parts of gypsum within the anhydrite. The deposits are interspersed with numerous fissures through which water and fragmented tailings material penetrate, which further pollutes the deposits of gypsum, described by Gabrić et al. [2].

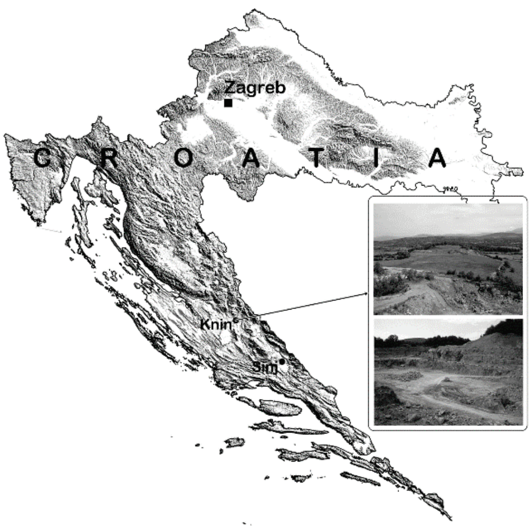

Figure 1 Locations of natural gypsum exploitation in the Republic of Croatia

Due to such conditions, blasting was originally chosen as a way of excavation in the Knin area. However, there are negative effects of this way of exploitation because natural gypsum has the ability of plastic deformation and this makes it more resistant to breakage. This behaviour is confirmed by some previous studies published in the literature and Dashnor et al. [3], based on the results of laboratory tests on the samples taken from underground gypsum quarry which indicate that the current behaviour of natural gypsum occurs mainly due to the mechanism of plastic deformation. In addition, during the exploitation of gypsum in the Knin area there are relatively high levels of underground water, which further complicates the excavation of mineral raw material by mining.

Due to the above stated disadvantages, there is a need to identify more effective ways of excavation such as those by means of excavation machines. Therefore, in 2010 laboratory testing of physical and mechanical properties of rock material was conducted. Testing of this kind of material is not easy to implement due to the generally weak resistance of gypsum to the physical and chemical wear. Accordingly, the methodology of laboratory tests of this kind of material requires long term tests which should be carried out with caution. An additional difficulty in the extraction and testing of gypsum is the dissolution of gypsum in water which can be represented by chemical equation

$$CaSO_4\,2H_2O + H_2O \rightarrow Ca^{+2} + SO_4^{-2} + 3H_2O, \qquad (1)$$

Upon the testing of saturated samples the great solubility of gypsum in water should be taken into account, which is circulated, and is not saturated with calcium sulphate so 1 m^3 of such water may dissolve 2,5 kg of gypsum [4]. In addition to the dissolution, gypsum is susceptible to a higher temperature and is stable at temperatures below 38 °C [4]. The testing methodology should be adjusted to these facts.

2 Sampling and testing methodology

In order to determine the physical and mechanical properties in this paper, according to the recommendations of the ISRM ([5÷8]), the following laboratory tests were performed: determination of the uniaxial compressive strength, indirect determination of tensile strength by means of the Brazilian test, determining the point load strength index and determination of hardness using the Schmidt hammer. The sampling was carried out in the way that the larger irregular pieces of natural gypsum were taken from the excavation field, by laboratory coring and other processing the total of 62 different samples required for the previously described tests. Tests were conducted with two sets of samples. The first set of 31 samples comprised dry samples and the second set of 31 samples were samples saturated with water (moisture content is from 7,54 to 12,69 %). Special attention was paid to the sampling capabilities of the future comparisons of results in order to establish regression. Since the test of a uniaxial compressive strength required the highest sample, when the core of sufficient height was drilled, from its immediate proximity, samples for other tests were taken since they required a lower height, as shown in Fig. 2. Drying of the samples was carried out at 30˚C for 48 hours and then the samples were kept in a desiccator for 6 more days in order to continue the separation of any residual moisture in the sample, so that the sample could reach the final weight. The second set of samples that were examined in a saturated condition was dipped in water for 8 days because previous studies conducted by Yilmaz [9] have shown that after this period a reduction of strength is already achieved.

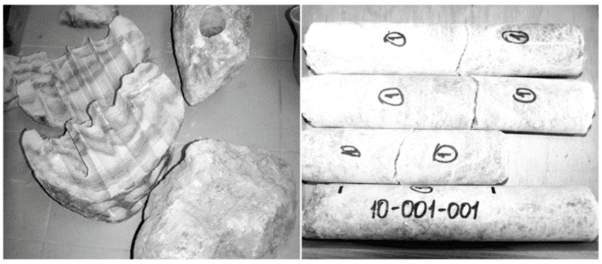

Figure 2 Coring of field samples and pattern matching for test

2.1 Processing of test results

Table 1 shows the results of the tests and the basic statistical analysis of the results for dry and saturated samples. The rows of the table contain the results of different tests that are comparable with each other inside dry and saturated series. Figure 3 shows the presentation of mean values for dry and saturated UCS and TS (from table 1) with Mohr's circles.

Table 1 Results of testing physical and mechanical properties

	Dry samples				Saturated samples			
	UCS (MPa)	*TS* (MPa)	$I_{s(50)}$ (MPa)	*SRH*	*UCS* (MPa)	*TS* (MPa)	$I_{s(50)}$ (MPa)	*SRH*
	8,471	1,037	0,4325	33	6,157	0,626	0,6052	29
	12,706	1,304	0,899	36	12,325	0,765	0,7243	31
	12,706	1,35	1,0066	37	13,099	0,883	0,9297	31
	17,673	1,446	1,5032	39	15,675	1,019	1,0345	32
	18,033	2,112	1,9098	42	17,571	1,376	1,0347	36
	17,724	1,58	1,7236		5,851	0,539	0,5778	
		0,487	0,2755			0,273	0,2796	
		1,052	0,5722			0,301	0,3305	
		1,389	1,1395			0,355	0,434	
		1,446	1,3416			0,443	0,4664	
x_{min}	8,471	0,487	0,2755	33	5,851	0,273	0,2796	29
x_{max}	18,033	2,112	1,9098	42	17,571	1,376	1,0347	36
x_{mv}	14,552	1,32	1,08	37,4	11,78	0,658	0,642	31,8
s'	3,891	0,419	0,549	3,362	4,848	0,355	0,28	2,588

UCS - uniaxial compressive strength; *TS* – tensile strength; $I_{s(50)}$ – point load strength index; *SRH* – Schmidt rebound hardness; x_{min} - minimum value; x_{max} - maximum value; x_{mv} - mean value; s' - standard deviation;

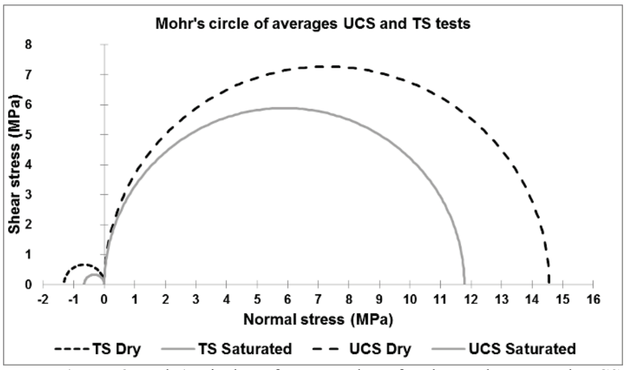

Figure 3 Mohr's circles of mean values for dry and saturated *UCS* and *TS* tests

Table 2 Comparison of results of testing physical and mechanical properties

	UCS (MPa)	TS (MPa)	$I_{s(50)}$ (MPa)	SRH
$\bar{x}_d$	14,552	1,32	1,08	37,4
$\bar{x}_{sat}$	11,78	0,658	0,642	31,8
$\bar{x}_{sat}/\bar{x}_d$	0,81	0,498	0,594	0,85
$\bar{x}_d - \bar{x}_{sat}$	2,772	0,662	0,438	5,6
%	19,05	50,15	40,56	14,97

$\bar{x}_d$ - mean value of dry samples; $\bar{x}_{sat}$ - mean value of saturated samples

Comparing the mean value of the test results in dry and saturated condition the reduction of measured physical and mechanical properties was determined, as shown in Tab. 2. Accordingly, the largest reduction is present in tensile strength and point load strength index.

3 Results of estimation obtained by using the equation from the literature and discussion

The difficulties associated with the testing and analysis of test results in terms of comparison with other studies necessitate the checking capabilities of estimates based on the previous research carried out by different authors. Although some authors have tried to establish the universality, the utilization of the previously established equations, it still depends on the rock material in which these equations were produced. Therefore, this paper focuses on the previous research that could be compared with natural gypsum investigated in this paper.

Most authors were involved in the evaluation of the uniaxial compressive strength on the basis of various index tests. International Society for Rock Mechanics in its recommendation [7] states that the uniaxial compressive strength can be estimated so that the point load strength index is increased 20 times in the case of soft rocks, and 25 times in the case of stronger rocks. Accordingly, in the case of natural gypsum, which is one of the softer rocks, the equation for estimating uniaxial compressive strength can be shown by the equation

$$UCS = 20\ I_{s(50)}. \tag{2}$$

However, it was noticed that the recommendations were too general and searching/finding the equation that attempts to better estimate the uniaxial compressive strength was continued. O'Rourke in 1989 [10], analyzing samples of sandstone, siltstone, limestone and anhydrite, established a regression Eq. (3) to evaluate the uniaxial compressive strength (*UCS*) in kPa using the Schmidt hardness (*SR*H) and, for comparison purposes in this study, the equation was corrected to get values in MPa.

$$UCS = (702\ SRH - 1104)/1000, \tag{3}$$

For gypsum from the area Sivas in Turkey, Yılmaz and Sendir in 2002 [11] showed the interdependence of the uniaxial compressive strength (*UCS*) with Schmidt hardness (*SRH*) using the equation in the exponential form, which reads

$$UCS = e^{(0,818+0,059\ SRH)}, \tag{4}$$

Quane and Russell [12] published in 2003 the equation for weak rocks (5) that, based on the point load strength index ($I_{s(50)}$), estimates the uniaxial compressive strength (*UCS*)

$$UCS = 3,86\ I_{s(50)}^{2} + 5,65\ I_{s(50)}, \tag{5}$$

In the paper by the authors Yilmaz and Yuksek in 2008 [13], which deals with the indirect estimation of physical mechanical properties of gypsum, among other things, the authors provide the regression in a linear form that can be used to estimate the uniaxial compressive strength by point load strength index (6) and the Schmidt hardness (7) which read as follows

$$UCS = 12,4\ I_{s(50)} - 9,0859, \tag{6}$$
$$UCS = 1,2483\ SRH - 24,723. \tag{7}$$

Fewer authors dealt with the assessment of the tensile strength as its testing could be easily carried out by an indirect method using the Brazilian test. Eq. (8) to estimate the tensile strength (*TS*) from uniaxial compressive strength, given by Hoek [14] is one of the oldest correlations.

$$TS = UCS/10. \tag{8}$$

According to Zhang [15], tensile strength (*TS*) can be estimated through point load strength index ($I_{s(50)}$) using the formula

$$TS = -1,5\ I_{s(50)}. \tag{9}$$

Kılıc and Teymen [16] found the equation by which the tensile strength can be estimated using point load strength index (10) and Schmidt hardness according to the expression (11)

$$TS = 7,5\ \ln(I_{s(50)}) + 2,22, \tag{10}$$

$$TS = 0,058\ SRH^{1,2749}. \tag{11}$$

In order to obtain a better comparison of evaluation performance, parameters were computed which validate the performance of the model being evaluated. Usually for the evaluation of the performance, Root Mean Square Error (*RMSE*) is used, which is a square performance parameter estimation and provides "average" magnitude of the error, weighted proportionally by squares of individual errors. The formula for calculation is shown in Eq. (12)

$$RMSE = \sqrt{\frac{1}{N}\Sigma\left(y_{Mi} - y_{Pi}\right)^2}\ , \tag{12}$$

where *RMSE* is the Root Mean Square Error; y_{Mi} an actual (measured) value of the i^{th} case; y_{Pi} an estimated value of the i^{th} case; *N* total number of values (samples).

The standard error of regression may have a value ranging from 0 to infinity, and 0 represents the perfect prediction. According to Motulsky and Christopoulos [17] it is possible to calculate another parameter of performance - criterion AIC (Akaike information criterion), which is a relative measure of how well suited the model is and takes into account the number of adjusted parameters. Due to the fact that the data set is several times larger than the number of parameters, a variant of this criterion cAIC (corrected AIC) is calculated according to the formula (13).

$$cAIC = \left(N \cdot \ln\left(\frac{SS}{N}\right) + 2K\right) + \frac{2K(K+1)}{N-K-1}\ , \tag{13}$$

where *cAIC* is the corrected Akaike information criterion; *N* a total number of values (samples); *SS* a sum of squared deviations from the established curve; *K* number of estimated parameters in the equation +1.

Showing the usability of uniaxial compressive strength evaluation based on the equations stated in the literature is presented in Table 3. The negative deviation indicates that the estimated target value is too big. Such is the case with Eqs. (2) and (3) which assess on the basis of strength index, and Eqs. (3), (4), (8) which estimate based on the Schmidt strength. Using Eq. (6) it was not possible to estimate the cases where the point load strength index was less than 1,19 MPa, because its original range used in forming/development was greater than 1,19 MPa. In this case the *cAIC* criterion would indicate an incorrect assessment of the evaluation performance so it is not listed in Tab. 3. Estimation by Eq. (5) has shown a very good accuracy in the case of dry samples where the arithmetic mean of the estimated cases differed only 4,27 % compared to the measured value. However, with saturated samples, the difference was 38,3 %.

Table 3 Comparison of estimates of uniaxial compressive strength

Equation ID	Original range		State	Deviation		*RMSE*	*cAIC*
	UCS	$I_{s(50)}$		MPa	%		
(2)	-	-	D	−10,364	71,22	12,407	38,219
			S	−4,574	38,83	4,79	26,799
(5)	2,3 ÷ 76	< 5	D	0,622	4,27	4,39	35,753
			S	4,512	38,3	5,112	37,579
(6)	8,1 ÷ 35,6	1,19 ÷ 3,23	D	6,173	42,42	7,839	-
			S	8,471	71,91	12,209	-
Equation ID	Original range		State	Deviation		*RMSE*	*cAIC*
	UCS	*SRH*		MPa	%		
(3)	14 ÷ 215	19 ÷ 52	D	−11,233	80,71	11,359	54,3
			S	−8,255	63,67	8,648	51,573
(4)	15 ÷ 30	30 ÷ 44	D	−6,995	50,26	7,123	49,633
			S	−1,973	15,22	3,079	41,244
(8)	8,1 ÷ 35,6	27 ÷ 48	D	−8,046	57,81	8,127	50,951
			S	−2,008	15,49	2,793	40,27

UCS – uniaxial compressive strength; $I_{s(50)}$ – point load strength index; *SRH* – Schmidt hardness; D − dry state of sample; S − saturated state of sample; *RMSE* − Root Mean Square Error; *cAIC* – corrected Akaike information criterion

The usability of the published equations for estimating the tensile strength is shown in Tab. 4. The Eq. (8) estimated very good results for dry samples when the difference was only 1,15 % lower than the mean value of the measured samples. However, in the case of saturated sample, the estimate was 35,71 % higher. The Eq. (8) should be taken with reserve because it was not made for estimating the indirect strength by the Brazilian test. In addition, this equation estimates tensile strength for which the process of determining is simpler than the value for which estimate is being made.

Table 4 Comparison of the estimates of tensile strength

	Original range		State	Deviation		*RMSE*	*cAIC*
	TS	*UCS*		MPa	%		
(8)	-	-	D	0,017	1,15		
			S	−0,31	35,71		
Equation ID	Original range		State	Deviation		*RMSE*	*cAIC*
	TS	$I_{s(50)}$		MPa	%		
(9)	-	-	D	−0,301	22,8	0,536	−6,748
			S	−0,305	46,35	0,329	−16,542
(10)	1,1 ÷ 19	17 ÷ 62	D	−2,961	224,32	3,264	-
			S	−1,55	235,56	1,148	-
Equation ID	Original range		State	Deviation		*RMSE*	*cAIC*
	UCS	*SRH*		MPa	%		
(11)	1,1 ÷ 19	17 ÷ 62	D	−4,427	305,31	4,437	44,899
			S	−3,844	411,56	3,85	43,48

TS – tensile strength; $I_{s(50)}$ – point load strength index; *SRH* – Schmidt hardness; D – dry state of sample; S – saturated state of sample; *RMSE* – Root Mean Square Error; *cAIC* – corrected Akaike information criterion

The Eq. (10) published by Kılıc and Teymen [16] was not usable because it was not made for the point load strength index values of less than 0,9 MPa.

3 Regression

Based on the results obtained in this paper regression diagrams were produced and regression equations were established, both for the uniaxial compressive strength and for the tensile strength, because these two properties are often used in planning the machine excavation of mineral resources. As an indicator of the representativeness of the regression model the coefficient of determination R^2 was used.

Fig. 4 shows diagrams of relations between uniaxial compressive strength (*UCS*) with other tested characteristics. The diagram shows that the regression of uniaxial compressive strength in a dry and saturated condition is better compared to the point load strength index as it achieves the coefficients of determination (R^2) 0,9806 for dry and 0,9193 for saturated samples. It also has a larger coefficient of determination of 0,9275 in relation to the tensile strength of saturated samples. For dry samples, the coefficient of determination is also very high in relation to Schmidt hardness and totals 0,9179.

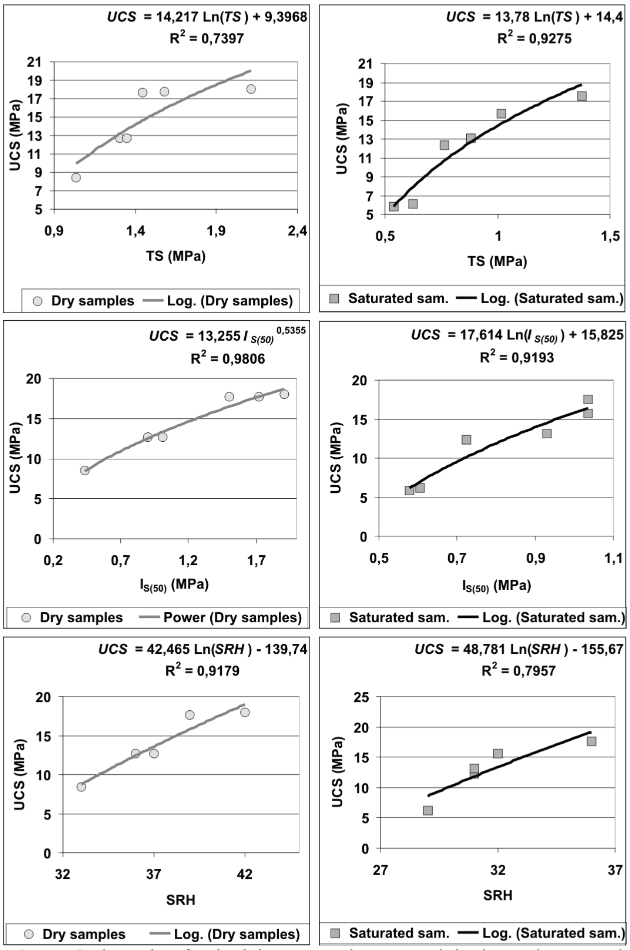

Figure 4 The ratio of uniaxial compressive strength in dry and saturated condition to other properties

Fig. 5 shows diagrams of dependence of tensile strength and other examined properties. The highest coefficients of determination (R^2) are those in relations with Schmidt hardness. For dry samples it equals 0,9478, and with saturated samples it is 0,9627. A successful regression is also achieved through the point load strength index which gives a regression coefficient of 0,8606 for dry samples, and 0,9617 for saturated samples. The successful regression over the uniaxial compressive strength is confirmed because in this case it provides a coefficient of 0,9275 for saturated samples.

The regressions of uniaxial compressive strength (UCS) presented in this paper show that the assessment is most efficiently done with the point load strength index ($I_{S(50)}$) and then the equation for the dry condition takes the form of general power and is shown by the expression (14) when it reaches the coefficient of determination of 0,9806.

$$UCS = 13{,}255\, I_{S(50)}^{0{,}5355}, \tag{14}$$

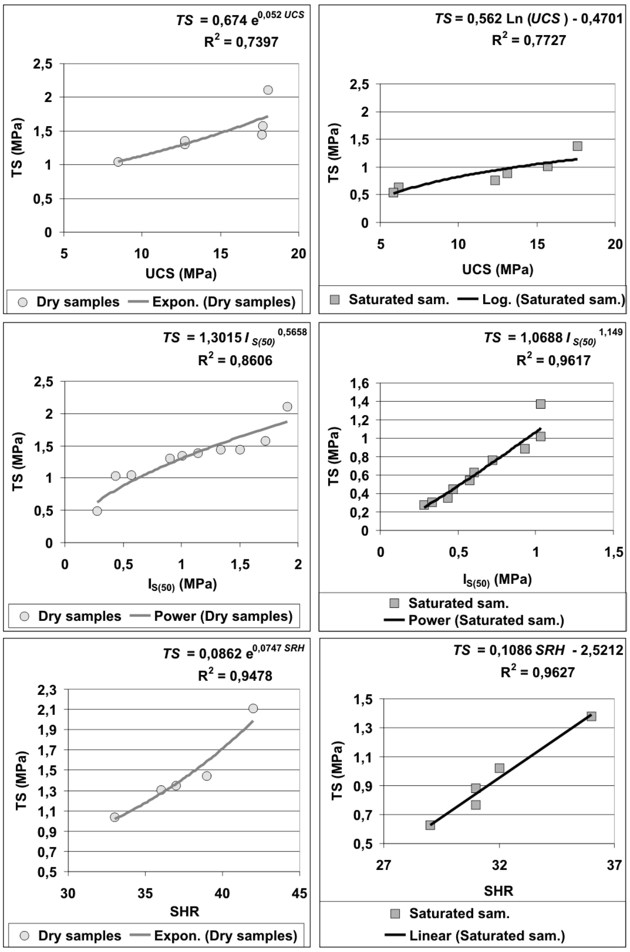

Figure 5 The ratio of tensile strength in dry and saturated condition related to other properties

In the case of a saturated state the equation is in a logarithmic form and is given by the expression (15) with R^2 of 0,9193.

$$UCS = 17{,}614 \cdot \ln(I_{S(50)}) + 15{,}825. \tag{15}$$

In the case of the tensile strength (*TS*) the established regression shows the best results with Schmidt hardness (*SRH*) and in the case of dry samples it has an exponential form as shown by the expression (16) and achieves the coefficient of determination 0,9478 for the range of hardness from 33 to 42.

$$TS = 0{,}0862 e^{0{,}0747\, SRH}. \tag{16}$$

A saturated tensile strength (*TS*) can be estimated by the equation in the linear form (17) and it achieves a coefficient of determination of 0,9627 for a range of values of the Schmidt hardness from 29 to 36.

$$TS = 0{,}1086\, SRH - 2{,}5212. \tag{17}$$

Tab. 5 presents the evaluation of the performance of equations for estimating the uniaxial compressive strength, which in this study demonstrated the best ability to estimate and Tab. 6 presents ratings of performance of estimates for tensile strength.

Table 5 Evaluation of performance of the regression model of estimating the uniaxial compressive strength

Range of values		State	*RMSE*	*cAIC*
UCS	$I_{s(50)}$			
8,471 ÷ 18,033	0,4325 ÷ 1,9098	D	0,619	12,244
5,851 ÷ 17,571	0,5778 ÷ 1,0347	S	1,257	10,743

Table 6 Evaluation of performance of the regression model of estimating the tensile strength

Range of values		State	*RMSE*	*cAIC*
TS	*SRH*			
8,471 ÷ 18,033	33 ÷ 42	D	0,087	5,602
6,157 ÷ 17,571	29 ÷ 36	S	0,095	6,447

5 Discussion

According to Tab. 2, the highest decrease in value due to saturation is in tensile strength and strength index. This fact due to the nature of these tests has positive implications in the potential of machine excavation of the deposit parts with high levels of ground water. In view of the influence of saturation of samples to uniaxial compressive strength, previous studies have shown that in the case of saturation a reduction of the uniaxial compressive strength of 64,07 % may be expected, as was the case for gypsum from the Sivas region (Yilmaz, 2010). However, in case of natural gypsum in the Knin area, the reduction totals 19,05 %, indicating a diversity of two properties of the same material but different places and forming conditions.

The reason for the unsuccessful estimate by previously determined Eqs. (2) to (11) which have been published in the literature is primarily the fact that the equations were developed for the natural state of humidity. The equations made for natural gypsum (4), (6) and (7) did not achieve satisfactory evaluation, because the layers of gypsum in Sivas, that were tested on this occasion, are generally massive and have a very low proportion of clay, calcite and anhydrite. This distinguishes them from the layers of gypsum that are found in deposits in the Knin area.

Comparing the results of the assessment of the realized estimates in Tabs. 3 and 4 with the results in Tabs. 5 and 6 it can be concluded that the equations derived in this paper have a better standard error of regression and the corrected AIC criterion relative to other comparable equations.

6 Conclusion

The ratio of the value of physical and mechanical properties of saturated and dry state of natural gypsum in the area of Knin is for the uniaxial compressive strength 0,81; for the tensile strength 0,498; for point load strength index 0,594 and for Schmidt hardness 0,85.

The usability of the previously published equations proved to be insufficient in the case of evaluating the uniaxial compressive strength and tensile strength. In the case of the future strictly preliminary engineering tasks in gypsum from a deposit in the Knin area, better estimates can be achieved by the equations established in this paper because they take into account the condition of saturatedness of samples and are made on the basis of experiments on a specific site, for which estimate is made. Upon the assessment, it is important to use the equations in the range of values for which they were made.

Uniaxial compressive strength of natural gypsum from beds in the Knin area in the dry state can be estimated using the regression model through the point load strength index using the Eq. (12), and in a saturated state/condition using the Eq. (13). The equations prove the performance of the coefficient of determination R^2 = 0,9806; with the standard regression error *RMSE* = 0,619 and the corrected AIC criterion *cAIC* = 12,244 for dry state, and R^2 = 0,9193; *RMSE* = 1,257 and *cAIC* = 10,743 for saturated state. Tensile strength can be assessed most successfully using the regression model through the Schmidt hardness with the Eq. (14) for the dry state when values R^2 = 0,9478, RMSE = 0,087 and *cAIC* = 5,602 are reached. The Eq. (15) can be used most successfully to evaluate the tensile strength in the saturated state when values for the coefficient of determination R^2 = 0,9627; *RMSE* = 0,095 and *cAIC* = 6,447 are reached.

Acknowledgements

Dissemination process is supported by the Development Fund of the Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb.

7 References

[1] Marković, S. Mineral resources of Croatia. Institute for Geological Research - Geology Department, 2002.

[2] Gabrić, A.; Šinkovec, B.; Sakač, K.; Kuljak G. Gypsum Deposits in Republic of Croatia. // The mining – geological – petroleum engineering bulletin. 14, 1(2002), pp. 21-36.

[3] Dashnor, H.; Françoise, H.; Christophe, A. Deformation of Natural Gypsum Rock: Mechanisms and Questions. // Engineering Geology, 86(2006), pp. 1-17. DOI: 10.1016/j.enggeo.2006.04.002

[4] Yilmaz, I. Gypsum/anhydrite: Some Engineering Problems. // Bulletin of Engineering Geology and the Environment. 59(2001), pp. 227-230. DOI: 10.1007/s100640000056

[5] ISRM. Suggested Methods for Determining the Uniaxial Compressive Strength and Deformability of Rock Materials. // International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts. 16, 2(1979), pp. 135-140.

[6] ISRM. Suggested Methods for Determining Tensile Strength of Rock Materials; Part 2: Suggested Method for Determining Indirect Tensile Strength by the Brazil Test. // International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts. 15, 3(1978), pp. 99-103. DOI: 10.1016/0148-9062(78)90003-7

[7] ISRM. Suggested Method for Determining Point Load Strength. // International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts. 22, 2(1985), pp. 51-60. DOI: 10.1016/0148-9062(85)92327-7

[8] ISRM. Suggested Methods for Determining Hardness and Abrasiveness of Rock; Part 3: Suggested Method for Determination of the Schmidt Rebound Hardness. // International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts. 15, 3(1978), pp. 89-98. DOI: 10.1016/0148-9062(78)90002-5

[9] Yilmaz, I. Influence of Water Content on the Strength and Deformability of Gypsum. // International Journal of Rock Mechanics and Mining Sciences. 47, 2(2010), pp. 342-347. DOI: 10.1016/j.ijrmms.2009.09.002

[10] O' Rourke J. E. Rock Index Properties for Geoengineering in Underground Development. // Mining Engineering. (1989), pp. 106-110.
[11] Yılmaz, I.; Sendir, H. Correlation of Schmidt Hardness with Unconfined Compressive Strength and Young's Modulus in Gypsum from Sivas (Turkey). // Engineering Geology. 66(2002), pp. 211-219. DOI: 10.1016/S0013-7952(02)00041-8
[12] Quane, S. L.; Russell, J. K. Rock Strength as a Metric of Welding Intensity in Pyroclastic Deposits. // European Journal of Mineralogy. 15(2003), pp. 855-864. DOI: 10.1127/0935-1221/2003/0015-0855
[13] Yilmaz, I.; Yuksek, A. G. An Example of Artificial Neural Network Application for Indirect Estimation of Rock Parameters. // Rock Mechanics and Rock Engineering. 41, 5(2008), pp. 781-795. DOI: 10.1007/s00603-007-0138-7
[14] Hoek, E. Rock Mechanics – An Introduction for the Practical Engineer Parts I, II and III. // Mining Magazine. 144(1966), pp. 236-243.
[15] Zhang, L. Engineering Properties of Rocks Vol 4. Elsevier Publ, Amsterdam, 2005.
[16] Kılıc, A.; Teymen, A. Determination of Mechanical Properties of Rocks Using Simple Methods. // Bulletin of Engineering Geology and the Environment. 67(2008), pp. 237-244. DOI: 10.1007/s10064-008-0128-3
[17] Motulsky, H. J.; Christopoulos, A. Fitting Models to Biological Data Using Linear and Nonlinear Regression: A Practical Guide to Curve Fitting. GraphPad Software, Inc. 2003. http://www.graphpad.com. (23.10.2014)

Authors' addresses

Zlatko Briševac, PhD, Research assistant
University of Zagreb
Faculty of mining, geology and petroleum engineering
Pierottijeva 6, 10000 Zagreb, Croatia
zlatko.brisevac@rgn.hr

Trpimir Kujundžić, PhD, Associate professor
University of Zagreb
Faculty of mining, geology and petroleum engineering
Pierottijeva 6, 10000 Zagreb, Croatia
trpimir.kujundzic@rgn.hr

Marija Macenić, M.Sc., Assistant
University of Zagreb
Faculty of mining, geology and petroleum engineering
Pierottijeva 6, 10000 Zagreb, Croatia
marija.macenic@rgn.hr