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Analyzing the influence of the water saturation on the strength of sandstones

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ABSTRACT: Water content is one of the most important factors influencing rock strength. Considerable research has been carried out to investigate rock strength under both dry and water saturated conditions for different types of sandstones. According to these results, the petrophysical components of rocks (i.e. uniaxial compressive strength, elastic modulus, tensile strength) decrease with increasing water content and this can result in an increase in the mechanical compliance in some cases. In several cases, the strength decrease is remarkable after only 1% water saturation. For rock mechanics and rock engineering projects, it is strongly recommended that the dry uniaxial compressive strength is used for the purposes of strength classification, while for the actual engineering design it is essential to establish the wet strength and ideally the water sensitivity of the rock, in order to asses their potential change in strength and deformability. The goal of this paper is to show a method for calculating the sensitivity of sandstone rocks to water content, using the different published data. From measurements of the density and the uniaxial compressive strength in case of dry and saturated petrophysical states, the strength as a function of water content can be easily determined.

1 INTRODUCTION

Hawkins and McConnell (1992) investigated the influence of the water content on the strength and deformability of 35 different British sandstones from 21 localities, ranging in age from Pre-Cambrian to Cretaceous. They published values for the measured uniaxial compressive strength and for the tangent and secant deformation moduli in case of dry and fully saturated conditions. Vásárhelyi (2003) analyzed the published data and showed that there is a linear correlation between the dry and fully saturated uniaxial compressive strengths, σ_{c0} and σ_{csat} respectively (Fig. 1). The overall best-fit equation for the 35 investigated sandstones is:

$$\sigma_{c(sat)} = 0.759\ \sigma_{c(0)} \quad (R^2 = 0.906) \tag{1}$$

The same results were found for investigating the relationships between the dry and saturated petrophysical state the secant and tangent modulus, as well – they were decreased about 20% in both cases (Vásárhelyi, 2003). According to Vásárhelyi (2005), the decreasing value in case of fully saturated condition should be rock type dependent.

The results of Kleb & Vásárhelyi (2003) and Vásárhelyi (2002, 2005) show clearly, that the ratio between the different petrophysical constants (i.e. uniaxial and tensile strengths, modulus of deformation) is independent to the water content.

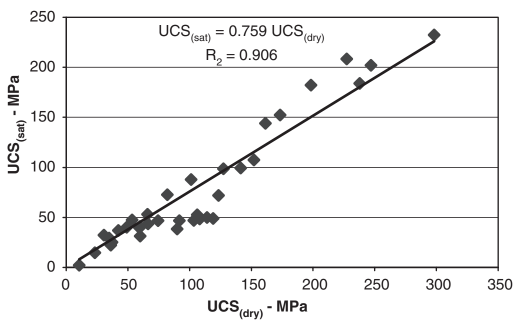

Figure 1. Relationship between the dry and the saturated uniaxial compressive strength (UCS) for 35 British sandstones (Vásárhelyi, 2003).

Investigating highly porosity limestones, an exponential equation was found between the strength and the density:

$$\sigma_c = \alpha e^{\beta\rho}, \tag{2}$$

where ρ is the density (dry or saturated), and α and β are material constants, which are depending on the

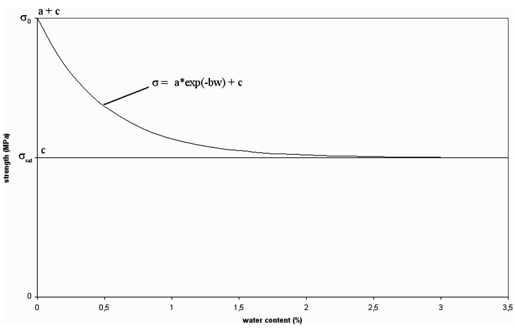

Figure 2. Influence of the water content for the strength of the rock – schematic curve according to Eq. (3).

petrophysical state. Similar relationship was found for the Young's modulus and the tensile strength, as well (Vásárhelyi, 2005). These material constants were determined for different types of tuffs (Vásárhelyi, 2002).

2 RELATIONSHIP BETWEEN THE MOISTURE CONTENT AND THE STRENGTH

Hawkins and McConnell (1992) carried out tests to determine the influence of the water content on the strength of 15 different types of sandstones. They found that the relationship between water content and uniaxial compressive strength could be described by an exponential equation of the form:

$$\sigma_{c(w)} = ae^{-bw} + c, \tag{3}$$

where $\sigma_{c(w)}$ is the uniaxial compressive strength (MPa), w is the water content (%) and a, b, and c are constants. It is obvious that the strength at zero water $\sigma_{c(0)} = a + c$ and the strength at full saturation $\sigma_{c(sat)} = c$ (the schematic curve is plotted in Figure 2).

The parameter b is a dimensionless constant defining the rate of strength loss with increasing water content. The determined constants for each of the 15 different types of sandstones (published by Hawkins & McConnell, 1992) with the respective R-values are listed in Table 1.

Figure 3 shows the best-fit lines plotted for the 15 different rock types for water content values up to 5%. It is apparent that the strength of the rock is very sensitive to the water content; an increase in water content of as little as 1% from the dry state can have a marked effect on strength. The parameter b characterizes this sensitivity, with larger values corresponding to more sensitive materials. Hence, the b parameter should be very important for rock engineering design, particularly in the context of abandoned mines where the groundwater will rebound (Li & Reddish, 2004).

Table 1. Numerical values of constants a, b, and c and respective R-value for best-fit exponential equations (according to Hawkins & McConnell, 1992).

Sandstone	a	b	c	R
Donegal Quartzite (DQ)	39.03	1.9601	184.23	0.93
Brownstone (LORS)	29.34	0.7646	105.23	0.78
Millstone Grit – T. D (MGD)	12.30	0.6821	96.27	0.71
Holcombe Brook Grit (HBGB)	36.13	0.7794	48.65	0.88
Thornhill Rock – T. A (TRA)	45.73	1.5942	40.29	0.97
Crackington Formation (CF)	84.01	6.4167	230.98	0.91
Pennant – Type A (PnA)	83.76	0.2306	51.02	0.86
Pennant – Type B (PnB)	28.81	0.5506	49.37	0.62
Pennant – Type C (PnC)	47.12	1.5439	47.65	0.95
Penrith – Type A (PrA)	7.01	0.0752	56.30	0.70
Penrith – Type B (PrB)	4.16	0.4061	28.90	0.87
Penrith – Type C (PrC)	17.27	1.0675	67.75	0.85
Penrith – Type D (PrD)	20.37	1.2629	87.29	0.88
Greensand – Type A (G)	6.14	0.1104	2.97	0.93
Greensand – Dogger (D)	19.12	0.2567	45.79	0.77

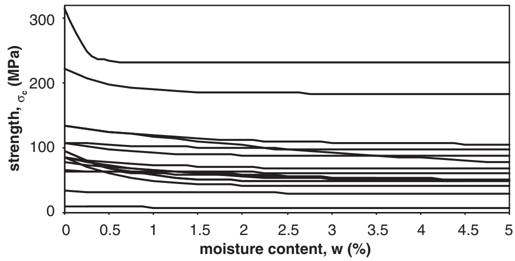

Figure 3. Strength-moisture content curves, fitted to experimental data up to 5%.

3 CALCULATING THE SENSITIVITY OF WATER CONTENT IN ABSOLUTE SCALE

The disadvantage of the analysis method of Hawkins and McConnell (1992) is that the saturated condition differs for each of the investigated sandstones, i.e. the absolute water content at full saturation can be very different. Further, the suggested fitting curve of equation (3) of Hawkins and McConnell changes if the relative water content goes to infinity.

For a better representation of the water dependence, we suggest a recalculation of the material constants b, with the water content expressed using an absolute measure such as the degree of saturation, S. This means that for all rocks, $S = 0$ in the case of dry condition and $S = 1$ in the case of fully saturated condition. The dimensionless constant b^* can be easily determined from the published data using the following equation:

$$b^* = -\ln\left(\frac{0.1}{\sigma_{c0} - \sigma_{csat}}\right) \tag{4}$$

Equation (4) assumes that the full saturation is achieved if the difference of the actual strength calculated by the fitted curves and the theoretical one is 0.1 [MPa]. The calculated b^* values are given in Table 2. Note the small variance of the b^* values. For the dry and saturated strengths $\sigma_{c(0)}$ and $\sigma_{c(sat)}$ we have accepted the values calculated by Hawkins and McConnell, as it is indicated by the fitted parameters a and c.

However, we suggest a different form for the exponential function of equation (3), considering that the fully saturated condition is achieved at 100% water content. In the proposed expression, given by equation (4), the exponential dependence is preserved but the parameters a and c are changed.

$$\sigma_c(w) = a^* + c^* e^{-b^* w} = \\ = \sigma_{c0} - \frac{(\sigma_{c0} - \sigma_{csat})}{1 - e^{-b^*}} + \frac{(\sigma_{c0} - \sigma_{csat})}{1 - e^{-b^*}} e^{-b^* w}. \tag{5}$$

Here, the previous relation between the parameters a^* and c^* is preserved as $a^* + c^* = \sigma_{c(0)}$, however, now the value of c^* is now given by

$$c^* = \frac{(\sigma_{c(0)} - \sigma_{c(sat)})}{1 - e^{-b^*}} \tag{6}$$

The corresponding rock types can be identified from their dry strength values (Vásárhelyi & Ván, 2006). One can see that there are some rocks where there is a significant difference in the strength between wet and dry, corresponding to a water content change of as much as 30%. The previously noted small variance of the b^* values is also apparent from Figure 4, where the relative strength is plotted as a function of the relative water content.

Knowing the water content under fully saturated conditions, the constant b in relative scale can be related to b^* according to:

$$b = \frac{b^*}{n_{eff}}, \tag{7}$$

where n_{eff} is the effective porosity of the rock. The relationship between the b-value and the effective porosity (n_{eff}) can be seen in the plot in Figure 5, where the results of Hawkins and McConnell (1992) are shown together with the results of Bell (1978, 1995) and 4 Hungarian sandstones (investigated by Török & Hajpál, 2005). These results are also presented in

Table 2. The calculated b^* and b values with the experimental result b value for the published sandstones (Hawkins & McConnell, 1992).

Sandstone	b^* (Eq. 4)	b	b-calculated (Eq. 8)
DQ	5.967	1.9601	1.8779
LORS	5.682	0.7646	0.7553
MGD	4.812	0.6821	0.7254
HBGB	5.890	0.7794	0.7352
TRA	6.125	1.5942	1.5385
CF	6.734	6.4167	5.9572
PnA	6.731	0.2306	0.2150
PnB	5.663	0.5506	0.5280
PnC	6.155	1.5439	1.4686
PrA	4.250	0.0752	0.0932
PrB	3.728	0.4061	0.6135
PrC	5.152	1.0675	1.4226
PrD	5.317	1.2629	1.5561
G	4.117	0.1104	0.1510
D	5.253	0.2567	0.2749

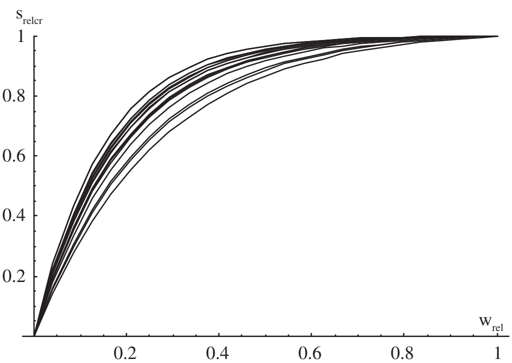

Figure 4. Relative strength as a function of water content.

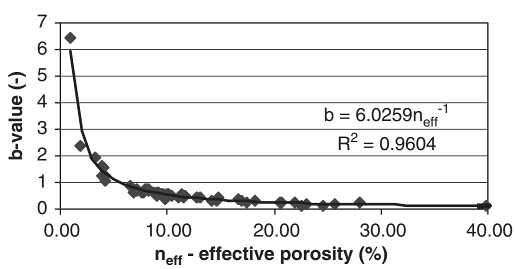

Figure 5. The b-value as the function of the effective porosity.

Tables 3 and 4. The equation of the line of best fit in Figure 5 is

$$b = \frac{6.0259}{n_{eff}} \quad (R^2 = 0.960), \tag{8}$$

and this can be used to determine the sensitivity of the sandstone to water content.

Table 3. Measured and calculated values for (1): the published data of Bell (1995) and (2): 4 different Hungarian sandstones.

Location	$\sigma_{c(0)}$	$\sigma_{c(100)}$	$n_{(eff)}$	b^*	b
Chatsworth grit[1]	39.2	24.3	14.6	5.0039	0.3427
Sherwood sandstone[1]	11.6	4.8	25.7	4.2195	0.1642
Keuper waterstone[1]	42.0	28.6	10.1	4.8978	0.4849
Bronllwyn Grit[1]	197.5	190.7	1.8	4.2195	2.3442
Balatonrendes[2]	45.67	34.99	4.23	4.6710	0.5190
Cserkút[2]	78.55	61.43	1.83	5.1428	1.2245
Pilisborosjenő[2]	20.41	17.73	13.45	3.2884	0.1462
Vác[2]	33.84	25.2	12.07	4.4590	0.1939

Table 4. Calculated b and b^* values from the measured data of Bell (1978) for Fell sandstones.

Depth (m)	$\sigma_{c(0)}$	$\sigma_{c(100)}$	$n_{(eff)}$	b^*	b
Surface	33.2	19.1	11.1	4.9488	0.4458
9.1	51.9	31.0	12.7	5.3423	0.4207
18.3	73.7	43.3	11.5	5.7170	0.4971
21.3	79.1	53.5	11.7	5.5452	0.4740
24.4	38.1	21.6	20.5	5.1059	0.2491
27.5	108.9	98.6	9.6	4.6347	0.4828
30.5	88.7	70.2	9.5	5.2204	0.5495
33.6	90.2	71.2	10.4	5.2470	0.5045
36.6	89.9	63.4	9.5	5.5797	0.5873
39.7	51.1	33.5	9.4	5.1704	0.5501
42.7	59.0	38.2	9.9	5.3375	0.5392
45.8	91.7	62.7	10.1	5.6699	0.5614
48.8	92.4	60.9	9.2	5.7526	0.6253
51.9	112.4	97.2	7.2	5.0239	0.6978
54.9	53.9	29.6	7.1	5.4931	0.7737
58.0	75.2	62.0	7.6	4.8828	0.6425
61.0	60.2	37.3	9.6	5.4337	0.5660
67.1	52.3	30.6	10.1	5.3799	0.5327
70.1	77.2	43.1	9.1	5.8318	0.6409
73.2	55.7	42.7	7.8	4.8675	0.6240
76.2	93.1	43.9	8.1	6.1985	0.7652
82.3	107.2	98.4	6.9	4.4773	0.6489
91.5	95.8	64.9	6.5	5.7333	0.8821
94.5	80.5	50.8	8.7	5.6937	0.6545

4 CONCLUSION

A method for estimating the sensitivity of sandstone to its water content has been presented. From an analysis of the results of Hawkins and McConnell (1992), this sensitivity is found to be highly dependent on the effective porosity (n_{eff}) and to be applicable to more than the strength reduction. An advantage of the presented method is that fewer tests are necessary for calculating the influence of the water content on the rock properties. From measurements of the density and the uniaxial compressive strength in case of dry and saturated petrophysical states, the strength as a function of water content can be easily determined, both in terms of relative (i.e. water content as a percentage of the rock mass) and absolute (i.e. degree of saturation) scales.

According to the results of Vásárhelyi (2002, 2003, 2005), the sensitivity of other mechanical constants (i.e. Young's moduli, tensile strength etc.) to changes in water content is likely to be similar to the sensitivity of the uniaxial compressive strength, and thus, this method could be used to estimate the water content sensitivity of these mechanical properties, as well.

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