INFLUENCE OF THE WATER SATURATION ON THE STRENGTH OF VOLCANIC TUFFS

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ABSTRACT

Different Hungarian volcanic tuffs (andesite, basalt and rhyolite) were investigated with the goal to determine the influence of the water on their strength. The following petrophysical constants were measured for all the samples both in dry and saturated condition: bulk density, ultrasonic wave velocity, unconfirmed compressive strength (UCS) and Young's modulus. The destruction work (strain energy) was calculated from the measured stress-strain curves, as well.

The influence of the water for the UCS, impedance (scalar of the density and the ultrasonic wave velocity) and the destruction work is shown. In these cases linear relationship can be written between the dry and the saturated constants. Both linear and power equation can be used for the effect of the water on Young's modulus. Finally the UCS is written as the function of the density and the impedance.

1. INTRODUCTION

Recently several investigations were carried out for determining the strength of different volcanic tuffs in Hungary: i.e. the most of the wine-cellars in North Hungary were mined in tuffs (e.g. the famous Tokaj wine cellars) or some of the castles and towers were built on the top of this type of rock (as important monument as for example Visegrád, the capital of Hungary during the Medieval ages). The purpose of this paper to analyse the results of 12 rhyolite tuffs, 8 andesite tuffs and 10 basalt tuffs which were from different parts of Hungary. Certainly, every tuff is from different formation thus had different mineral composition. Although the tuffs have different mineral contents, grain-size, porosity, etc. the results show same general characteristics for this type of rocks. The results of tests are summarised in Table 1, which values are the average of 5 tests.

Specimen preparation and testing were performed in the Rock Mechanics Laboratory at the Technical University of Budapest. Each tests were carried out in two petrophysical states: dry and water saturated and measured the bulk density (ρ) and the ultrasonic wave velocity (v) in which the impedance was calculated. Right circular cylinders were prepared, following the ISRM suggested methods (ISRM 1978), with a diameter of 54 mm and the height:diameter ratio is 2:1 or slightly above. In addition to the standard values of unconfined compressive strength (UCS) and modulus of elasticity (Young's modulus, E), the complete stress-strain curve was measured. From the stress-strain curve the destruction work (or strain energy – W) was also calculated in both petrophysical states.

Rhyolite tuff							
ρ [g/cm^3]		σ_c [MPa]		E [GPa]		v [km/sec]	
dry	*sat.*	*dry*	*sat.*	*dry*	*sat.*	*dry*	*sat.*
1.012	1.465	2.59	1.15	0.26	0,13	1.13	0.91
1.349	1.644	4.95	1.59	0.58	0,17	1.20	0.91
1.350	1.673	4.67	1.74	0.68	0,21	1.30	1.08
1.356	1.646	5.54	2.02	0.57	0.22	1.59	1.00
1.369	1.635	5.6	1.91	0.67	0.18	1.34	0.92
1.371	1.667	8.49	3.35	1.01	0.33	1.50	1.20
1.385	1.689	7.66	2.24	0.91	0.19	1.45	1.01
1.390	1.696	10.03	7.83	2.78	2.54	2.25	3.30
1.425	1.702	7.81	2.94	0.76	0.27	1.47	1.18
1.427	1.715	5.36	1.20	0.60	0.10	1.18	0.86
1.456	1.749	21.81	21.27	7.04	6.83	2.85	2.79
1.900	2.048	39.75	26.92	6.85	4.64	2.39	2.17
Andesite tuff							
ρ [g/cm^3]		σ_c [MPa]		E [GPa]		v [km/sec]	
dry	*sat.*	*dry*	*sat.*	*dry*	*sat.*	*dry*	*sat.*
1.846	2.043	26.00	20.20	6.62	6.44	2.70	2.74
1.921	2.068	33.50	27.74	9.82	9.26	2.93	3.23
1.929	2.101	30.33	22.32	11.45	8.59	2.49	3.30
2.060	2.223	16.30	8.62	3.84	1.89	-	-
2.287	2.355	32.60	21.50	-	-	-	-
1.976	2.088	19.80	10.10	-	-	-	-
1.843	1.926	15.60	11.30	-	-	-	-
1.916	2.055	28.60	19.80	-	-	-	-
Basalt tuff							
ρ [g/cm^3]		σ_c [MPa]		E [GPa]		v [km/sec]	
dry	*sat.*	*dry*	*sat.*	*dry*	*sat.*	*dry*	*sat.*
1.106	1.371	8.50	8.30	1.76	2.00	1.32	1.50
1.225	1.428	3.34	2.48	6.16	4.67	1.53	1.69
1.311	1.610	3.05	1.76	6.96	5.92	1.53	1.76
1.419	1.642	4.36	3.4	8.96	9.06	1.52	1.82
1.446	1.753	8.30	14.04	19.67	11.20	2.03	2.83
1.643	1.885	8.34	12.88	14.40	12.60	2.17	3.21
1.652	1.606	3.83	3.10	6.84	7.66	1.33	1.50
1.938	2.024	14.12	13.07	8.64	6.29	3.02	4.01
1.986	2.080	40.29	18.43	7.50	5.37	3.71	3.83
2.257	2.288	63.36	53.20	14.22	14.71	3.18	3.73

Table 1: *Summary of test results. ρ bulk density; σ_c uniaxial compressive strength; E Young's modulus and v ultrasonic wave velocity.*

Recently several investigations have been carried out for determining the influence of the rock structure and the water on the petrophysical constituents in different points of view – see e.g. Hawkins & McConnel (1992), Plachik (1999) and Přikryl (2001).

2. RELATIONSHIP BETWEEN THE DRY AND THE SATURATED STRENGTHS

Firstly, the influence of the water for the UCS was examined. Figure 1 shows the plotted results, using linear regression determining the relationship between the dry and saturated compressive strength. The best fitting equation is ($R^2 = 0.892$):

$$UCS_{sat} = 0.729\ UCS_{dry} \qquad (1)$$

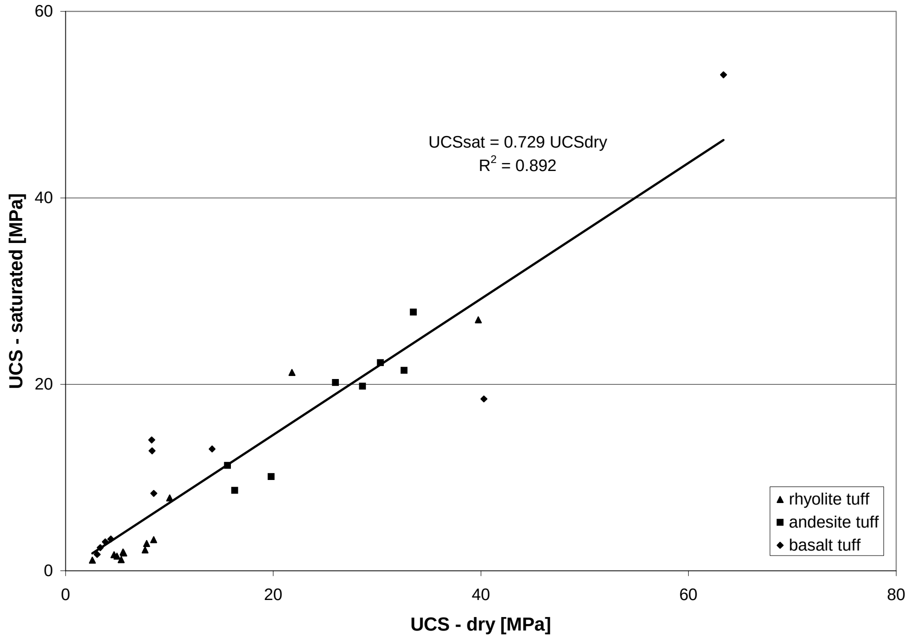

Figure 1: *Relationship between the dry and saturated UCS.*

The slope of the line for the different type of tuffs is the following: 0.712 ($R^2 = 0.858$), 0.759 ($R^2 = 0.864$) and 0.694 ($R^2 = 0.902$) in case of andesite, basalt and rhyolite tuffs, respectively.

Linear connection was found between the calculated dry and saturated impedance (z_a), as well (calculating with the scalar of the density and the ultrasonic wave velocity). Figure 2 shows the measured results with the curvilinear regression ($R^2 = 0.883$):

$$z_{sat} = 1.219\ z_{dry} \qquad (2)$$

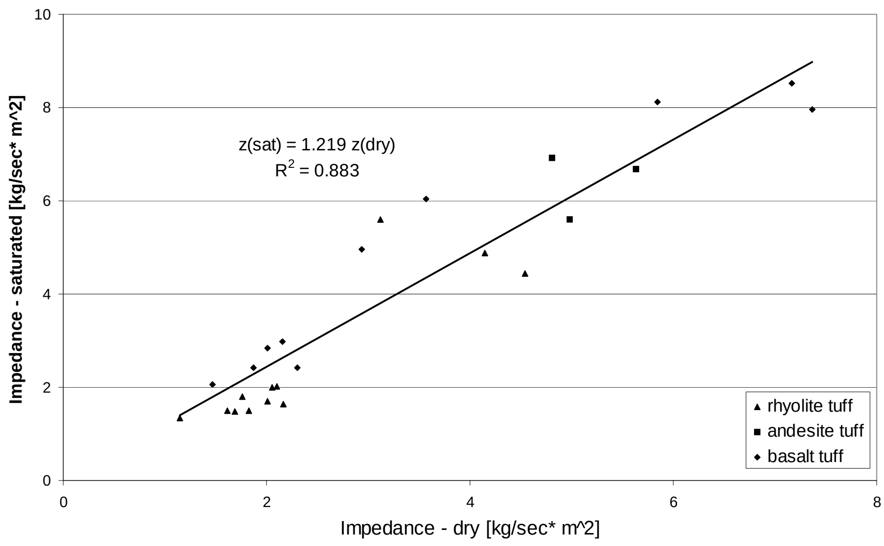

Figure 2: *Investigating the influence of the water for the impedance.*

The slope of the line is 1.096 (R^2 = 0.747) and 1.264 (R^2 = 0.888) for the rhyolite and the basalt tuffs, respectively, while for the andesite tuffs (due to the lack of measured results) it was undeterminable.

Writing the connection between the dry and saturated petrophysical state for the calculated destruction work (or strain energy - W) from the measured stress-strain curves linear regression can be written – see Figure 3. This notion was introduced by Thuro & Spaun (1996) and was also used for defining the dissipated energy by Vásárhelyi et al (2000). The slope of the line is 0.584 (R^2 = 0.849) - the slope for the different types: rhyolite tuff: 0.608 (R^2 = 0.885); andesite tuff: 0.672 (R2 = 0.861) and basalt tuff: 0.545 (R^2 = 0.833).

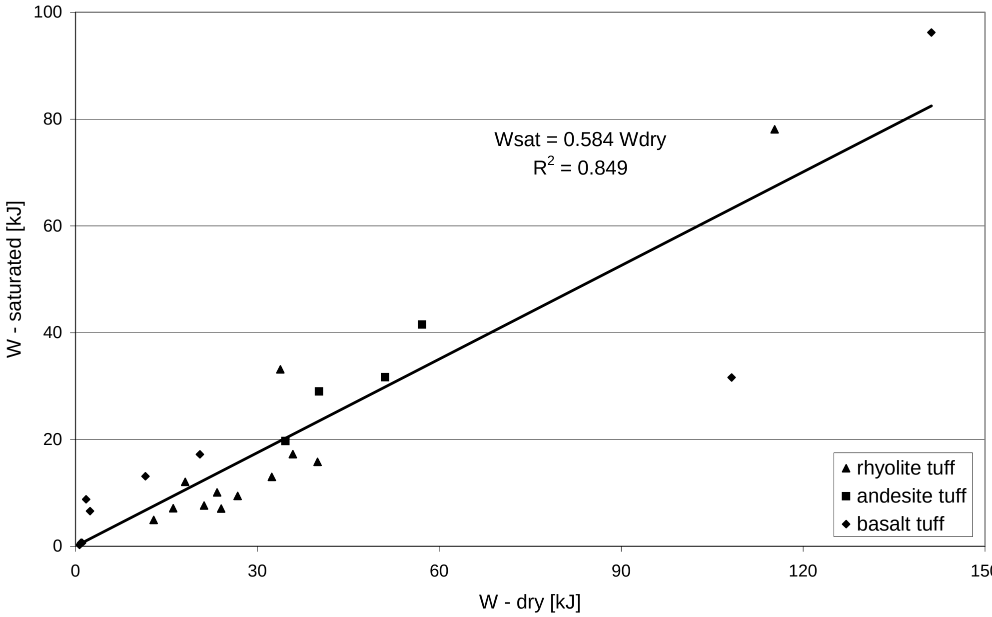

Figure 3: *Relationship between the dry and saturated destruction work (W).*

Using the squared fit method for writing the relationship between the dry and saturated Young's modulus we found that the squared regressions coefficients for linear and exponential laws were not significantly different. In the exponential equation we used the following form:

$$E_{sat} = aE_{dry}^{b} \tag{3}$$

where a and b are material constants, which are shown in Table 2. The linear regression was started from the 0; 0 point. The slope of the line (c) is shown in Table 3.

	a	*b*	R^2
Andesite tuff	0.318	1.441	0.903
Basalt tuff	0.587	1.305	0.809
Rhyolite tuff	0.379	1.368	0.926
Tuffs	**0.403**	**1.329**	**0.957**

Table 2: *The calculated constant according to Eq. (3) for the different types and the measured results, as well for the Young's modulus*

	c	R^2
Andesite tuff	0.836	0.861
Basalt tuff	0.799	0.694
Rhyolite tuff	0.812	0.938
Tuffs	**0.807**	**0.895**

Table 3: *The slope of the line in case of linear regression for the Young's modulus*

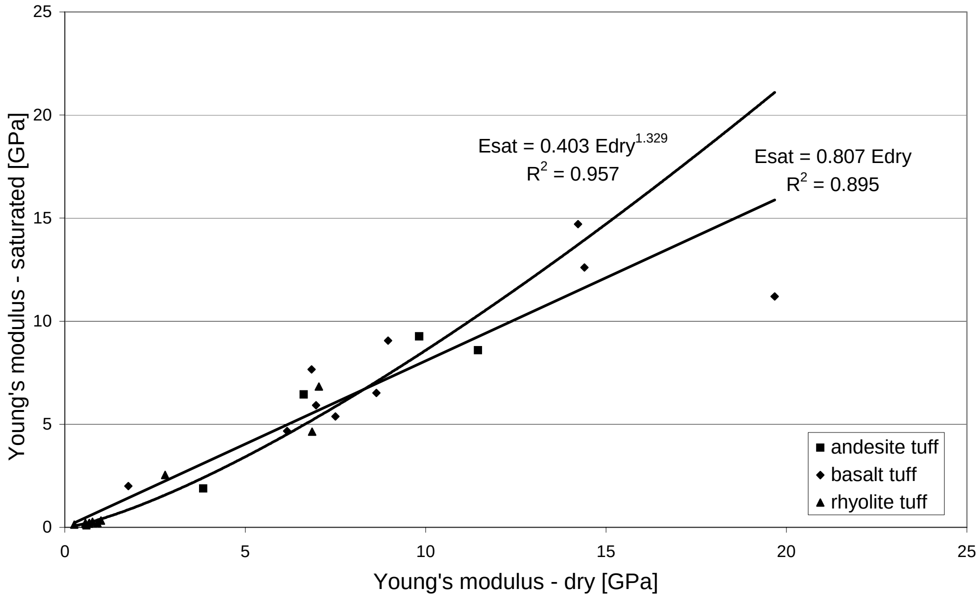

Figure 4: *Linear and power relationship between the dry and saturated Young's modulus.*

The UCS was represented in function of the density in Figure 5. In this case the following form of the relation was found:

$$\sigma = de^{e\rho} \qquad (4)$$

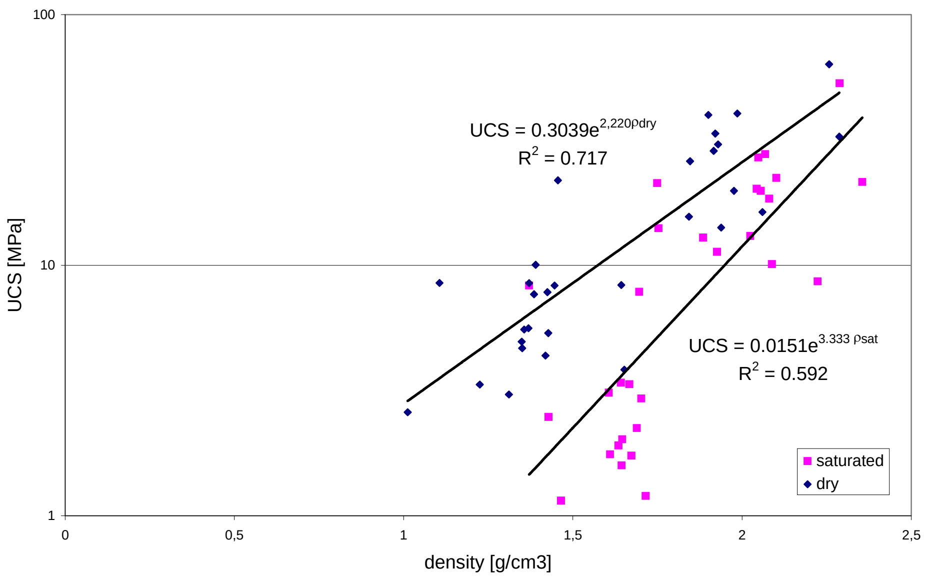

Figure 5: *Effect of density on uniaxial compressive strength. UCS in log scale.*

where *d* and *e* are material constants and ρ is the density of the investigated rock. These values are shown in Table 4. This connection coincides with the results of Smorodinov et al. (1970) where the similar result was found for different dry carbonate rocks.

	dry	saturated
d	0.304	0.015
e	2.220	3.333

Table 4: *The measured material constants for Eq. (4). The R-square is 0.717 and 0.592 in case of dry and saturated condition, as well.*

The intersection of the dry and saturated lines should be around the average bulk density of the tuffs, which is 2.70 g/cm^3. The theoretical UCS of these tuffs without porosity could be determined with these equation and it is around 122 MPa.

The relationship between the impedance and the UCS is shown in Figure 6. It can be seen that UCS increases with impedance. The relationship between UCS and impedance follows exponential (see Table 5) and power (see Table 6) laws. The R-squares were the following:

a) experimental regression 0.804 and 0.780 in case of dry and saturated states;
b) power regression: 0.800 and 0.825 in case of dry and saturated petrophysical states, respectively.

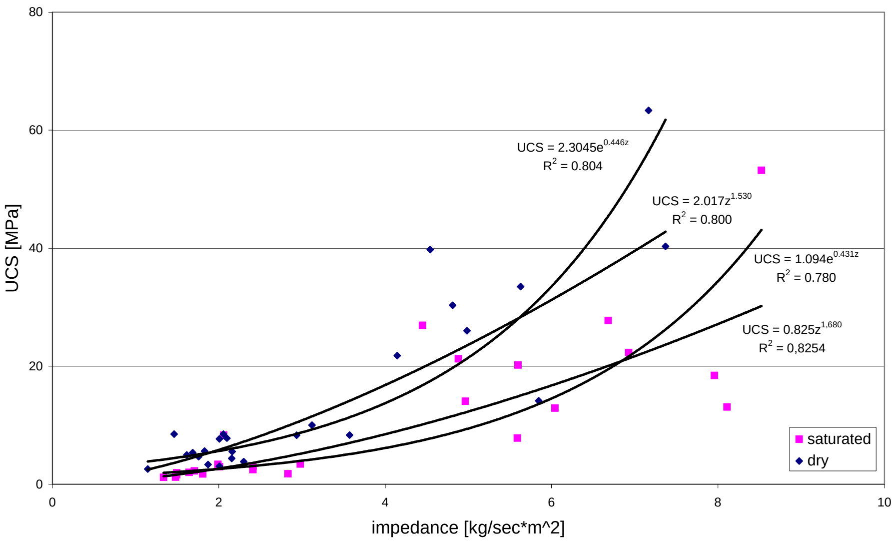

Figure 6: *The uniaxial compressive strength in function of the impedance - dry and saturated conditions.*

UCS = fe^{gz}	dry	saturated
f	2.305	1.094
g	0.446	0.431

Table 5: *UCS in function of impedance – exponential regression (f and g are material constants, z is the impedance).*

UCS = hz^i	dry	saturated
h	2.017	0.825
i	1.530	1.680

Table 6: *UCS in function of impedance – power regression (h and i are material constants, z is the impedance).*

3. CONCLUSIONS

The goal of this paper was to observe the influence of the water on the UCS, Young's modulus and the destruction work for different type of tuffs. Linear regression was found between the dry and the saturated UCS, impedance and destruction work, while both linear and power equations can be written for the Young's modulus. There is an exponential relationship between the density and the UCS in both petrophysical states. Both exponential and power equations can be used for predicting the UCS from the impedance. These results are in coincidence with the results of Vásárhelyi (2002) investigating the influence of the water on the petrophysical constituents of different type of sandstones. With this methods the "in situ" determination of physical and mechanical properties of rocks without sampling can be well elaborated (see in details: Kleb &Vásárhelyi, 2003).

The observed uniformity is somehow unexpected from the theoretical point of view. That is a fact that can not be explained in the frame of fracture mechanics. Up to now there is only a thermodynamic theoretical frame where such relation could be treated which is the stability theory of Ván (2001) and Ván & Vásárhelyi (2001).

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