A discussion on the decrease of unconfined compressive strength between saturated and dry rock samples

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ABSTRACT: The unconfined compressive strength (UCS) of a rock is a basic parameter for many characterization systems, strength criteria and calculation methods. It is well-known fact that it depends on the water content of the samples, and decrease when the water content increases. The paper discusses the possible causes of this reduction. From published data by Vásárhelyi and co-workers and others authors some empirical tentative guidelines for this reduction are proposed, which can be used in rock engineering problems where changes in water content occur regularly (dam and bridges foundations, harbors…).

1 INTRODUCTION

The unconfined compressive strength (UCS) is probably the most used of the rock index properties for their characterization. So all the standards have detailed regulations on the test and many authors have published on the effect of the sample size on the results of the test. The standards detail also the form and dimensions of the sample, the conditions of parallelism of the faces, even the speed of load application. But almost none of the standards say anything about the humidity of the samples. This is a surprising lack because the samples can be absolutely dry, air dry, semi saturated or saturated. And the water content, or the saturation state, has a clear influence on the results of the test. As a rule the strength diminishes when the water content increase, with a minimum in saturated samples.

So some experienced engineers advise to test the rock in the same humidity conditions in which the rock mass is going to stay. This is especially important in dam foundations (which are going to be saturated) or in rockfills. Some rules of thumb have been proposed to cope with this problem (Romana, 2003) when working with geomechanics classifications

There are a scarcity of published data on the unconfined compressive strength (UCS) of saturated samples with the exception of the work by Vásárely and co-workers. For instant Vásárhely and Ledniczky (1999) say that "it is known that saturated materials have lower strengths…than air-dry ones".

The aim of this paper is to point at the problem, to recollect the scarce published data, and to offer a first tentative quantitative approximation of the reduction in unconfined compressive strength of saturated rocks

2 DECREASE IN UNCONFINED COMPRESSIVE STRENGTH OF SATURATED ROCKS

Figure 1 (Pells, 1993) shows a Deere-Miller diagram (failure strength vs. deformation modulus at 50% of failure strength) containing data from compression tests in dry and saturated Hawkesbury sandstone. Saturation implies a reduction almost proportional in both parameters, but the relationship between them would remain approximately constant. Unfortunately no numerical result can be deduced due to the lack of numerical definition of the data

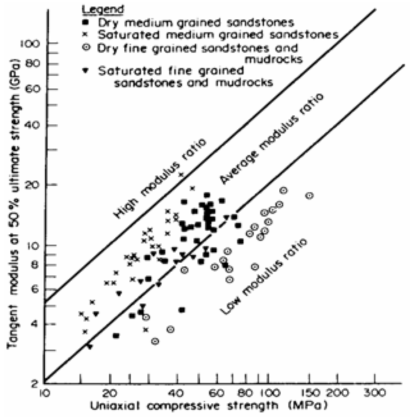


Figure 1.Strength data on Hawkesbury Sandstone (Pells, 1993)

.Hsu and Nelson (1993), in a preliminary research for the not built Super Collider, correlated the unconfined compressive strength of many types of shale (from Canada and USA) with the water content. Their results (fig 2), show a marked negative correlation between water content and compressive strength

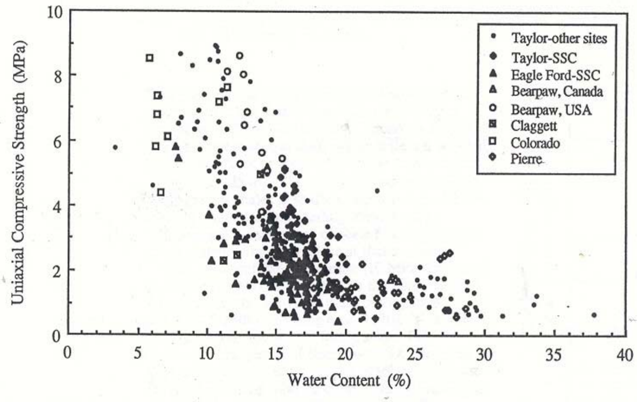


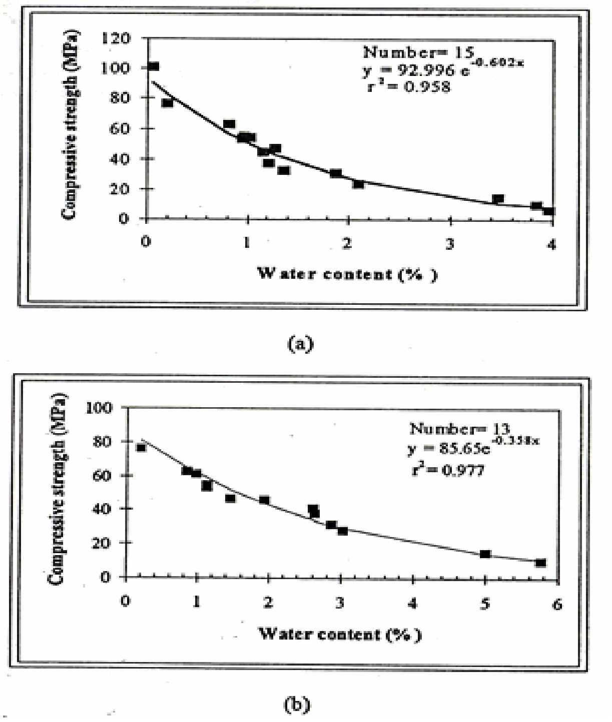
Fig 2 Unconfined compressive strength vs. water content for clay shales (Hsu and Nelson, 1993)

Ballivy and Colin (1999) have analyzed the increase in triaxial strength related to changes in the dielectric constant of the fluid saturating the rock. In a propane storage cavern in shale the tension strength of the rock increased 150-200% due to the change in the dielectric constant, with a reversal to the prior strength when the propane evaporated. In their opinion changes in the saturation fluid cause changes in the effective stresses, a result already stated by Vutukuri (1974). In the same paper they show increases in the compressive strength of 20% when testing gneiss saturated with salt water (with a small decrease in the dielectric constant) over the same test saturated with distilled water, and increases in the compressive strength of 25-50% of dry samples over the same test saturated with distilled water. These results show a clear trend but cannot be generalized due to the small number of tests done. The respective dielectric constant are: 80, distilled water; 74, salt water; 0 dry state

Lashkaripour and Passaris (1993) compiled a data base with selected values of shale rock properties. Fig 3 shows data from two coal mines. There is also a marked negative correlation between water content and compressive strength

3 CAUSES OF THIS DECREASE

In strong indurated rocks of low porosity the compressive failure is preceded by the growth of cracks from the border of existing micro pores. The cracks coalesce into growing cracks finally extending to the sample dimension and failure happens.



(a)

(b)

Fig 3. Unconfined compressive strength vs. water content for two shales (Lashkaripour and Passaris, 1993). (a) Linton Lane coal mine, (b) Rye Hill coal mine

According to Vásárhely and Bobet (2000) there are three fundamental theories on crack initiation criteria: maximum tangential stress (Erdogan and Sih, 1963), maximum energy release rate (Hussain et al, 1974) and minimum energy density (Sih, 1974). Any of them can reasonably predict tensile crack initiation, both in tension and/or compression, but not in shear. In the simpler case the crack initiation occurs as “a progressive lengthening of the crack across the infinite plate” (Rummel, 1974).The mathematical formulation “involves a consideration of the energy change during the crack growth”. Following Rummel there are three energy terms to be considered: change in potential energy of the applied forces, change of strain energy due to the existence of the crack and change in surface energy. So the Griffith criteria for tensile fracture can be stated (in the simpler formulation) as $\sigma_t = (2\ E\ \gamma\ /\ \pi\ c)^{1/2}$

where: σ_t is the tensile strength of the material
E is the deformation modulus
γ is the specific surface energy
c is the crack initial half length

As has been shown by Ballivy and Colin (1999) the nature of liquid has a direct influence in the crack openings, a fact due to the decrease in surface energy of the crack borders when the pore is full of water. A similar explanation is offered by Vásárhely and Ledniczky (1999): “moisture diminishes the spread of free surface energy, i. e. it facilitates micro-cracks propagation by decreasing the elastic limit and the peak strength also”

On the other hand the crack growth can be originated by increasing water pressures within the pores when the rock is saturated. Both effects can happen simultaneously

In poorly cemented rocks the presence of water can affect to the cementation between the grains by different ways: solution, dispersion…Finally in soft argillaceous rocks the water diminishes the strength of the grains and/or the cementation

So there are different causes which produce, together or unconnectedly, the reduction in strength

4.-SOME PUBLISHED DATA

Steiger and Leundt (1990) gave some data extracted from an EXXON comprehensive research program on shale typical properties, shown in table 1

Table 1.-Data on UCS of typical shales (Steiger and Leundt, 1990)

Shale	Dry UCS (MPa)	Sat UCS (MPa)	Decrease	Surface area (m^2/g)
E	96,5	44,8	32 %	2,2
F	82,7	27,6	67 %	3
G	34,5	3,5	90 %	10

Shale G is composed by a 50% of smectite, which can explain the big drop in strength and the simultaneous increase in surface area

Hawkins A. B. & Mc Connell B J. (1992) published a paper analyzing the sensitivity to water saturation of several mechanical properties of 35 British sandstones. Their results have been revised by Vasarhely and Van (2006) which have found a clear correlation between saturated and air dry unconfined strengths.

Lau et al (1993) carried out a study on the effects of temperature and water saturation on the mechanical properties o the Lac du Bonnet granite. “The water saturated specimens were observed to display lower stress values associated with crack initiation…when compared with dry specimens”. The reduction was in the order of 13% and was explained as “due to the very low permeability, and the undrained test conditions, the increase of pore water pressure during loading”

Ajalloian and Karimzadeh (2003) described the engineering properties of Givi dam foundation on andesitic rocks. Unconfined compressive test were performed both in saturated and dry condition in samples of the right bank. The reduction in strength was in the order of 18%.

Sachpazis (2004) collected representative samples of Bernician Great limestone (England) from four different metamorphic degrees, toward marble: A, none; B, low; C, high; D, completely metamorphised. Several geomechanics tests were performed, both in dry and saturated conditions. The mean results for unconfined compression tests are shown in the table 2. All the samples were very strong

Table 2.- Data on UCS of different limestones (Sachpazis, 2004)

Rock grade	Dry UCS (MPa)	Sat UCS (MPa)	Decrease
A	211,2	189.7	10%
B	106,1	94,6	11%
C	81,3	62,9	22%
D	87,8	74,8	15%

Vásárhely and coworkers have studied systematically the reduction in unconfined compressive strength (and also in deformation modulus) when saturating different rocks. Their results are shown in the figures 4, 5 and 6, and resumed in the table3

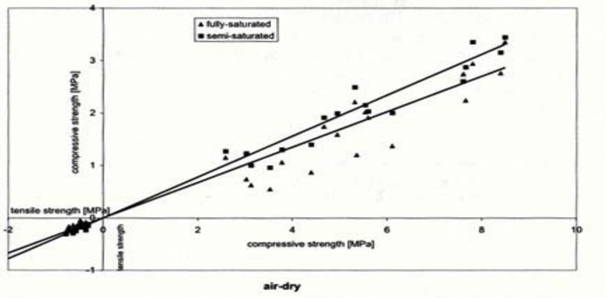


Fig 4 Saturated and semi saturated UCS vs. dry UCS in tuff samples (Kleb and Vásárhely, 2003)

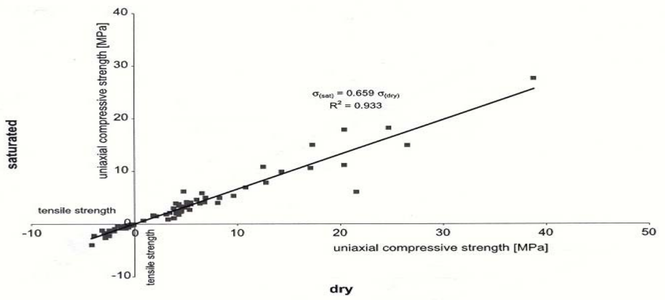


Fig 5 Saturated UCS vs. dry UCS in Miocene limestone samples (Vásárhely, 2005)

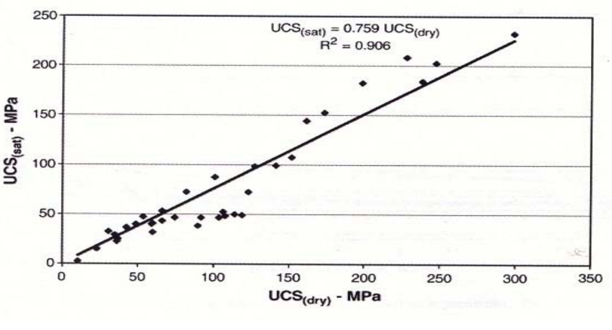


Fig 6 Saturated UCS vs. dry UCS in British sandstone samples (Vásárhely, 2006)

Table 3.-Decrease in UCS of saturated rocks (Vásárhely and co workers)

Rock type	Decrease (%)	$\sigma_{sat}/\sigma_{dry}$	Reference	Year
Sivac marble	7	0,93	Vásárhely & Ledniczky	1999
Volcanic tuffs	27	0,729	Vásárhely	2002
Miocene limestone	40	0,659	Vásárhely	2005
British sandstones	30	0,759	Vásárhely & Van on Hawkins & Mc Connell	2006

5.-CONCLUSIONS

Clearly more work is needed to quantify the reduction of unconfined compressive strength in saturated rocks. From the data collected for this paper a tentative rule of thumb could be proposed for the preliminary estimations needed when working with geomechanics classifications:

- well indurated strong rocks: UCS_{sat}/UCS_{dry} = 0,80-0,90
- cemented medium strength rocks: UCS_{sat}/UCS_{dry} = 060-0,70
- soft argillaceous rocks: UCS_{sat}/UCS_{dry} = 0,30

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