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RESEARCH ARTICLE

Influence of Water Content on the Mechanical Parameters of the Intact Rock and Rock Mass

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Abstract

The goal of this paper is to present the influence of the water saturation of the intact rock on different mechanical parameters, such as internal friction angle, cohesion, Hoek-Brown constant (m_i). Analyzing the previously published results, it was found that due to water saturation both the uniaxial compressive strength and tensile strength decrease similarly, i.e. the ratio of these two values is constant, thus the internal friction angle does not change but only the cohesion. Likewise, Hoek-Brown constant (m_i) remains constant; it is independent on the moisture content.

The ratio of the elastic modulus and the uniaxial compressive strength of the intact rock is also calculated. According to the laboratory results, this ratio (namely modulus ratio) is also independent on the water content.

It is shown that the mechanical parameters of the rock mass (such as compressive strength, tensile strength, deformation modulus) similarly depend on the water content than the intact rock.

Keywords

rock mechanics, water saturation, mechanical parameters, internal friction angle, cohesion, rock mass

1 Introduction

Recently, several researches have carried out various studies focusing on the influence of the water content on the mechanical parameters (e.g. uniaxial compressive strength, tensile strength, modulus of elasticity) of the intact rock. Wong et al. [1] collected the most important results in their review article.

According to the laboratory tests results, different mechanical parameters decrease due to increasing moisture content of the rock. Hawkins & McConnell [2] investigated the influence of the moisture content on the strength of the rock and they suggested the following form:

$$\sigma_c(w) = ae^{-bw} + c\ , \qquad (1)$$

where $\sigma_c(w)$ is the uniaxial compressive strength (MPa), w is the water content (%) and a, b and c are material constants. It is obvious that the strength at zero water content $\sigma_c(0) = a + c$, and the strength at full saturation $\sigma_c(sat) = c$. The schematic curve is plotted in Figure 1.

The parameter b is a dimensionless constant defining the rate of strength loss with increasing water content. According to the large number tests (investigated different British sandstones by [2]) these material constants are between 4.16–84.01; 0.0752–6.147; 2.97–231 for a, b and c, respectively.

Hawkins & McConnell [2] did not investigate the relationships between these material constants. However, it was not goal to analyse the published data, but it should be noted: parameter b can linearly depend on parameter a (see Fig. 2).

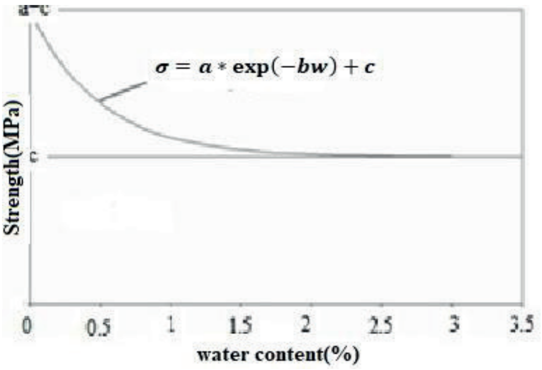

Fig. 1 Influence of the water content on the strength of the rock – schematic curve according to Eq. (1) [2]

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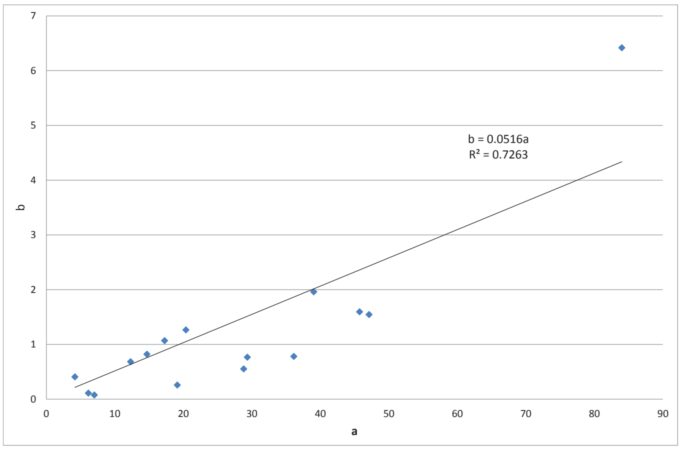

Fig. 2 Connection between parameters *a* and *b* (Eq. (2), data from Hawkins & McConnell [2]).

The disadvantage of the analysis method of Hawkins & McConnell [2] 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. Furthermore, the suggested fitting curve of Eq. (1) of Hawkins & McConnell changes if the relative water content goes to infinity. Vásárhelyi & Ván [3] recalculated the published data and changing Eq. (1) to absolute scale:

$$\sigma_{ci}(w) = a^* e^{-b^* w} + c^*, \tag{2a}$$

where $\sigma_c(w)$ is the uniaxial compressive strength (MPa), w is the water saturation (S). The strength at zero water content

$$\sigma_{ci}(S = 0) = a^* + b^*, \tag{2b}$$

and the strength at full saturation

$$\sigma_c(S = 1) = a^*\, exp(-100\, b^*) + c^*, \tag{2c}$$

and statistically b^* is 6.0259 [3]. According to Eqs. (1) and (2), the strength of the rock highly (exponentially) depends on the moisture content – there is not significant difference between the half saturated and fully saturated strength (see the results of Kleb and Vásárhelyi [4]). Thus only the dry and fully water saturated conditions are examined in this paper.

Due to water saturation, the mechanical parameters decrease and this ratio is rock type dependent. In Table 1. the ratio of saturated ($\sigma_{ci(sat)}$) and dry ($\sigma_{ci(dry)}$) uniaxial compressive strengths are summarized, using the collection of Zhang [5].

Therefore, we express the uniaxial compressive strength of the intact rock (σ_{ci}) in a single formula for the two petrophysical conditions (i.e. $S = 0$ – dry and $S = 1$ fully saturated) as indicated in Fig. 2.

$$\sigma_{ci(s)} = \sigma_{ci0}(S(\omega - 1) + 1), \tag{3}$$

where σ_{ci0} is the strength of the rock at dry condition, and ω is the ratio according to Table 1.

An example of the measured saturated strength as a function of dry strength is presented in Fig. 3 (results of [10]).

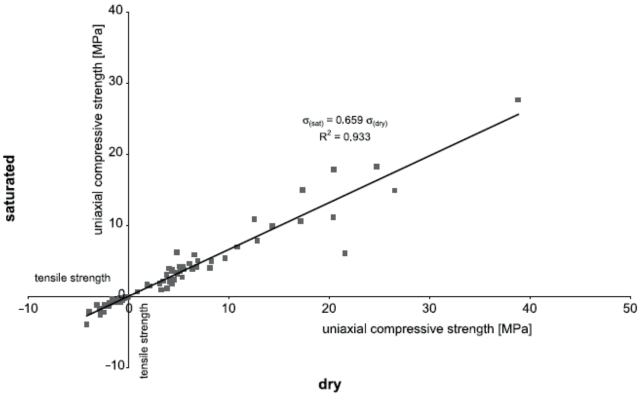

Fig. 3 The measured saturated strength as a function of the dry strength – miocene limestone [10]

Table 1 Ratio of unconfined compressive strength at saturation condition ($\sigma_{c(sat)}$) to that dry condition ($\sigma_{c(dry)}$) – ω - for different rock [5]

$\omega = \sigma_{c(sat)}/\sigma_{c(dry)}$	rock	reference
0.50	Shale and quartzitic sandstone	Colback & Wild [6]
0.76	Penrith sandstone	Dyke & Dobereiner [7]
0.75	Bunter sandstone	
0.66	Waterstone	
0.22–0.92	35 British sandstone	Hawkins & McConnell [2]
0.97	Oolitic limestone	Lashkaripour & Ghafoori [8]
0.62	Sandstone and sandy limestone	
0.81	Oolitic limestone and limy sandstone	
0.52	Shale	
0.76	British sandstone	Vásárhelyi [9]
0.66	Miocene limestone	Vásárhelyi [10]
0.59	Jastrzebie sandstone	Kwasneski & Oitaben [11]
0.49	Anna mudstone	
0.35	Gypsum	Yilmaz [12]
0.36–0.69	Limestone	Rajabzadeh et al. [13]
0.29–0.85	Dolomitic limestone	
0.33–0.64	Marble	
0.33	Tuffs from Eger (Hungary)	Kleb & Vásárhelyi [4]
0.729	Hungarian tuffs	Vásárhelyi [29]
0.88	Travertine	Török & Vásárhelyi [14]

Similar result was found between the dry and saturated Young's modulus (see Fig. 4). Zhang [5] collected some results (see Table 2). According to the published data, the Young's modulus of the intact rock decreases linearly due to water saturation, i.e.

$$E_{(sat)} = E_{(dry)}(S(\theta - 1) + 1)\,, \tag{4}$$

where $S = 0$ and $S = 1$ in case of dry and fully saturated condition, respectively. (note: for different moisture content the formulas presented in Eqs. (1) and (2) can be used).

Unfortunately, there is not any information about the influence of the water content on the Poisson's ratio – up to now it was not investigated.

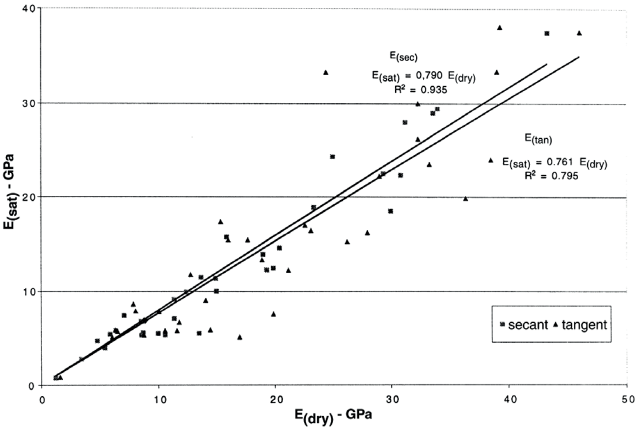

Fig. 4 influence of water content on the tangent and secant Young's modulus – British sandstones [9]

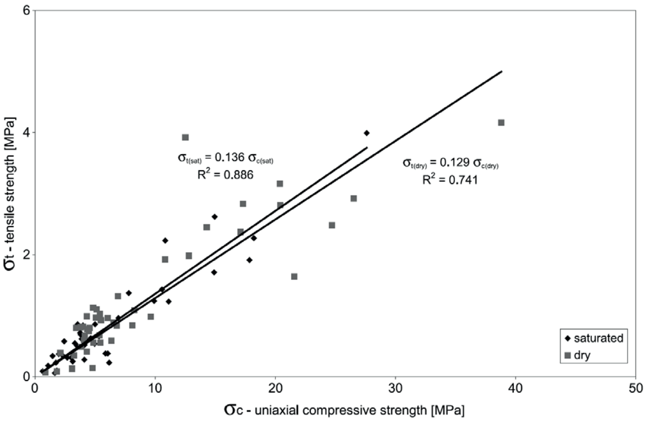

Fig. 5 Tensile strength in function of the uniaxial compressive strength as a dry and saturated condition [10]

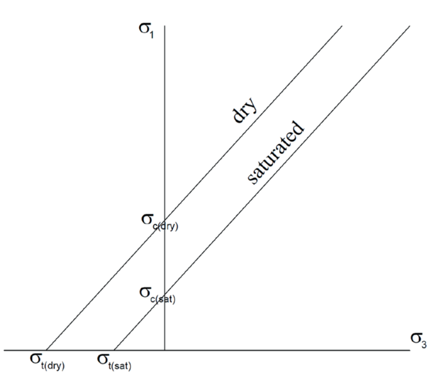

Fig. 6 Influence of the water content on the Coulomb-line

Table 2 Ratio of elastic modulus at saturated condition $E_{(sat)}$ to dry condition $E_{(dry)}$ for different rocks [5]

$\theta = E_{(sat)} / E_{(dry)}$	rock	reference
0.76	British sandstone	Vásárhelyi [9]
0.66	Miocene limestone	Vásárhelyi [10]
0.68	Jastrzebie sandstone	Kwasneski & Oitaben [11]
0.34	Anna mudstone	
0.54	Gypsum	Yilmaz [12]
0.81	Hungarian tuffs	Vásárhelyi [29]
0.79	Andesite	Karakul & Ulusay [15]
0.19	Ignimbrite	
0.32	Marl	

2 Influence of the water content on the failure of the intact rock

Vásárhelyi [10] investigated the influence of the water content on the ratio of tensile strength and compressive strength using large number of laboratory tests of high porosity Hungarian Miocene limestones. The ratio of these two mechanical parameters (i.e. uniaxial compressive strength, tensile strength) were constant, thus it is independent on the water saturation (e.g. see Fig. 5).

According to Cai [16], the rigidity of the intact rock can be calculated as the ratio of the uniaxial compressive strength and the Brazilian tensile strength of the rock, i.e.:

$$R = \frac{\sigma_c}{\left|\sigma_t\right|}. \tag{5}$$

Based on the measured and published data, R is a material constant, which is independent on the water content.

The test dataset compiled by Sheorey [17], although limited in number, shows a large variation of the strength ratio (R), from 2.7 to 39 with an average of 14.7. Vutukuri et al [18] stated that the strength ratio of most rocks varies from 10 to 50 and it is rock type dependent factor.

2.1 Mohr-Coulomb parameters

According to the Coulomb failure criteria, the internal friction angle (ϕ) can be calculated from the ratio of the uniaxial compressive strength (σ_c) and the tensile strength (σ_t):

$$R = \frac{\sigma_c}{\left|\sigma_t\right|} = \frac{1+\sin\varphi}{1-\sin\varphi}, \tag{6}$$

as it was shown before, this ratio is independent of the water ratio, thus the internal friction angle is material constant which is not influenced by the moisture content.

The cohesion of the rock (c) parallel decreases of the uniaxial compressive strength (see Eqs. 1 and 2).

The changing of the Coulomb failure criterion due to water saturation is presented in Fig. 6 – the two line should be parallel with each other.

2.2 Hoek-Brown parameters

Many laboratory tests were conducted for the development of the Hoek-Brown failure criterion for intact rocks (according to Hoek and Brown [19]):

$$\sigma_1 = \sigma_3 + \sigma_c \left(m_i \frac{\sigma_3}{\sigma_c} + 1 \right)^{0.5}, \tag{7}$$

where σ_1 and σ_3 are the major and minor principal stresses, respectively, m_i is a material constant and σ_c is the UCS of the intact rock.

Cai [16] showed that m_i constant in the Hoek-Brown failure criterion (Eq. 6) is equal to the ratio of UCS (σ_c) to tensile strength (σ_t) (see Eq. 4). This statement is true only if the strength ratio is high and it is assumed that the Hoek-Brown failure criterion correctly describes the strength behavior both tension and compression. According the calculation of Cai [16], when $R \geq 8$, the error for approximating m_i by R (Eq. 3) is less than 1.6 %, thus the Hoek-Brown parameter (m_i) can be calculated using the following form:

$$m_i \approx R = \frac{\sigma_c}{\left|\sigma_t\right|}, \tag{8}$$

according to Hoek [20], m_i values range from 4 to 33 for some commonly encountered rocks in engineering practice and m_i depends on many factors such as mineral contents, foliation and grain size (texture) – but as it was shown previously, m_i value is independent on the water content.

Shen & Karakus [21] emphasized the difficulties in determining the m_i values of rocks. They suggested to normalize the Hoek–Brown constant (m_i) by using strength of the intact rock (σ_{ci}). The modified version of the Hoek–Brown Eq. (7) is as follows:

$$\sigma_1 = \sigma_3 + \sigma c(m_{in}\sigma_3 + 1)0.5. \tag{9}$$

Where $m_{in} = m_i/\sigma_{ci}$. Recently, Vásárhelyi et al. [22] analyzed this equation and it was also denoted that the failure envelope of the intact rock can be determined more exactly with the help of this equation. In this case Eq. (3) can be used for determining the m_{in} value.

3 Modulus Ratio

The published data of different British sandstones by Hawkins and McConnell [2] were statistically analysed by Vásárhelyi [9]. He showed that the ratios between different mechanical parameters (such as tangent and secant modulus and uniaxial compressive strength) are independent on the water content. Fig. 7 shows an example of his paper [9]: the ratio of tangent modulus (E_{tan}) and uniaxial compressive strength (UCS) are 178 and 174 for dry and saturated states, respectively.

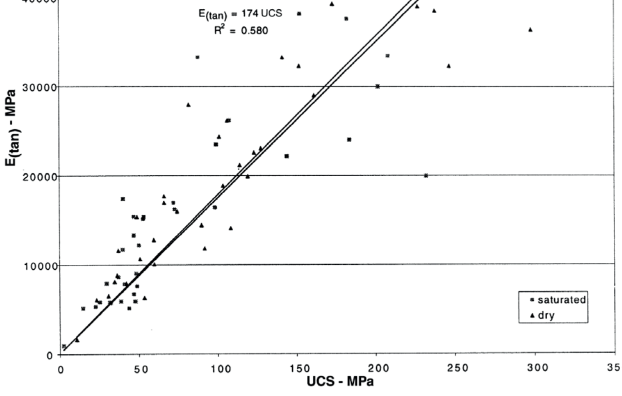

Fig. 7 Relationship between the uniaxial compressive strength (UCS) and the tangent Young's modulus (E_{tan}) in dry and saturated conditions [9]

The ratio of the Young modulus (E) and the strength of the rock (σ_{ci}) is the modulus ratio (MR), which can be used for calculations. This parameter is used in rock engineering when deformation of different structural elements of underground storage, caverns, tunnels or mining opening must be computed [23].

According to the measured results, this modulus ratio is independent on the water content, i.e.:

$$MR = E/\sigma_{ci} = \text{constant}. \tag{10}$$

4 Rock Mass mechanical parameters

There are several empirical formulas for calculating the mechanical parameters of the rock mass (see review article by Vásárhelyi & Kovács [24]). Recently, the generalized Hoek-Brown failure criterion is widely used in the rock engineering practice.

The generalized Hoek-Brown failure criterion for jointed rock masses is defined by [25]:

$$\sigma_1{}' = \sigma_3{}' + \sigma_{ci}\left(m_b\frac{\sigma_3{}'}{\sigma_{ci}} + 1\right)^a, \tag{11}$$

where σ_1' and σ_3' are the maximum and minimum effective principal stress at failure; and the Hoek-Brown parameters m_b, s and a are:

$$m_b = m_i e^{\frac{GSI-100}{28-14D}}, \tag{12}$$

$$s = e^{\frac{GSI-100}{9-2D}}, \tag{13}$$

and

$$a = \frac{1}{2} + \frac{1}{6}\left(e^{-GSI/15} - e^{-20/3}\right), \tag{14}$$

D is a factor which depends upon the degree of disturbance due to blast damage and stress relaxation [25], i.e. this value is independent on the petrophysical state of the rock.

GSI is the Geological Strength Index, can be calculated from the structure of the rock mass and the joint surface quality [20, 26, 27], thus this value is also independent on the water content.

It means that both Eq. (13) and Eq. (14) are independent on the saturation degree of the rock. As it was presented previously, the Hoek-Brown constant m_i is also not changing due to water saturation, i.e. Eq. (11) is independent on the water saturation.

It means, only the strength of the intact rock (σ_{ci}) decreasing in case of increasing moisture content in Eq. (11) – according to Eqs. (1…3).

Applying Eq. (11), the uniaxial compressive strength of the rock mass (σ_{rm}) can be calculated, using the following equation:

$$\sigma_{rm} = \sigma_{ci} s^a, \tag{15}$$

Where s and a constants are independent of the water content and the uniaxial compressive strength of the intact rock (σ_{ci}) can be calculated according to Eq. (3), or using Table 1.

Similarly, the tensile strength of the rock mass (σ_{trm}) can be calculated as following:

$$\sigma_{trm} = -\frac{s\sigma_{ci}}{m_b} . \qquad (16)$$

The deformation modulus of the rock mass (E_{rm}) can be calculated from the Young's modulus of the intact rock (E_i) and the rock mass classification (using e.g. GSI value), using the following form:

$$E_{rm} = E_i e^{\frac{GSI-100}{A}} , \qquad (17)$$

where A is an empirical constant (see [24]) – independent value on the petrophysical state. The deformation modulus of the rock mass should be decreasing linearly due to water saturation, according to Eq. (4), it is independent on the rock mass quality.

Ván & Vásárhelyi [32] suggested the following form for calculating the modulus ratio of the rock mass:

$$\frac{E_{rm}}{\sigma_{rm}} = \mathrm{MR.e}^{\frac{2(\mathrm{GSI}-100)}{100}} , \qquad (18)$$

where MR is the modulus ratio of the intact rock (see Eq. 10), E_{rm} and σ_{rm} are the deformation modulus (see Eq. 17) and the rock mass strength (see Eq. 15), respectively. According to the results, MR is a material constant, which is independent on the water content, thus the modulus ratio of the rock mass is also independent on the saturation degree of the rock.

Unfortunately, there is not any published data about the Poisson's ratio value of the rock mass.

Tokshiki and Aydan [33] proposed a direct method of determining the Poisson's ratio from the Rock Mass Rate (RMR) value:

$$\nu_{\mathrm{rm}} = 0.5 - 0.2\frac{RMR}{RMR + 0.2(100 - RMR)} . \qquad (19)$$

Using Eq. (19) the Poisson rate of the rock mass (v_{rm}) is between 0.3 and 0.5, independently of the water saturation.

Later, Aydan et al [34] modified Eq. (19). According to their publication, if the Poisson's ratio of the intact rock (v_i) is known, the following relationship can be used to determine the Poisson's ratio of the rock mass (v_{rm}) in the function of the Rock Mass Rate (RMR):

$$\frac{\nu_{\mathrm{rm}}}{\nu_i} = 2.5 - 1.5\frac{RMR}{RMR + (100 - RMR)} . \qquad (20)$$

According to Eq. (20), due to water saturation the Poisson ratio of the rock mass (v_{rm}) has to be changing similarly than the Poisson ratio of the intact rock (v_i).

Vásárhelyi & Kovács, [24] and Vásárhelyi [28] proposed the following relationship between the Hoek-Brown constant (m_i), the Geological Strength Index (GSI) and the Poisson's ratio of the rock mass (v_{rm}) – see Fig. 8.:

$$v_{rm} = -0.002GSI - 0.003m_i + 0.457 . \qquad (21)$$

As it was shown previously, both GSI and m_i are independent on the water content, thus one may suppose that Poisson's ratio value of the rock mass should be independent, as well, i.e. does not change due to water saturation. (Thus the Poisson ratio of the rock should be independent of the moisture content, as well).

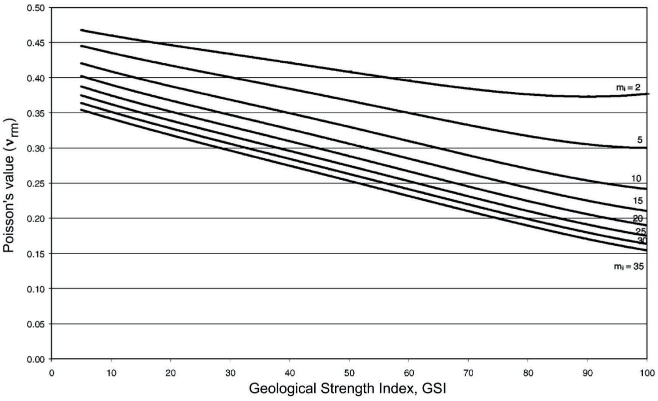

Fig. 8 Estimated Poisson's rate values (v_{rm}) in the function of the geological strength index (GSI) in case of different Hoek-Brown (m_i) constants [28]

5 Conclusions

Generally, due to the water saturation, the mechanical parameters of intact rock decreases. According to the experimental results, the ratio of the dry and saturated mechanical parameters are constants, it is rock material dependent. It should be mentioned, that similar results were obtained for different environmental effects (eg. [35]).

The mechanical parameters of the rock mass similarly depend on the water content than the intact rock, according to the empirical equations [24]. It means, the exact determination of the rock mass quality (e.g. Geological Strength Index – GSI or Rock Mass Rate – RMR) is very important for calculation the mechanical behavior of the rock mass but does not influence by the water content. The sensitivity of GSI based equations were calculated by Ván & Vásárhelyi [29] and it was found that these relationships are highly dependent on the input parameters changing one parameter with 5 %, and the final results may change more than 50 %!

In this paper mostly the results of Hungarian Miocene limestone [10] British sandstones [2, 3, 9] and rhyolitic tuffs from Eger (Hungary) [4] were analyzed, but similar results were found for other Hungarian tuffs [30] and these results can be used in general [31]. Notably, for a more precise and fundamental description of the mechanical behavior of rock, one should apply non-equilibrium continuum thermodynamics along the lines of [36, 37] and beyond. The similarity of the regression lines for the different rock types was unexpected from a theoretical point of view, although it is of note that a similar relationship has been reported as a consequence of damage related thermodynamic stability [38, 39].

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Nomenclature

c	cohesion
E	Young’s modulus
GSI	Geological Strength Index
m_i	Hoek-Brown parameter of intact rock
MR	modulus ratio
RMR	Rock Mass Rate
S	water saturation
w	water content
ϕ	internal friction angle
v	Poisson ratio
σ_{ci}	uniaxial compressive strength
σ_t	tensile strength

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