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Saturation Influence on Reduction of Compressive Strength for Carbonate Dimension Stone in Croatia

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Abstract: Dimension stone is a valuable mineral raw material whose importance is increasing worldwide. According to its mineralogical and petrographical composition, Croatian dimension stone belongs to the carbonates, primarily limestones. As saturation influences the reduction of compressive strength, in this study, the relationship between the uniaxial compressive strength in the dry and saturated states is shown, which has a coefficient of determination of 0.9605. Models were created to estimate the compressive strength based on the values of water absorption, total porosity, and real density of the material from 26 sites, all determined according to the European standards EN 1936:2006 and EN 13755:2008. Thirty varieties of dimension stones were tested, and 150 values were collected from different tests. A dependence between the uniaxial compressive strength in the saturated state was established, including the explanation in which cases the correlation can be used to estimate the uniaxial compressive strength of carbonate dimension stones with a remarkably high degree of confidence (0.994 and 0.9374). In addition, the limitations of geomechanical estimation of the uniaxial compressive strength of rock material and its unsuitability for estimating of dimension stones construction are described.

Keywords: dimension stone; limestone; uniaxial compressive strength; wet/dry ratio; estimation

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1. Introduction

The presence of water has a strong effect on rock properties and has been associated with several geological disasters, such as landslides, rockfalls, and fault activation. Accordingly, this fact must be considered when planning interventions in the natural environment [1]. Moisture is also known to affect the mechanical characteristics of brittle building materials [2] and gypsum [3–5], but the effects on stronger dimension stones should not be ignored. Dimension stone is a natural stone that is quarried and shaped into specific forms [6]. The dimension stone was used much more in past historical periods, especially in ancient times with the construction of representative buildings. In modern times, although dimension stone is primarily used as a decorative protective cladding for buildings, it has a broader application, including use for paving in the form of floor slabs, cubes, and others. It is usually formed into slabs of different thicknesses, which are then used for cladding interiors or exteriors, vertical or horizontal surfaces, staircases, landscaping, or the construction of monuments, as well as for restoration work on sacred and secular buildings [7]. Buildings constructed with dimension stone are exposed to various influences over time, especially the influence of moisture. An increase in humidity reduces the strength of the stone, which can have a significant impact on the renovation of historic buildings and the design of new buildings [8].

The effects of humidity on compressive and tensile strength have been studied more frequently [9–12], but in this study, the focus is on the effects on uniaxial compressive strength (*UCS*). Probably the first paper to demonstrate that moisture content has a significant effect on the compressive strength of rock was published by Price in 1960 [13]. He examined four different coal-measure rocks in oven-dried, air-dried, and saturated states

and found a reduction in compressive strength of up to 55%. In addition, Colback and Wiid [14] studied shale and quartzite-sandstone lithologies and found a 50% decrease in *UCS* in the water-saturated state. After these publications, many other papers were written, the most important of which will be mentioned in this chapter. The first explanations of the mechanism of reduction of rock strength under "humid" conditions were given based on tests on mine shales at different degrees of humidity [15]. It was concluded that moisture reduces the fracture work and increases the internal length of the cracks, reducing the strength of the shale.

In general, the influence of moisture content on *UCS* has been the most studied issue, and there are few papers on the influence on other physical and mechanical properties [8,16]. The research of Priest and Selvakumar [17], who studied Bunter sandstone, Bath limestone, Portland limestone, Carboniferous sandstone, Carboniferous limestone, and Magnesian limestone, should be highlighted. They found that the *UCS*, Young's modulus (E), and brittleness index decreased significantly with increasing moisture content, in agreement with the simple exponential model. On the other hand, no effect was found on Poisson's ratio. The empirical relationship [17] between *UCS* and moisture content (w) is shown by a negative exponential function:

$$UCS = ae^{-wb} + c, \quad (1)$$

where *UCS* is the uniaxial compressive strength (MPa), w is the moisture content (%), and a, b, and c are constants. In articles by Hawkins and McConnell [18] and Hawkins [19] that proposed a classification of sandstones according to their loss of strength owing to moisture, this equation was also employed. In this vein, Winkler [20] summarized several previous studies on changes in compressive strength due to saturation and proposed a "wet/dry" strength ratio (Table 1) as a rough indicator of the durability of stone.

Table 1. Durability of stone, according to Winkler [20].

Wet/Dry Ratio	Durability
0.8–1.0	Excellent
0.7–0.8	Good to excellent
0.6–0.7	Fair to poor
0.5–0.6	Poor
<0.5	Very bad durability

It is interesting that the study [18] inspired Vasarhelyi [21] to analyze the relationship between the strength of dry and saturated sandstone samples and establish a linear relationship between them:

$$UCS_{sat} = 0.759\, UCS_{dry};\ \left(R^2 = 0.906\right), \quad (2)$$

where UCS_{sat} is the uniaxial compressive strength (MPa) of saturated samples, and UCS_{dry} is the uniaxial compressive strength (MPa) of dry samples. Vasarhelyi and Van [22] modified Equation (1) by adjusting the constant b based on the effective porosity, so that equation had the form (3):

$$UCS = a^* e^{-wb^*} + c^*. \quad (3)$$

Majeed and Abu Bakarb [23] tested thirty-four sedimentary rocks (including limestones, sandstones, and dolomites) and generated an equation of interdependence:

$$UCS_{sat} = 0.57\, UCS_{dry} + 5.63;\ \left(R^2 = 0.72\right). \quad (4)$$

Four porous calcarenite building stones were examined by Rabat et al. [24] and generated an interdependence equation:

$$UCS_{sat} = 0.5416\, UCS_{dry};\ (R^2 = 0.939). \quad (5)$$

Tomor et al. [8] have created an Equation (5) based on the analysis of sandstone samples.

$$UCS_{sat} = 0.8017\, UCS_{dry} - 8.6108;\ \left(R^2 = 0.9138\right). \quad (6)$$

Bell and Culshaw [25] found that petrographic properties had a negligible effect on reducing physical and mechanical properties in saturated conditions for some sandstones, but later studies show that this cannot be true for all rock types. Wong, Maruvanchery, and Liu [26] conducted a comprehensive study and found that the reduction in *UCS* due to saturation is greater for sedimentary rocks than for igneous and metamorphic rocks. In addition, in papers that investigated the effect of saturation on the strength of sandstone from Taiwan [27,28], porosity was found to have a greater effect on *UCS* than grain and matrix content.

Turkish scientists [12] found that experimental results show that the properties of rock strength and deformability decrease with increasing saturation levels. Based on this research, they developed a predictive model (7) based on the principle of a multivariate equation with independent variables such as P-wave velocity (V_p), degree of saturation (S_r), and effective clay content (*ECC*).

$$\log(UCS) = 1.368 + 0.794 \log\left(1 + V_p\right) - 0.201 S_r - 0.056 ECC;\ (R^2 = 0.911). \quad (7)$$

Siltstone samples from Eidsvold in Australia were examined by Zhang et al. [29] at various saturation levels. About 32% of *UCS* was lost because of saturation. The model developed by Priest and Selvakumar (8) looks like the following equation in their case:

$$UCS = 22.104\, e^{-7.782\, s} + 48.571;\ (R^2 = 0.988), \quad (8)$$

where s is the saturation level, with $s = 0$ for dry and $s = 1$ for full saturation. Equation (9) was prepared on a similar principle but based on the testing of 41 sandstone specimens from Longchang, Sichuan Province, China [30].

$$UCS = 80.604\, e^{-0.9044\, w} + 43.17;\ R^2 = 0.97521, \quad (9)$$

where w is the moisture content (%).

In addition, various low-cost and non-destructive tests have been used to estimate the *UCS* for dimension stones [31–33]. The research [34] that looked at the relationship between *UCS* and Schmidt hammer rebound at a particular level of saturation is also worth highlighting. Fourteen different types of Turkish volcanic, sedimentary, and volcano-sedimentary rocks were investigated. On this basis, the degree of saturation (*Sr*) and Schmidt hardness (*N*) are used as independent variables to estimate the *UCS* according to the equation presented:

$$\log(UCS) = -1.656 + 2.269 \log(N) - 0.1023(Sr);\ \left(R^2 = 0.94\right). \quad (10)$$

Carbonate rocks were also analyzed, e.g., highly porous limestone samples from the Miocene [35] were analyzed using the proposed ISRM methods [36] and highly porous limestone samples [37]. Based on the analysis, linear and exponential equations (Table 2) were created to estimate *UCS* based on density.

In general, more attention should be paid to different types of rocks, which have often not been studied in the research described so far. Therefore, one of the main objectives of this study is to calculate the average *UCS* moisture loss for the carbonate type of dimension stone. For this purpose, the available data from tests of Croatian dimension stones on *UCS* in dry and saturated states according to EN 1926:2006 [38], as well as tests of water absorption, density, and total porosity, were analyzed. A new feature is that only European standards are used for testing stones for construction. Tests from a geomechanical point of view, which are common in this type of research, are not used. In this way, a more realistic

assessment of the effects of saturation on the *UCS* of stone used in construction is achieved, and there is no confusion with the practical study of the effects of saturation on stones in situ.

Table 2. Equations for estimating the dry and saturated *UCS* of limestone.

Rock Type	Equations	Source
Porous Miocene limestone	$UCS_{dry} = 55.791\ \rho - 87.74$; ($R^2 = 0.58$) $UCS_{sat} = 24.073\ \rho - 37.165$; ($R^2 = 0.924$) $UCS_{dry} = 8{\cdot}10^{-15}\ e^{20.622\ \rho}$; ($R^2 = 0.603$) $UCS_{sat} = 8{\cdot}10^{-10}\ e^{13.276\ \rho}$; ($R^2 = 0.905$)	[35]
Highly porous limestone	$UCS_{dry} = -4.6\ \rho + 9.51;\ (R^2 = 0.05)$ $UCS_{sat} = 2.1\ \rho - 1.1$; ($R^2 = 0.01$)	[37]

2. Materials and Methods

2.1. The Analyzed Material

Dimension stone is one of the most important non-energetic mineral raw materials in Croatia, exploited in the form of stone blocks, monoliths, or thin slabs. In the natural stone standard—Denomination criteria [39]—45 different stone varieties from Croatia were included; most of them are limestones [40,41] that are used in many Croatian and cultural heritage buildings and monuments worldwide [42–44]. Croatia is a country where stonework tradition and culture represent an important part of history, and the most famous dimension stone varieties on the market today are from the Istrian peninsula and from the island of Brač [45].

Taking into consideration the above-mentioned importance, several data points on the compressive strength of dimension stone varieties under dry and saturated conditions have been collected in Croatia during many years of research (Table A1, Figure 1).

Data on 300 different stone samples from 26 different sites were analyzed, and in this way, data for 30 varieties of stone materials were obtained. Among thirty materials, twenty-two petrographically different varieties can be distinguished. Most varieties are named after the quarry where they are excavated. Ten materials are from Istria, while nine are from the island of Brač. Three materials are quarried in the vicinity of Split, six in the vicinity of Zadar, and only two materials are from the inland—in the vicinity of Zagreb; the capital of Croatia.

Grožnjan, Lucija, Vinkuran, Kirmenjak, Selina, Kanfanar, and Valtura are both quarries and dimension stone varieties exploited on the Istrian peninsula. According to the petrographic features of Upper Cretaceous bioclastic limestones, Vinkuran can be divided into two basic sub-varieties: unito and fiorito, which differ in their properties [46]. Unito varieties are petrographically determined as biomicrite limestones. Their main petrographic characteristic is that rudist fragments are smaller than 2 mm and homogenously distributed through the stone. Unlike unito varieties, rudist fragments in fiorito varieties are larger than 2 mm and well preserved as large fragments. "Fiorito" varieties are mostly determined as biomicrudites. Similar varieties to Vinkuran are Grožnjan and Valtura, where both can be divided into two sub-varieties—unito and fiorito. Lucija is also Upper Cretaceous bioclastic limestone of a dark brown color. Stone is petrographically determined as bimicrudite, with numerous fragments of rudist bivalves in a dark matrix colored by a significant amount of organic matter and bituminous components. Kirmenjak is limestone of late Jurassic age, petrographically determined as micritic, dense, and whitish as ivory. Its main petrographic feature includes numerous parallel stylolites, spaced between 5 and 10 mm apart sporadically, even more of which influence the stone's properties. Stone has been used in numerous sensitive parts of the construction in Venice, usually in the areas where it is constantly exposed to alternating tidal wetting and drying [42,47]. Both Selina and Kanfanar are Lover Cretaceous oncolytic limestones with a distinct yellowish color that can be found on the market under the common name Istrian yellow. Stone variety is determined as oncoid

floatstone where the mass occurrence of the algae *Bacinella irregularis* RADOIČIĆ can be observed as the nucleus within numerous oncoids [48].

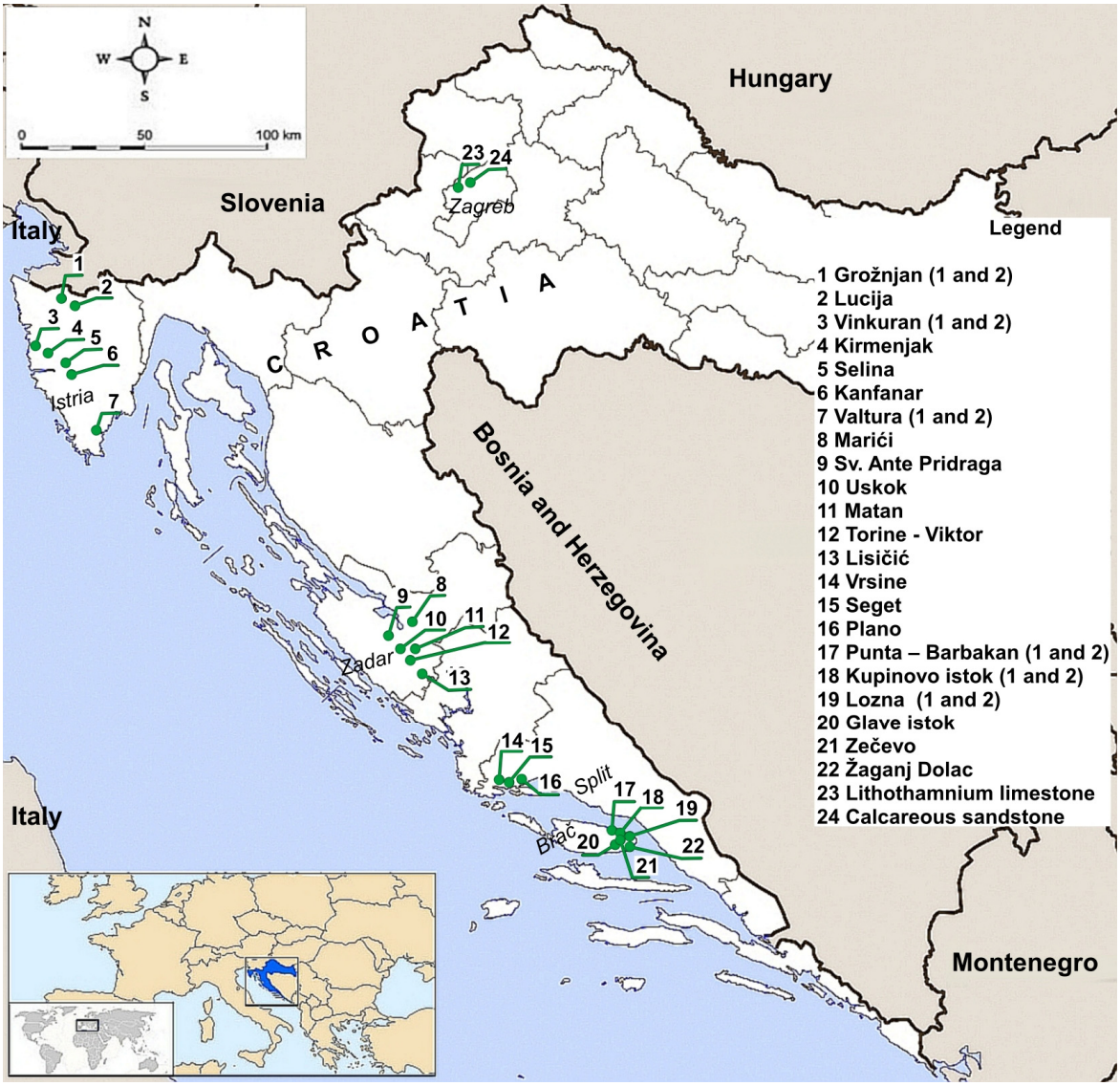


Figure 1. Sites where the varieties of dimension stone material were analyzed.

Marići, Sv. Ante Pridraga, Uskok, Matan, Torine—Viktor, and Lisičić are stone varieties and quarries in the hinterland of Zadar. Only the Marići variety is a clastic sedimentary rock, while other varieties are limestones. The Marići variety is a limestone conglomerate [41] to grayish in color composed of limestone fragments of different dimensions. Although stone is determined to be conglomerate and not limestone, because of its predominantly limestone composition, its properties could be compared with those of other stone varieties. The other five stone varieties (Sv. Ante Pridraga, Uskok, Matan, Torine—Viktor, and Lisičić) are similar in composition and petrographic characteristics, and on the market, they are commercially named Benkovac platy stone after the small town of Benkovac. The Benkovac platy stone of the Upper Eocene age is thinly bedded limestone, yellowish to grayish in color. This stone is traditionally used in the building industry, especially in the Benkovac town area. Bedding and lamination as structural anisotropy are the key features influencing its properties, while two different lithotypes (grainy and micritic) can be distinguished [49].

Three stone varieties (Vrsine, Seget, and Plano) of Upper Cretaceous age are rudist limestones named after the same quarries in the vicinity of Split [41,42]. All three varieties

are mostly homogenous and determined as bioclastic limestones (biomicrites to biosparites) with numerous visible fragments of rudist bivalves of different sizes, mostly up to 2 mm.

Two considerably different varieties commercially known as Veselje unito and Veselje fiorito of the Upper Cretaceous Age are quarried from three neighboring quarries (Punta Barbakan, Kupinovo Istok, and Lozna) on the island of Brač [41]. Both varieties are bioclastic limestones composed mainly of fragments or complete rudist bivalve shells. Veselje unito is characterized by completely crushed fragments of rudists that are smaller than 2 mm, while sometimes complete rudist fragments (larger than 2 mm) remain in the Veselje fiorito variety. The unito variety is often wrongly named "Brač marble" [42]. Dimension stone variety, commercially named San Giorgio, is quarried from the Glave quarry, while the Zečevo variety is named after the quarry of the same name [41]. Both varieties are dolomitized limestones determined as dolomitized biomicrite, beige in color with distinct darker bituminous veins that randomly cut through the stone. Stone varieties are partially dolomitized, and processes of dolomitization could influence stone material properties. Žaganj Dolac is a quarry where the commercially named Rasotica variety is quarried [41]. Rasotica is bioclastic limestone determined as biomicrudite with numerous visible cross-sections of rudist bivalves in a dark binder. This stone is dark brown in color due to abundant organic matter and bitumen, but the color fades over time due to the atmospheric conditions [42].

Lithothamnium limestone and calcareous sandstone of the Miocene age are two varieties that are no longer exploited, but during history, they were important building stone materials in the City of Zagreb [50]. Lithothamnium limestone is determined to be bioclastic limestone, with numerous fragments of coralline algae as *Lithothamnion*. Calcareous sandstones of mostly carbonate composition are associated with lithothamium limestone varieties, and accordingly, they can also be used in this study. Both varieties are porous and not durable under atmospheric conditions. Stone varieties that are autochthonous to the Zagreb area mutually differ in petrographic characteristics and durability to atmospheric conditions [42,51].

2.2. Methodology of the Dimension Stone Test

As for petrographic characteristics and their anisotropy influence on the physical and mechanical properties, macroscopic and microscopic petrographic analysis was carried out on thirty different carbonate samples, mostly limestones. Petrographic examination was carried out according to the European standard 12470 Natural Stone Test Methods—Petrographic Examination [52] for correct terminology during the determination of samples. European standard 12670 Natural Stone—Terminology [53] was used. The macroscopic description of samples was carried out by hand lens, while a microscopic description of thin sections was carried out with the polarizing microscope Leica DM LSP at the Faculty of Mining, Geology, and Petroleum Engineering, University of Zagreb.

The determination of real density, porosity, and water absorption was carried out according to the European Standards EN 1936:2006 and EN 13755:2008 [54,55]. The real density (kg/m^3) is expressed (11) by the ratio of the mass of the crushed dried specimen (m_e) to the volume of liquid squeezed out by the mass (m_e), using the equation:

$$\rho_r = \frac{m_e}{m_2 + m_e - m_1} \cdot \rho_{rh}, \tag{11}$$

where ρ_r is the real density (kg/m^3), ρ_{rh} density of water (kg/m^3), m_e mass of a crushed and dried sample (g), m_1 the mass of a pycnometer filled with water, and a crushed specimen (g), m_2 the mass of a pycnometer filled with water (g).

Total (absolute) porosity is expressed as the ratio (%) of the pore volume (open and closed) and apparent volume of the specimen with pores by the equation:

$$p = \left(1 - \frac{\rho_r}{\rho_b}\right) \cdot 100, \tag{12}$$

where p is total porosity (%), ρ_r real density (kg/m^3), ρ_b apparent density of the sample (kg/m^3).

Water absorption at atmospheric pressure is the ratio of the mass of the saturated specimen to the mass of the dry specimen. Water absorption (A_b) at atmospheric pressure is calculated according to the formula:

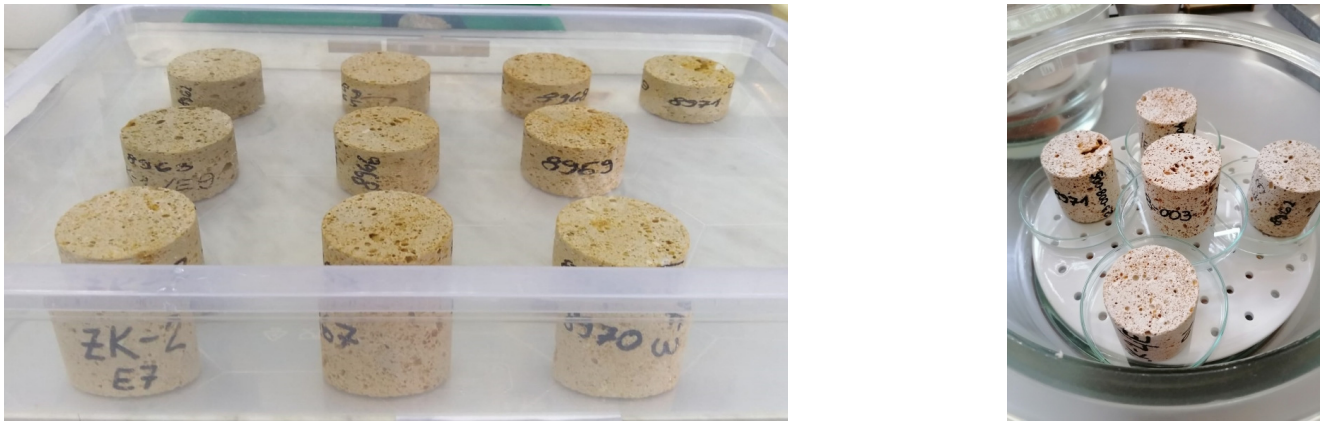
$$A_b = \frac{m_s - m_d}{m_d} \cdot 100, \tag{13}$$

where A_b is absorption of water at atmospheric pressure (%), m_d dry specimen mass (g), m_s mass of water saturated sample (g).

The determination of *UCS* was also carried out according to European Standard EN 1926:2006 [38]. The basic principle of this test method is the application of a uniformly distributed and continuously increasing load on dimension stone specimens of regular shapes until failure occurs. The specimens can be cubes with edges 70 ± 5 mm or 50 ± 5 mm or a circular right cylinder whose diameter and height are equal to 70 ± 5 mm or 50 ± 5 mm. The *UCS* is defined as the ratio (14) of the failure load of the specimen to its cross-section area before testing.

$$UCS = \frac{F}{A}\ , \tag{14}$$

where *UCS* is uniaxial compressive strength (MPa), F the highest force applied to the tested specimen (N), and A cross-sectional area of the undeformed specimen (mm^2). Before the UCS_{sat} test, the samples were saturated in water (Figure 2a), and before the UCS_{dry} test, the samples were dried and cooled in a desiccator (Figure 2b) without moisture.



(**a**) (**b**)

Figure 2. Sample preparation: (**a**) Saturation of calcareous sandstone samples; (**b**) Placing lithothamnium limestone samples in a desiccator for cooling.

2.3. Modelling Methodology

Previous studies have used simple and complex methods to create models to estimate the physical and mechanical properties of stone [56–60]. Simple models are based on diagrams and simple regression equations, while complex models are known as multiple regression equations, neural networks, fuzzy logic models, regression trees, etc. In this study, simple and multiple regression equations were created because the intention was to allow a wide application of the established models. The application of more complex models practically requires the possession of software packages that are not yet available in broad engineering practice. This is not the case with the use of equations. Therefore, the models in this study were created in Excel and the Statistica 14 software package [61],

which is a proven tool for statistical processing of the collected data and the creation of various types of linear and non-linear equations.

3. Results

The test results of the uniaxial compressive strength in dry and saturated states, density, porosity, water absorption, and calculated wet/dry ratio are presented in Table A1. The difference in the values of physical and mechanical properties between varieties is especially evident. The average values of UCS_{dry} and UCS_{sat} are 106.417 MPa and 93.054 MPa, respectively. The maximum value of UCS_{dry} for Žaganj Dolac is approximately 12 times higher than the value for calcareous sandstone, while UCS_{sat} for the same two varieties is even higher and amounts to 20 times. According to the average values of UCS_{dry} and UCS_{sat} materials, they belong to the category of medium-high *UCS* values [62]. Although five materials, three from the Istrian peninsula (Grožnjan 2, Vinkuran 2, and Valtura 2) and two from the Zagreb area (lithothamnium limestone and calcareous sandstone), show values of UCS_{sat} less than 38 MPa while having UCS_{dry} less than 45 MPa. These five materials are categorized as having extremely low values of *UCS* [62]. The average value for the wet/dry ratio of all tested materials is 0.854, belonging to the "excellent category" of durability. According to the average values of the wet/dry ratio, thirteen materials show values above 0.9, with the Vrsine variety having values of 0.982. While twelve materials have values in the range between 0.8 and 0.9, only five materials out of 30 show values below 0.8 (Valtura 1, Marići, Lozna 1, Lithothamnium limestone, and calcareous sandstone). Calcareous sandstone has the lowest wet/dry ratio values (0.559), which means that such a variety belongs to the "poor durability" category according to Winkler [20]. The other four materials have values between 0.5 and 0.6 and accordingly belong to the category of "poor to fair durability".

The average value of water absorption, as an important property influencing the UCS_{sat}, is 1.503%, which means that materials can be categorized as having moderate water absorption values [62]. It should be noted that six varieties (Kirmenjak, Selina, Valtura 2, Marići, Uskok, and Žaganj Dolac) have values less than 0.5%, corresponding to the category of very low water absorption values. Ten materials having values between 0.5 and 1% belong to the category of little water absorption, while 12 materials have moderate values. Only two materials, both from inland (Lithothamnium limestone and calcareous sandstone), belong to the category of high-water absorption values (4.29% and 9.97). In addition, both materials have values of total porosity greater than 10%, although the average value of total porosity for all 30 materials is 5.62%. According to the average values, all materials belong to the very porous material category [62]. Ten materials out of 30 have values less than 2.5% and are slightly porous, the same as the other ten materials, which have values between 5 and 10% and are moderately porous. The average value of the real density for the materials is 2681 kg/m^{3,} which is in accordance with the prevalent carbonate composition.

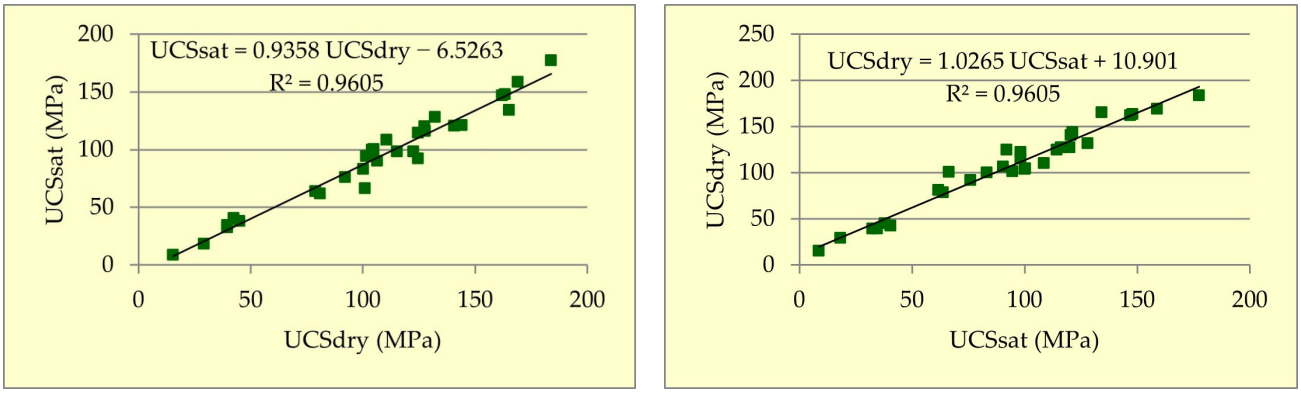
A high correlation was found between UCS_{sat} and UCS_{dry}, which is shown in Figure 3a,b. On this basis, Equations (15) and (16) were constructed, which have a coefficient of determination of 0.9605.

$$UCS_{sat} = 0.935\, UCS_{dry} - 6.5263;\ \left(R^2 = 0.9605\right), \tag{15}$$

$$UCS_{dry} = 1.0265\, UCS_{sat} - 10.901;\ \left(R^2 = 0.9605\right). \tag{16}$$

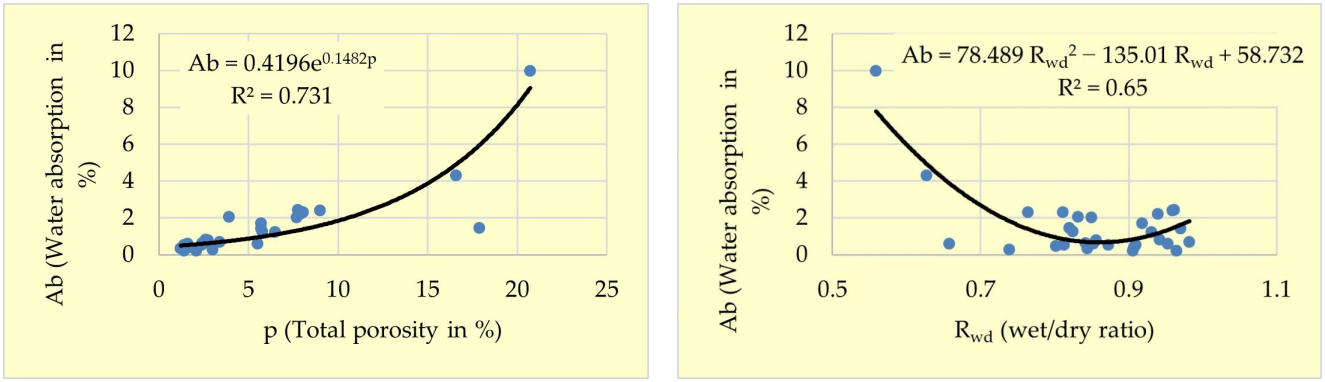
Other direct correlations with UCS_{sat} proved not to be sufficiently good, according to the coefficient of determination, so more complex analyses had to be carried out. The results of the other tests show no significant mutual correlations, except in the case of water absorption and porosity (Figure 4a). To some extent, water absorption is dependent on the values of total porosity, since the total porosity is defined by all pores in the materials, regardless of their origin, not just the ones that can absorb water. The wet/dry ratio shows a certain correlation (R^2 = 0.6591) to the values of water absorption (Figure 4b). Although

it was expected that the correlation would be significant, it can be assumed that not only water absorption influences UCS_{sat}, but other reasons could be connected to different petrographic characteristics of carbonate materials.



(**a**) (**b**)

Figure 3. *UCS* interdependence diagram: (**a**) UCS_{sat} with UCS_{dry}; (**b**) UCS_{dry} with UCS_{sat}.



(**a**) (**b**)

Figure 4. Interdependence diagram: (**a**) Correlations between water absorption and total porosity; (**b**) Correlations between water absorption and wet/dry ratio.

To investigate the influence of saturation on the reduction of *UCS*, modified constants of the moisture content dependence function were calculated for each individual dimension of stone material (Table A2). The constants were calculated according to the principle of Vasarhely and Van [22], using total porosity rather than effective porosity.

A non-linear regression equation was modeled using the Statistica 14 program package:

$$ln(UCS_{sat}) = -5.89598 - 0.03352A_b - 0.05528\ p + 10.78177\ ln(\rho_r); \quad (17)$$

were A_b water absorption (%), ρ_r real density (t/m^3), and p porosity (%). The coefficient of determination of this model is 0.7197, so it provides a satisfactory perspective for estimating UCS_{sat} for the entire set of 30 data points collected.

However, it was possible to make a better model for estimating UCS_{sat} at lower values up to 38 MPa. This Statistica 14 model works on the fixed nonlinear regression type and has the following form:

$$UCS_{sat} = 38.27062 - 4.73601\ A_b + 0.000000017e^{(p)}; \quad (18)$$

$$UCS_{sat} = 36.21556 - 2.97583\ A_b, \quad (19)$$

where A_b is water absorption (%) and p porosity (%). So, it provides an excellent perspective for estimating UCS_{sat} for the set of 5 data collected from Grožnjan 2, Vinkuran 2, Valtura 2, Lithothamnium limestone, and Calcareous sandstone. The performance of the developed equations is shown in Table 3.

Table 3. Performance of developed equations.

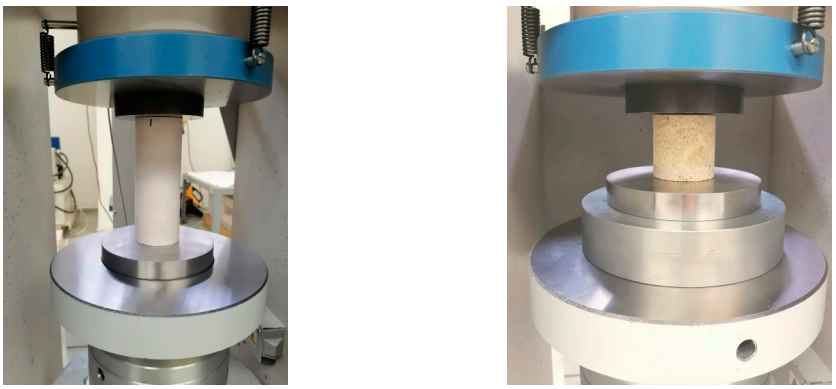
Equation	*R*	R^2	Adjusted R^2	Std. Error
17	0.84832953	0.71966299	0.6873164	0.37865
18	0.99714102	0.99429022	0.98858043	1.3286
19	0.96818005	0.93737262	0.91649682	3.5927

R—correlation coefficient, R^2—coefficient of determination, Std. Error—standard error of the estimate.

4. Discussion

The study of the effects of moisture content on *UCS* is especially important, as saturation leads to a reduction in the strength of dimension stone used in both historic and modern buildings, especially if the stone material is exposed to constant wetting under the load. Accordingly, among other things, different estimations must be used. The authors of this study are aware that *UCS* estimation cannot replace the performance of real *UCS* tests, but in certain situations, estimation can be relevant. For example, in the context of preliminary planning when investigating possible sites for mineral resources such as dimension stone, research was conducted towards the possibility of an estimation based on simpler and more accessible results of water absorption, density, and porosity tests.

Also, it should be noted that the definition of *UCS* in the EN 1926:2006 standard [38] can create some confusion in professional use, considering the same definition as well as the test method that was introduced a long time ago by the International Society for Rock Mechanics [36], which is quite different from this one. The main difference is in the height-to-diameter ratio of the test specimen, which, according to the Suggested Methods of the International Society for Rock Mechanics, should be 2.5–3.0 (Figure 5a).



(**a**) (**b**)

Figure 5. *UCS* testing: (**a**) according to the Suggested Methods ISRM [37]; (**b**) according to the standard EN 1926:2006 [38].

This is a significant difference in the failure mechanism and test results. Based on numerous tests conducted by different authors, it was determined that for a height-to-diameter ratio less than 2.5, there is a significant friction between the ends of the sample and the steel plates by which the load is applied to the sample, known as the clamping effect [63]. This results in an increase in the uniaxial compressive strength. However, a series of standard test methods (EN 1926:2006 [38]) were introduced for determining the uniaxial compressive strength of the sample with a height-to-diameter ratio equal to 1 (Figure 5b) for the purpose of determining the quality of the stone used as the construction material. It is interesting that the standard EN 1926 issued in 1999 [64] defined this test as

compressive strength, not uniaxial compressive strength, which in the author's opinion is a more appropriate definition. In any case, when interpreting, using, and creating *UCS* estimation models, one should pay close attention to the test method and use the prediction models appropriately.

The equation models develop to estimate *UCS* under saturated (15) and dry (16) conditions give excellent results, reflected in a remarkably high coefficient of determination of 0.9605. The average values of estimated UCS_{sat} (Table A2) are 93.877, with a difference between estimated and calculated UCS_{sat} of 0.8236. The estimated values for fourteen materials are lower than the calculated ones, while 16 materials act differently and have larger estimated values than the calculated ones. Eight materials out of 30 have a difference between estimated and determined values for UCS_{sat} (D_{e-d}) larger than 1, with a maximum value of 6.355 for Marići limestone conglomerate. As Marići is slightly different from the other materials, values were expected. Other materials have values lower than 1, regardless of the minus or plus sign. The minimum difference between the estimated and calculated UCS_{sat} is −0.064 for homogenous limestone Plano.

Compared to other published equations, the coefficient of determination of Equations (15) and (16) is higher [8,18,23,24]. In some situations where a quick estimation is required, the dependency equations established are therefore suitable for estimating the strength of carbonate-dimension stone material under dry and saturated conditions.

Constant reductions were calculated (Table A2) for all 30 variants studied, which can be used to estimate UCS_{sat} based on total porosity. This is a novelty compared to previous publications where the estimation was based on the effective porosity and the calculation was only presented for a few rock types.

The Equations (18) and (19) were based on material from Istrian sites (Grožnjan 2, Vinkuran 2, Valtura 2) and from the Zagreb area (lithothamnium limestone and calcareous sandstone). These materials show UCS_{sat} lower than 38 MPa with data of 32.4 MPa, 34.5 MPa, 38 MPa, 18.307 MPa, and 8.606 MPa (Table A1). The main reason for such values of UCS_{sat} (but also lower values of UCS_{dry}) should be related to the petrographical characteristics of varieties. Dimension stone varieties from Istria are bioclastic rudist limestones, usually named Fiorito varieties. Fiorito varieties have rudist fragments larger than 2 mm "swimming" in the micritic matrix and are mostly determined as floatstone. Fragments are not homogenously distributed through the material but are shaped as "flowers" in the matrix, hence the name. Because of larger fragments and their distribution, fiorito varieties in general have lower values of the *UCS* in both dry and saturated states than unito varieties, as evident in the case not only from Grožnjan, Vinkuran, and Valtura but also from Punta—Barbakan and Kupinovo istok materials from the island of Brač. Similarly, UCS_{sat} data should be connected to the values of total porosity and water absorption, which is especially evident for the lithothamnium limestone and calcareous sandstone varieties. These two varieties not only differ petrographically from the previously mentioned ones, but they also have significant values of water absorption and total porosity (Table A1). Compared to the previously published equations [35,37], Equation (18) has a much higher R^2. Therefore, it may be more suitable for the estimation of the UCS_{sat} of porous carbonates. Nevertheless, the authors advise some caution in its use, as it was created with only five data points.

In contrast to the previous studies, which dealt mainly with sandstones [2,8,18,19,21,25,27,28,30], this study deals with carbonate stone materials, which are used in Croatia as dimension stones for the construction and facades of buildings. Although raw materials of various geological types were mined in the Republic of Croatia in the past [43], today only carbonate types of dimension stone, mainly limestone, are mined [41,42,45]. It can be noted that limestones from Croatia are a heterogeneous group of stone varieties with different petrographic characteristics. Limestones can predominantly be micritic to the ones that are bioclastic with different fossil sizes (unito and fiorito varieties). Some varieties are more homogenous than those characterized by structural anisotropy such as layering or lamination. Precisely these differences in petrographic characteristics such as composition,

structure, homogeneity, and anisotropy can affect the properties of the stone material [42]. The investigation covered most sites geographically, and the results of this study can be applied to the Croatian cases as well as to the study of the influence of saturation on the strength of carbonate dimension stones in general.

Further research should be directed towards the inclusion of some index tests, such as the determination of Schmidt hardness; the equation with a higher R^2 than that obtained with Equation (17) could be modeled. Those tests can easily be performed on larger samples, e.g., commercial blocks in a quarry [65]. Therefore, they may also be suitable for evaluating *UCS* in a saturated state. Laboratory tests on rocks of volcanic, sedimentary, and volcano-sedimentary origin already strongly indicate this [34]. The influence of saturation on other types of strength (flexural and shear) has not been sufficiently studied, so more research should be conducted in this direction.

5. Conclusions

Since dimension stone is an important raw material not only in Croatia but also in other countries, it was imperative to determine the influence of water absorption and other properties on the reduction of compressive strength. The Croatian cases, as well as this study on the influence of saturation on the strength of dimension stones, can be applied to carbonate dimension stones in general. Indeed, it is a heterogeneous group of stone varieties with different petrographic properties, which needs to be thoroughly considered while estimating *UCS* in a dry and saturated state. In the material studied, the limestones are micritic to bioclastic and have different fossil compositions or sizes. In addition, some varieties are more homogeneous, while there are limestone varieties characterized by structural anisotropy such as layering or lamination. Nonetheless, the *UCS* estimation proved to have perspective considering the carbonate dimension stone from Croatia.

In this study, the UCS_{dry} ranged from 15.409 to 183.9 MPa, and the UCS_{sat} ranged from 8.606 to 177.5 MPa. The material had a water absorption of 0.2 to 9.97%, a real density of 2.386 to 2.773 (1000 kg/m^3), and a total porosity of 1.2 to 20.73%. The values of water absorption, real density, and total porosity can be easily determined with simpler, frequently performed tests. The values obtained are valuable and are suitable as input data for modeling the *UCS* estimate in the dry and water-saturated states. Tests were carried out on thirty different dimension stone materials with carbonate compositions, mainly limestone. For modeling the *UCS* estimate in the saturated state for dimension stones, it is recommended to use strength tests according to construction standards such as EN 1926:2006 [38] instead of methods where the rock is tested from a geomechanical point of view.

Based on research, various equations have been established in this study to estimate the *UCS* values. Equations (15) and (16) relate to the dependence between the *UCS* in the saturated and dry states. They can be used to estimate the *UCS* with remarkably high reliability for the limestone type of dimension stones. The coefficient of determination obtained in Equation (17), considering water absorption, real density, and total porosity, was 0.7197. In addition, reduction constants were calculated for the entire data set (Table A2), which can be used to estimate UCS_{sat} based on total porosity. The calculated correlation proved to be a satisfactory perspective for estimating UCS_{sat} preliminary design purpose for the complete set of 30 collected data points. Equations (18) and (19) can be used with caution to estimate UCS_{sat} values up to 38 MPa. Although the equations have extremely high coefficients of determination (0.994 and 0.937), they are still valid for a limited data set.

Further research is needed to determine the influence of moisture content on other types of strength, such as the flexural and shear strengths of dimension stones. In addition, other types of dimension stones, especially those with anisotropic petrographic features, could be tested for *UCS* estimation.

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Appendix A

Table A1. Test results.

Location	UCS_{dry}	UCS_{sat}	A_b	ρ_r	p	Wet/Dry Ratio
Grožnjan 1	115.2	98.2	0.583	2.713	5.5	0.852
Grožnjan 2	39.5	32.4	1.44	2.727	17.9	0.82
Lucija	127.6	116.1	0.534	2.689	2.4	0.91
Vinkuran 1	42.5	40.5	0.606	2.66	1.6	0.953
Vinkuran 2	39.5	34.5	0.517	2.668	1.5	0.873
Kirmenjak	163.3	148	0.215	2.72	1.4	0.906
Selina	162	147	0.366	2.718	1.6	0.907
Kanfanar	165	134.2	0.532	2.698	1.4	0.813
Valtura 1	101	66.5	0.578	2.712	1.6	0.658
Valtura 2	45	38	0.338	2.386	1.2	0.844
Marići	124.5	92	0.28	2.733	3	0.739
Sv. Ante Pridraga	144	121.3	0.62	2.69	2.42	0.842
Uskok	122.5	98.3	0.459	2.727	2.97	0.802
Matan	92	75.9	1.24	2.68	5.78	0.825
"Torine—Viktor"	127.5	120.1	0.8	2.69	2.6	0.942
Lisičić	140.7	120.5	0.78	2.725	2.75	0.856
Vrsine	110.5	108.5	0.678	2.701	3.4	0.982
Plano	101.5	94.5	1.234	2.702	6.5	0.931
Seget	132	128	1.42	2.708	5.7	0.97
Punta—Barbakan 1	106.4	90.4	2.02	2.703	7.7	0.85
Punta—Barbakan 2	100	83.2	2.06	2.705	3.91	0.832
Kupinovo istok 1	124.6	114.4	1.7	2.699	5.7	0.918
Kupinovo istok 2	104.7	100.4	2.4	2.712	9	0.959
Lozna 1	80.8	61.7	2.312	2.719	8.05	0.764
Lozna 2	78.7	63.8	2.288	2.714	7.96	0.811

Table A1. *Cont.*

Location	UCS_{dry}	UCS_{sat}	A_b	ρ_r	p	Wet/Dry Ratio
Glave istok	104	100	2.44	2.773	7.753	0.962
Zečevo	169	158.8	2.2	2.751	7.9	0.94
Žaganj Dolac	183.9	177.5	0.2	2.698	2.1	0.965
Lithothamnium limestone	29.199	18.307	4.29	2.465	16.59	0.627
Calcareous sandstone	15.409	8.606	9.97	2.457	20.73	0.559
Min value	15.409	8.606	0.2	2.386	1.2	0.559
Max value	183.9	177.5	9.97	2.773	20.73	0.982
Average value	106.417	93.054	1.503	2.681	5.62	0.854
Standard deviation	44.573	42.559	1.858	0.087	5.017	0.104

UCS_{dry}—uniaxial compressive strength in dry state (MPa), UCS_{sat}—uniaxial compressive strength in saturated state (MPa), A_b—water absorption (%), ρ_r—real density (1000 kg/m^3), p—total porosity (%).

Table A2. Values of constants according to [22].

Location	b*	b	c*	a*	EUCS_{sat}	D_{e-d}
Grožnjan 1	5.308	1.93	20.301	120.399	98.955	0.755
Grožnjan 2	5.081	0.879	16.201	75.799	32.315	−0.085
Lucija	5.489	1.848	24.3	98.2	116.92	0.82
Vinkuran 1	4.304	1.655	7.501	119.999	40.738	0.238
Vinkuran 2	5.425	2.242	22.8	121.2	35.073	0.573
Kirmenjak	5.075	0.659	16.101	90.299	153.122	5.122
Selina	5.124	1.31	16.901	83.099	149.312	2.312
Kanfanar	4.625	0.811	10.301	114.299	135.566	1.366
Valtura 1	3.761	0.418	4.402	100.298	67.581	1.081
Valtura 2	5.252	0.652	19.201	61.599	39.588	1.588
Marići	5.004	0.629	15.001	63.699	98.355	6.355
Sv. Ante Pridraga	4.625	0.585	10.301	158.699	121.989	0.689
Uskok	3.689	0.476	4.103	99.897	100.156	1.856
Matan	4.159	1.98	6.502	177.398	75.829	−0.071
"Torine—Viktor"	5.03	3.593	15.401	147.899	120.239	0.139
Lisičić	5.136	0.934	17.101	98.099	120.722	0.222
Vrsine	4.263	0.238	7.201	32.299	108.671	0.171
Plano	4.745	1.977	11.601	115.999	94.436	−0.064
Seget	5.011	3.132	15.101	146.899	127.919	−0.081
Punta—Barbakan 1	5.73	4.093	30.9	134.1	90.3	−0.1
Punta—Barbakan 2	5.844	3.653	34.6	66.4	83.099	−0.101
Kupinovo istok 1	4.248	3.54	7.102	37.898	114.303	−0.097
Kupinovo istok 2	2.996	1.873	2.105	40.395	100.299	−0.101

Table A2. *Cont.*

Location	b^*	b	c^*	a^*	$EUCS_{sat}$	D_{e-d}
Lozna 1	3.912	2.608	5.102	34.398	61.599	−0.101
Lozna 2	5.784	1.928	32.6	91.9	63.699	−0.101
Glave istok	2.996	0.881	2.105	108.395	99.898	−0.102
Zečevo	4.248	0.654	7.102	94.398	158.699	−0.101
Žaganj Dolac	3.689	0.647	4.103	127.897	180.228	2.728
Lithothamnium limestone	4.691	0.283	10.993	18.206	18.206	−0.101
Calcareous sandstone	4.22	0.204	6.904	8.505	8.505	−0.101

b^*, b, c^*, a^*—constants according to Vasarhelyi and Van [22], $EUCS_{sat}$—Estimated UCS_{sat} (MPa), D_{e-d}—difference estimated − determined for UCS_{sat}.

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