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Original scientific paper

CORRELATION BETWEEN UNIAXIAL COMPRESSIVE STRENGTH AND WATER CONTENT OF BEOČIN MARLS

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Abstract: The uniaxial compressive strength (UCS) is one of the most important strength parameters for evaluating the mechanical behavior of rocks and is widely used as a fundamental input in rock mass characterization systems, empirical classifications, strength criteria, and various engineering design and calculation methods. Weak rocks, such as marls, exhibit a pronounced sensitivity to water content, which can significantly influence their strength and deformation characteristics. This paper investigates the correlation between water content and the reduction in UCS of marl samples. A series of laboratory tests were conducted on specimens with varying water contents. The results show a clear inverse relationship between water content and UCS, with strength decreasing progressively as water content increases. This reduction is attributed to the weakening of interparticle bonds, softening of the clay matrix, and increased pore water effects within the rock structure. The experimental data were analyzed to establish empirical relationships between water content and UCS reduction, providing a basis for predicting strength degradation under different environmental conditions. The findings highlight the critical role of water content in controlling the mechanical behavior of marls and emphasize the need to account for water content in geotechnical design and stability assessments in marl formations.

Keywords: uniaxial compressive strength (UCS), water content, marls

1 INTRODUCTION

The uniaxial compressive strength (UCS) is one of the most fundamental mechanical parameters used to characterize intact rock and plays a central role in rock mass classification systems, empirical strength criteria, and engineering design methods. Reliable estimation of UCS is essential for evaluating the stability of slopes, foundations, and underground excavations. However, in weak rocks such as marls, UCS is highly

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sensitive to environmental factors, particularly water content, which can significantly alter strength and deformability and introduce uncertainty into engineering design.

Marls are transitional sedimentary rocks composed of varying proportions of clay minerals and calcium carbonate. Figure 1 represents the conventional mineralogical composition of the marls. The yellow shadow is to highlight the three sections where the marls are located. Clay mineral range between 25–75% and calcium carbonate range 75 – 25%. The rest up to 10% is mostly in the form of quartz and feldspar (Bahhou et al., 2021).

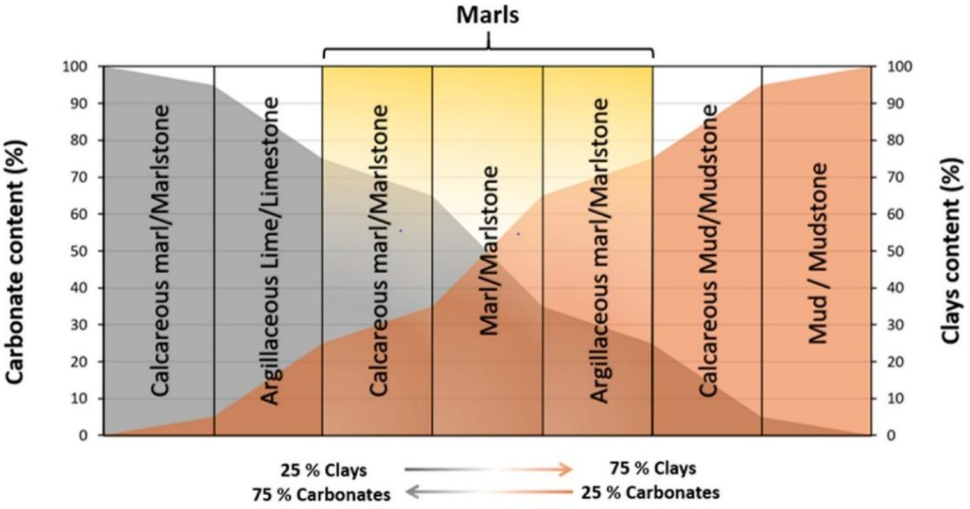

Figure 1 Conventional marls classification (Bahhou et al., 2021)

Due to this heterogeneous composition, marls exhibit complex mechanical behavior that can range from soil-like to rock-like depending on mineralogy, structure, and degree of cementation (Jaeger, 2007; Hoek & Brown, 1997). Their engineering properties are strongly controlled by factors such as clay content, porosity, and bonding, resulting in high variability in strength and stiffness (Bell, 2007). Recent studies further confirm that marl properties span a wide spectrum, from low-strength friable materials to well-cemented rocks with relatively high UCS values (Görög & Török, 2026).

A defining characteristic of marls is their strong sensitivity to water. Numerous experimental studies have demonstrated that increasing water content leads to a significant reduction in UCS (Vásárhelyi & Ván, 2006; Hawkins & McConnell, 1992). This behavior is primarily attributed to the softening of the clay matrix, degradation of interparticle bonding, and the influence of pore water pressure. Recent research confirms that the UCS of marls decreases noticeably under saturated conditions, even when initial dry strength is relatively high (Görög & Török, 2026). In addition, water affects the internal microstructure, leading to increased deformability and reduced stiffness.

The influence of water content on strength is not limited to marls but is a well-established phenomenon in other weak and clay-bearing rocks. Recent experimental and numerical studies show that water-rock interaction induces softening, crack propagation, and mechanical degradation under coupled hydro-mechanical conditions (Vásárhelyi & Ván, 2006; Cheng et al., 2024). Similarly, investigations on mudstones and other clay-rich geomaterials demonstrate that water absorption leads to swelling, microstructural changes, and significant reductions in strength due to physicochemical interactions (Wang & Yan, 2023; Comakli & Bayramov, 2024). These findings reinforce the understanding that water plays a critical role in weakening geomaterials, especially those containing clay minerals.

Recent literature has also focused on quantifying the relationship between water content and strength reduction. For example, studies on building stones indicate that UCS can decrease by up to 20–45% between dry and saturated states, with a large portion of strength loss occurring at relatively low water content levels (Tomor et al., 2024). This nonlinear behavior has also been observed in marls and similar materials, where rapid initial strength loss is followed by a more gradual decline with increasing saturation (Tomor et al., 2024; Bensaada et al., 2023). Such findings highlight the importance of considering partial saturation conditions in addition to fully dry and fully saturated states.

In parallel, recent research has explored stabilization and improvement techniques for marl materials to mitigate water content-induced weakening. For instance, the use of nanosilica additives has been shown to enhance the stability and durability of marl soils by modifying their microstructure and reducing deleterious reactions (Amiri et al., 2024). Other studies have investigated lime and thermal treatments, showing that controlled stabilization can significantly increase UCS and alter the material's microstructural behavior (Bensaada et al., 2023).

Despite these advances, predicting the strength behavior of marls remains challenging due to their inherent heterogeneity and sensitivity to environmental conditions. Existing empirical models often require calibration for specific materials and geological settings. Therefore, site-specific investigations are essential for accurately assessing the relationship between water content and UCS.

This paper focuses on marl formations located in Beočin, where such weak rocks are widely encountered in engineering practice. The geological conditions of this area provide a suitable framework for investigating the effects of water content on rock strength. The primary objective of this research is to examine the correlation between water content and UCS reduction through laboratory testing. By establishing empirical relationships tailored to the studied material, this work aims to improve the understanding of water content-dependent behavior and contribute to safer and more reliable geotechnical design in marl-dominated environments.

1.1 Cement Marl Mining at the "Filijala" Open Pit

The early exploitation of Beočin marlstone, locally referred to as “Beočin Kaja,” dates back to the 19th century. According to historical records from 1839, the British engineer Adam Clark used Beočin marlstone for the construction of the piers of the Széchenyi Chain Bridge between Buda and Pest. However, due to the lack of reliable documentation, it remains unclear whether Adam Clark can be credited with the “discovery” of this material, or whether it had already been exploited and used earlier, as suggested in some historical accounts (Vlajić et al., 2019).

In 1855, Josif Čik acquired the Beočin quarry from the company Weiner Wasser Bauamt and initiated the production of Roman cement at the present-day Filijala mining field, thereby establishing the first cement plant within the Habsburg Monarchy (Vlajić et al., 2019). The modernization of the production process was completed in 1869, when Portland cement manufacturing commenced. This period corresponds to the broader historical transition from natural (Roman) cement to Portland cement, which became the dominant construction material in the late 19th century (Varas et al., 2005).

The “Filijala” cement marl deposit, where the open-pit mine of the same name is located, represents the principal source of raw material for cement production today. The deposit consists of three mining sectors of unequal size and degree of exploitation: “Severno polje” (Northern Field), “Srednje polje” or “Međupolje” (Central Field), and “Južno polje” (Southern Field) (Ganić et al., 2012). The marl belongs to Upper Miocene (Pannonian) deposits and has been extensively studied in terms of its lithological and engineering-geological properties, Figure 2 and 3 (Ganic et al., 2010).

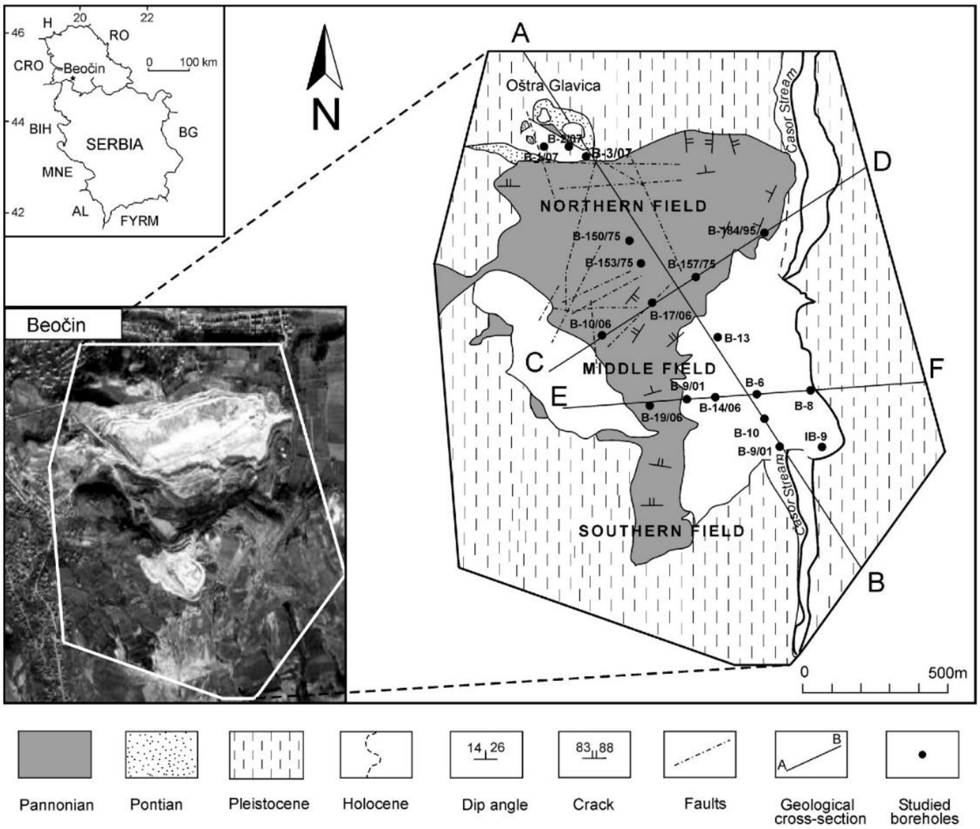

Figure 2 The geological sketch map of the "Filijala" Open Pit near Beočin. (Ganic et al., 2010)

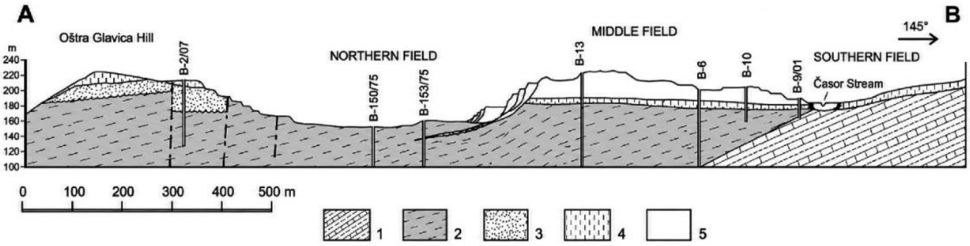

Figure 3 Geological cross-section A–B through the Miocene sediments on the "Filijala" Open Pit near Beočin. Legend: 1, Sarmatian (only in cross section) laminated marl, sandy marl, banded silty marl and siltstone, marly sandstone, stratified sandy limestone, lenses of conglomeratic marl, coaly clay, etc.; 2, Pannonian marl; 3, Pontian sand; 4, Pleistocene loess; 5, Holocene alluvial–prolluvial deposits, recent delluvial deposits and artificial deposits. (Ganic et al., 2010)

The “Filijala” Open Pit was initially developed within the “Severno polje” mining area. With the advancement and expansion of mining operations, the open-pit mine progressively evolved in accordance with production requirements and geological conditions (Vu et al., 2021).

The primary exploitation method is continuous mining technology, employing a bucket wheel excavator system, which remains widely used in large-scale surface mining due to its high production capacity and efficiency in homogeneous soft rock formations (Čelebić et al., 2024). However, due to variable geological and geotechnical conditions in cement marl deposits—such as heterogeneity, changes in water content, and variable strength—exclusive application of continuous mining is not feasible across the entire deposit (Vu et al., 2021).

Consequently, discontinuous mining technology is also applied. This method is used in zones where bucket wheel excavators cannot operate effectively due to high digging resistance, lithological variability, or selective extraction requirements (Čelebić et al., 2024). In addition, coordinated use of continuous and discontinuous systems is applied to ensure blending, quality control, and homogenisation of cement marl prior to processing in cement production plants (Vu et al., 2021).

Modern optimisation approaches in open-pit mining also highlight the importance of integrated production scheduling, equipment allocation, and haulage system design to improve efficiency and reduce operational costs, particularly in systems combining truck–shovel and continuous conveyor-based mining technologies (Čelebić et al., 2024).

1.2 Mineralogical–Petrographic and Chemical Composition of Marl

Mineralogical–petrographic investigations determined that the analyzed rock material can be classified as marl. The microcrystalline groundmass of the marl from the Filijala Deposit consists of approximately 75% finely dispersed carbonate material and about 23% clay fraction, dominated by montmorillonite with the presence of hydromica–illite. The coarser (sand-sized) fraction is represented by up to 2% of the rock mass and consists of rare angular grains of quartz, feldspar, fossil fragments, and occasional flakes of hydromica (Mihajlović et al., 2007).

Based on the statistical analysis of the chemical composition test results, the variability of the qualitative properties of the marl was determined. The statistical parameters describing the variability of the chemical properties of marl from the Filijala Deposit are presented in Table 1 (Mihajlović et al., 2007).

Table 1 Parameters of variability of chemical properties of marl

Component	Minimum value (%)	Maximum value (%)	Mean value (%)	Standard deviation (%)	Coefficient of variation (%)
SiO_2	7.420	31.841	18.362	2.838	15.454
Al_2O_3	2.71	7.957	6.061	0.994	16.401
Fe_2O_3	2.100	4.552	3.256	0.464	14.252
CaO	4.780	41.210	35.015	3.730	10.652
MgO	0.650	3.040	2.126	0.435	20.441
SO_3	0.526	3.934	1.738	0.415	23.857
$CaCO_3$	46.457	73.606	63.787	4.008	6.284
Loss on ignition (LOI)	23.216	37.760	31.520	1.640	5.204

With the modernization of the technological process and the application of the “dry process” for cement production, it is necessary to ensure that the technological requirement of a minimum $CaCO_3$ content of 60% is satisfied in the marl transported from the open-pit mine. The average $CaCO_3$ content in the “Severno polje” (Northern Field) mining sector is 64.42%, while in the “Južno polje” (Southern Field) it is 62.55%.

2 FIELD INVESTIGATIONS

At the test location within the "Filijala" Open-pit Mine, a detailed investigation program was conducted, comprising both field investigations and geomechanical laboratory testing. The field investigations included exploratory borehole drilling with continuous core recovery, followed by detailed core logging and mapping. A total of sixteen exploratory boreholes were drilled within the test zone of the open-pit mine, Figure 4

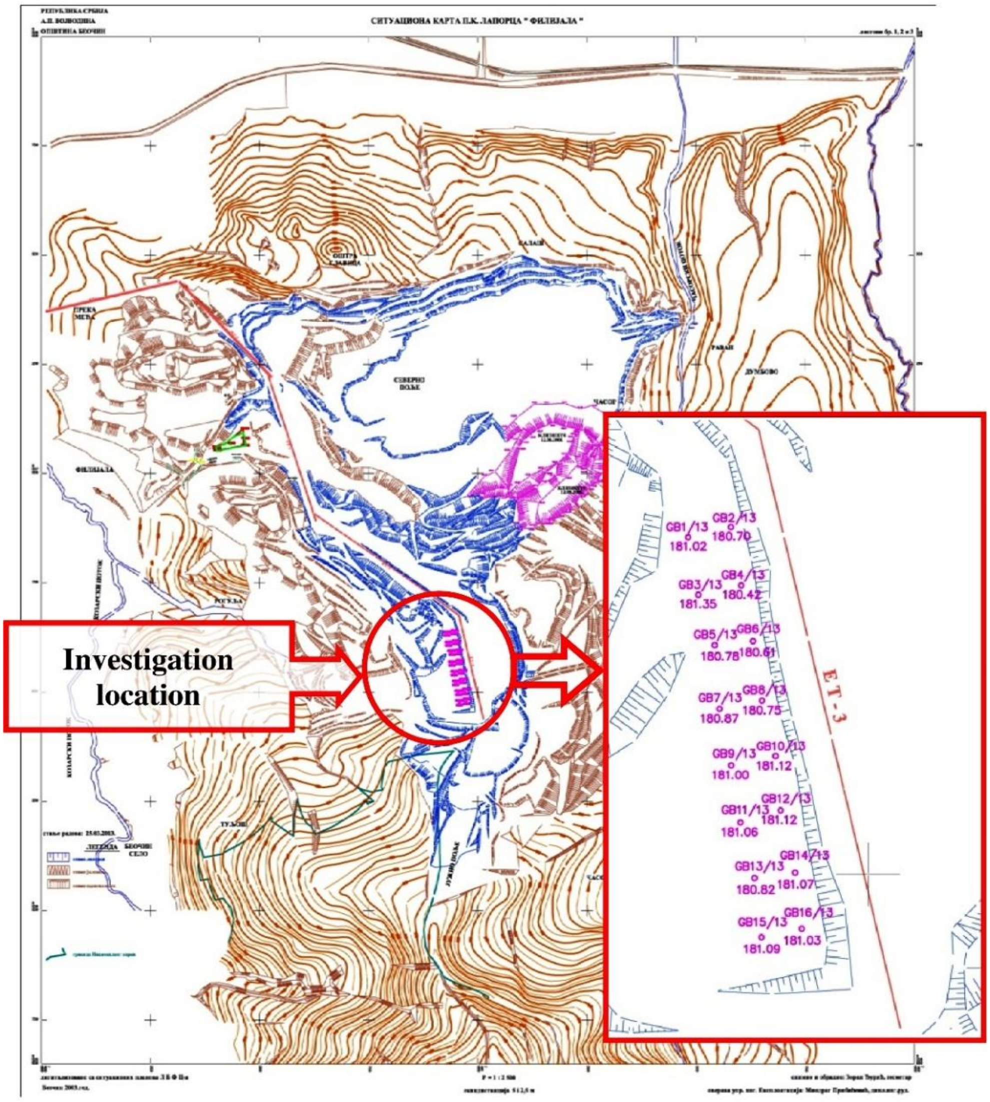

Figure 4 Disposition of investigation works at the test location within the "Filijala" Open Pit

Exploratory drilling was performed using a rotary drilling system with continuous coring. For this purpose, a GAK-300 drilling rig, together with the associated drilling equipment, was utilized. The primary objective of the field investigations was to determine the geological structure of the investigated micro-location. Based on the core logging results, representative intact rock material samples were selected, labeled, and prepared for subsequent geomechanical laboratory testing.

2.1 Methodology of Laboratory Testing

Cylindrical specimens were prepared in accordance with the recommendations of International Society for Rock Mechanics and ASTM International. The specimens were ground to obtain smooth, flat, and parallel end surfaces. The average specimen diameter was 85 mm, while the length-to-diameter ratio was 2.0.

Prior to testing, the dimensions and mass of each specimen were measured using a digital caliper and laboratory balance with precision of 0.01g. The water content condition of the samples was preserved during storage and preparation to ensure that the specimens used in the first testing group accurately reflected the in-situ conditions of the marl material.

Uniaxial compressive strength testing

Uniaxial compressive strength testing was conducted according to ISRM Suggested Methods (Ulusay & Hudson, 2007) and ASTM D7012 standards (ASTM D7012-07, 2007). Cylindrical specimens with a length-to-diameter ratio of approximately 2 were prepared from intact marl samples collected from the open-pit deposit. The specimen ends were ground flat and parallel prior to testing. Axial compression tests were performed using a servo-controlled hydraulic testing machine under displacement-controlled loading conditions at a constant stress rate of 0.5 MPa/s until failure, Figure 5. The UCS values were calculated as the ratio between the peak axial load and the original cross-sectional area of the specimen:

$$UCS = \frac{P}{A} \tag{1}$$

where:

•UCS is the uniaxial compressive strength (MPa),

•P is the maximum (peak) axial load (N),

•A is the initial cross-sectional area of the specimen (m²).

a) Before testing *b) After testing*

Figure 5 Appearance of marl testing specimens before (a) and after (b) uniaxial compressive strength (UCS) testing

Water content testing

The water content was determined by oven drying representative samples at 105 °C until constant mass was achieved. The water content was calculated as:

$$w = \frac{m_w - m_d}{m_d} \cdot 100 \tag{2}$$

where:

w is the water content (%),

m_w is the wet mass,

m_d is the dry mass.

2.2 Test Results

Uniaxial compressive strength (UCS) tests were conducted in five groups, each consisting of six test specimens. After the first testing series, the remaining specimens were placed in a drying oven and dried at a temperature of 105 °C. Considering the relatively large volume of the specimens, the subsequent series of specimens were tested after 48 hours of drying. The results of the uniaxial compressive strength (UCS) tests and water content of the test specimens, obtained according to the previously described procedure, are presented in Table 2.

Table 2 Uniaxial compressive strength (UCS) and water content test results

Specimen group	Property	Specimen No.					
		1	2	3	4	5	6
1	UCS (MPa)	5.25	5.63	5.71	4.99	5.63	5.50
	w (%)	24.51	24.68	25.24	25.26	25.61	26.08
2	UCS (MPa)	6.17	6.50	6.41	5.86	6.48	6.28
	w (%)	12.07	13.36	13.77	14.03	14.19	14.28
3	UCS (MPa)	6.99	6.67	6.52	7.52	7.05	7.04
	w (%)	6.04	6.32	6.46	6.49	6.84	7.81
4	UCS (MPa)	7.26	7.39	6.94	7.71	6.91	7.06
	w (%)	2.9	3.3	3.55	3.88	4.31	4.57
5	UCS (MPa)	7.08	7.60	7.41	7.35	7.47	7.79
	w (%)	1.63	1.94	2.14	2.16	2.37	2.69

2.3 UCS–Water Content Correlation Analysis

The relationship between uniaxial compressive strength (UCS) and water content was analyzed in order to evaluate the influence of water content on the mechanical behavior of marl samples from the “Filijala” open-pit deposit. Variations in water content significantly affect the strength and deformation properties of weak sedimentary rocks due to softening of the clay fraction, degradation of carbonate cementation, and reduction of interparticle bonding (Hawkins & McConnell, 1992) (Vasarhelyi, 2005).

The laboratory-determined UCS values were correlated with the corresponding natural water content values obtained for each specimen. Correlation analysis was performed using both linear and nonlinear regression models to identify the most representative relationship between the investigated parameters.

The general linear regression model can be expressed as:

$$UCS = a - b \cdot w \tag{3}$$

where:

- UCS is the uniaxial compressive strength (MPa),
- w is the water content (%),
- a and b are empirical regression coefficients.

In addition to the linear relationship, exponential regression analysis was evaluated because weak rocks commonly exhibit nonlinear strength degradation with increasing water content (Erguler & Ulusay, 2009).

The exponential model is defined as:

$$UCS = a \cdot e^{-b \cdot w} \tag{4}$$

where:

a and b are experimentally determined constants,

e is the base of the natural logarithm.

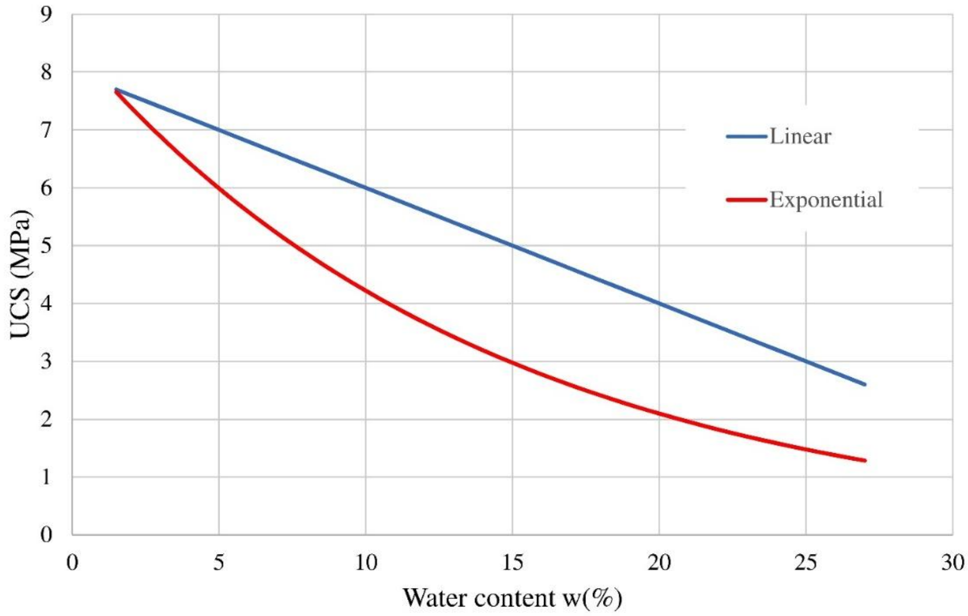

Figure 6 UCS–water content linear and nonlinear (exponential) correlation analysis

The goodness of fit of the regression models was evaluated using the coefficient of determination.

$$R^2 = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y})^2} \quad (5)$$

where:

- y_i represents measured UCS values,
- $\hat{y}_i$ represents predicted UCS values,
- $\bar{y}$ is the mean UCS value

A higher R^2 value indicates a stronger correlation between UCS and water content.

Based on the results presented in Table 2, the correlation analysis between UCS and water content (w) was performed for a linear correlation (Figure 7) and an exponential correlation (Figure 8).

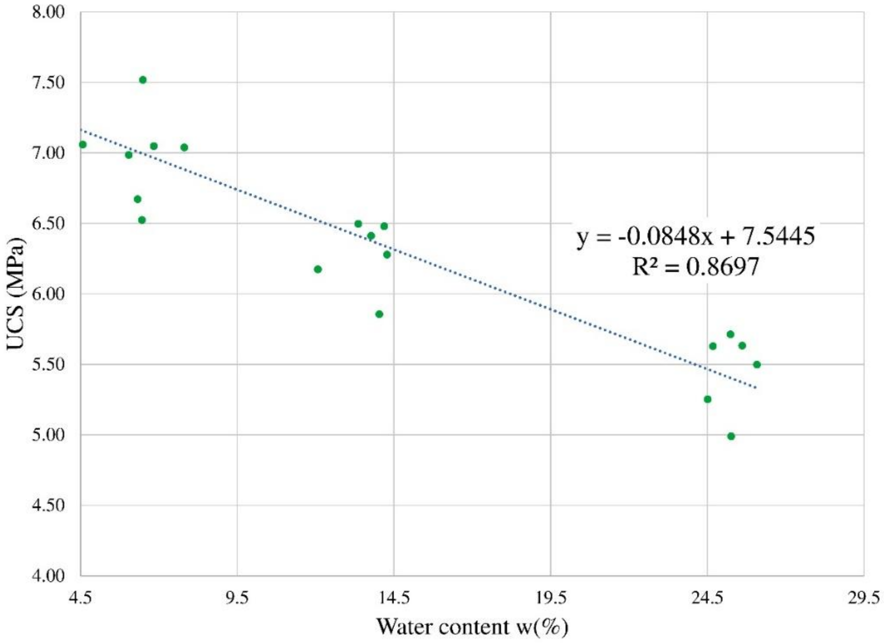

Figure 7 UCS–water content linear correlation analysis

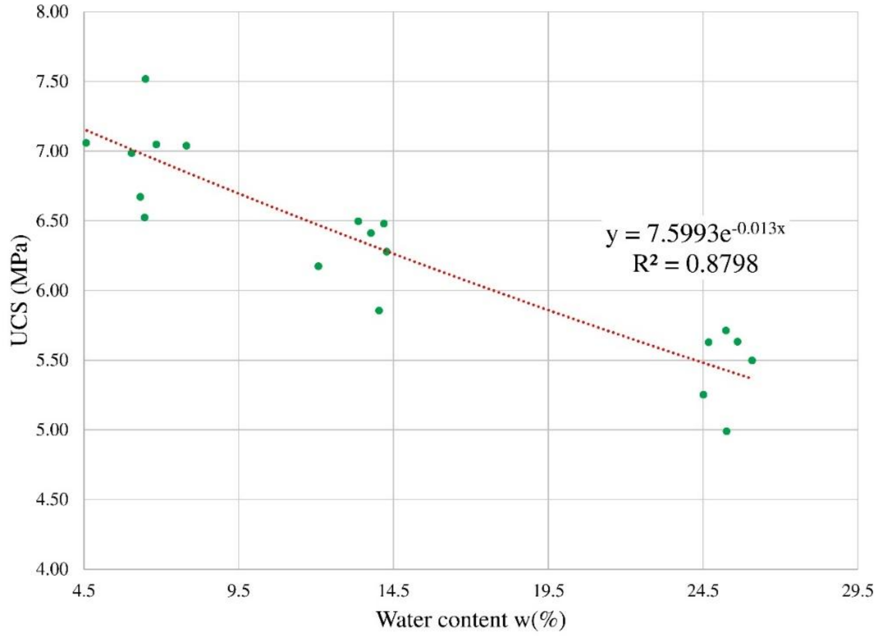

Figure 8 UCS–water content exponential (nonlinear) correlation analysis

Based on the analyses presented in Figures 7 and 8, the following correlation relationships between UCS and water content were established:

Linear correlation: $UCS = -0.0848 \cdot w + 7.5445$, $R^2 = 0.8697$

Exponential (nonlinear) correlation: $UCS = 7.5993 \cdot e^{-0.013 \cdot w}$, $R^2 = 0.8798$

Analysis of the coefficient of determination (R^2) values indicates that the exponential correlation has slightly greater potential for predicting UCS values for different water content (w) levels.

3 CONCLUSION

The investigated marls, known as "Pannonian marl" are composed of approximately 75% microcrystalline carbonate and 23% clay fraction (primarily montmorillonite and hydromica-illite). Chemical analysis confirms a mean $CaCO_3$ content of approximately 63.79%, meeting the industrial requirement of 60% for "dry process" cement production.

Previous investigations have demonstrated that increasing water content generally causes a substantial reduction in UCS due to:

- weakening of clay mineral bonds,
- dissolution and softening of carbonate cement,
- propagation of microcracks,
- reduction in matric suction,
- increase in pore-water pressure effects (Vasarhelyi, 2003).

These weakening mechanisms are especially pronounced in marls and other weak sedimentary rocks characterized by alternating carbonate and clay-rich components. water content-sensitive behavior significantly influences the stability of slopes, excavation faces, and foundation materials in open-pit mining and geotechnical engineering applications (Sabatakakis et al., 2008).

The paper confirms a significant inverse correlation between water content (w) and Uniaxial Compressive Strength (UCS). As water content increases, the UCS decreases due to the softening of the clay matrix and the degradation of interparticle bonding. Experimental data showed UCS values ranging from approximately 7.79 MPa at low water content ($w \approx 2.69\%$) to 4.99 MPa at high water content ($w \approx 25.26\%$).

Two regression models were developed to predict UCS based on water content:

- Linear Model: $UCS = -0.0848 \cdot w + 7.5445$, $R^2 = 0.8697$

- Exponential (Nonlinear) Model: $UCS = 7.5993 \cdot e^{-0.013 \cdot w}$, $R^2 = 0.8798$

The exponential model provides a slightly better fit (R^2 approx 0.88) for predicting the strength degradation of Beočin marl. This confirms that the mechanical weakening of these weak sedimentary rocks is nonlinear, with sensitivity to environmental water content being a critical factor for geotechnical stability and mining equipment selection (continuous vs. discontinuous mining) at the "Filijala" Open pit.

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