Marly soft rocks from Dalmatia (Croatia) and Budapest (Hungary) – correlation of intact rock physical and mechanical properties

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ABSTRACT: Soft rocks have an important role in the geological structure of Dalmatia (Croatia) and Budapest area (Hungary). In general, soft rocks are transitional material between the hard rock and soft soil with compressive strength below 25 MPa. A lower limit of soft rock strength is a subject of many discussions in geotechnics. Most of the soft rock material that occurs in the above-mentioned regions can be classified as marly material, which varies from clayey marls and marly clays to calcareous marls. These materials can cause serious problems in design and construction, due to their complex behavior under atmospheric conditions. Their properties mostly depend on their clay and carbonate contents. For the purpose of better understanding soft rocks behavior and their properties, a database with samples collected throughout Dalmatia was made and compared with the Budapest area samples. Based on the data from the database, correlations between physical and mechanical properties of intact marly rock were obtained. The relationships were applied to the Budapest area samples in order to validate the correlations and their applicability to materials from different regions and different geological origin.

Keywords: soft rocks; correlation; physical properties; mechanical properties

1. Introduction

Coastal region of Croatia (Dalmatia) lies on the Eocene flysch formations. The most common lithotypes of the flysch formations found in Dalmatia are breccias, breccia-conglomerates, sandstones, detrital limestones and marls with varying amounts of $CaCO_3$ components [1]. The Split area in Croatia, as well as the Budapest area in Hungary, abounds with marly material which varies from clayey marls to calcareous marls. Marl is a rock which contains clastic material of the clay dimension (< 0.002 mm) and carbonate (calcite), therefore it is defined as transitional rock material between clastic and chemical sedimentary rocks [2].

Based on their physical and mechanical properties, these materials are considered a soft rock. Due to complex structure and poor cohesive bonds between the solid particles, these materials are subject to deterioration and degradation under atmospheric agents, which may be referred to as weathering. Problems with sampling and site investigation due to degradation and crumbling, difficulties in the geomechanical classification under the usual systems, poor strength, fast weathering and many other characteristics make soft rocks demanding material in construction [3].

For the purpose of better understanding of the soft rock behavior and their properties, database with around 1500 samples collected in site investigation throughout Dalmatia, in the period between 1998 and 2016, was made and complemented with around 260 core samples from the Budapest area (Fig. 1.). The database consists of wide range of sedimentary rocks: limestone, marl, dolomite, breccia, conglomerate, sandstone, siltstone, calcareous sinter and tuff. In this research, the emphasis is on the behaviour and properties of marls. Therefore, the collected data were divided based on the material type, and the data referring to marly materials were extracted and then analyzed.

Figure 1. Locations of database samples – Budapest and Dalmatia area

The samples were mainly collected in site investigation and analyzed for the purpose of geotechnical design. Therefore, analyzed properties depend on the type of the planned construction works and structures and not all samples have the same properties tested. Most of the tested parameters were determined by the authors, under the controlled conditions of accredited laboratories and according to the suggested testing methods and standards (BS 1377-2 [4], ASTM D4373 [5], SM ISRM [6], ASTM D7012 [7]). A smaller part of the properties were determined in other different laboratories and possibly under different laboratory conditions and methods, which may affect the uniformity of obtaining procedures and availability of some tested parameters.

Based on the collected data, correlations between geotechnical intact rock parameters (especially mechanical properties of strength and deformability) and physical properties were obtained, using statistical methods of regression.

2. Physical and mechanical properties of marls

2.1. Dalmatian marls

Dalmatian marls are usually of a bright yellow, grey, brown or bluish color and contain between 15 and 85% of clay and between 15 and 85% of carbonate ($CaCO_3$) [8].

Mineralogical content of Dalmatian marls mostly consists of calcite, dolomite, quartz, plagioclase, chlorite, smectite, vermiculite and micaceous minerals in different ratios [9]. The term "micaceous minerals" refers to a mixture of clay minerals – illite, smectite and possibly muscovite. Based on the content of the calcite component marls are divided in several groups, which is shown in Table 1.

Table 1. Classification of carbonate rocks considering the content of the calcite component (Šestanović [2])

	$CaCO_3$ (%)
Limestone	95 – 100
Marly limestone	85 – 95
Calcareous marl	65 – 85
Marl	25 – 65
Clayey marl	15 – 25
Marly clay	5 – 15
Clay	0 – 5

In this research, the emphasis is on the analysis of samples defined as marls, weathered marls, clayey marls and marly clays (603 samples from the database). Main properties of these materials are shown in Table 2.

Around 25% of marl samples, with known *UCS* value, have the uniaxial compressive strength above the upper limit of what is considered to be a soft rock, which is around 25 MPa. Those are mostly samples with higher calcite content and can be described as calcareous marls.

Table 2. Properties of the Dalmatian marly materials in the database

		Min	Max	Mean	No. Samples
$CaCO_3$	(%)	13.95	84.83	57.04	504
γ_d	(kN/m^3)	14.14	25.92	22.06	370
w_0	(%)	0.05	26.63	7.01	385
N	(%)	0.31	45.63	15.31	369
UCS	(MPa)	0.04	89.69	17.38	400
$I_{s(50)}$	(MPa)	0.02	6.51	0.89	123
E_s	(GPa)	0.03	41.46	6.70	192
E_{dyn}	(GPa)	1.70	44.27	12.63	20
v_p	(m/s)	1050.00	4480.00	2869.88	26

$CaCO_3$ - calcium carbonate content; γ_d - dry unit weight; w_0 - water content; n - porosity; UCS - uniaxial compressive strength; $I_{s(50)}$ - point load strength; E_s – static Young's modulus; E_{dyn} - dynamic Young modulus; v_p – ultrasonic longitudinal pulse wave velocity

According to the engineering classification of intact rock [10, 11], shown in Fig 2., Dalmatian marls can be classified as low toughness and ductile rocks with low to medium strength due to low to medium E_s and *UCS* ratio. These types of rock show great instability when exposed to atmospheric agents (degradation and crumbling).

Weathered marls, clayey marls and marly clays, for which Atterberg limits were tested, can be observed through Casagrande – Mitchell plasticity diagram [12]. Using this diagram, clay component in marl can be determined based on plasticity index (I_p) and liquid limit (w_L) value. Clay component minerals react with water which leads to swelling and breaking of the cohesive bonds between the solid particles, respectively weathering. As it is shown on Fig 3., Dalmatian marls dominantly contain illite mineral, which is not very prone to swelling.

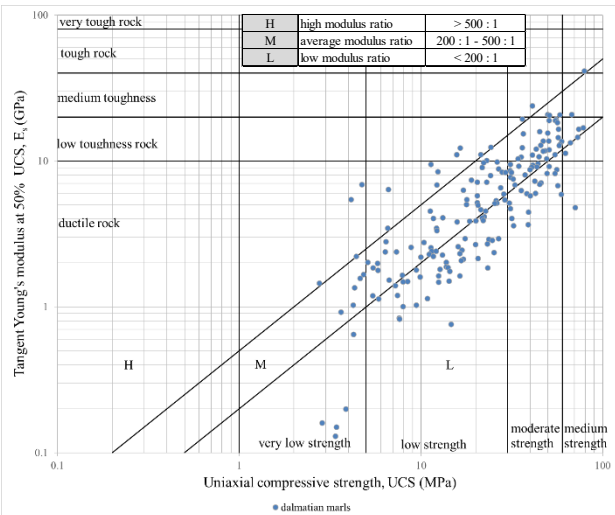

Figure 2. Engineering classification of intact rock with results obtained for tested marls [10, 11]

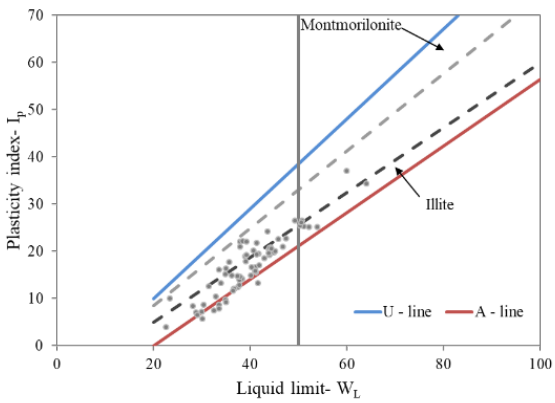

Figure 3. Casagrande – Mitchell plasticity diagram [12]

2.2. Marls from Budapest

In the Budapest region, there are two formations that are considered marls according to their calcium-carbonate content: the Eocene Buda Marl Formation and the Oligocene Kiscell Clay Formation.

The calcium-carbonate content of the Buda Marl is around 30-70%, while the mean carbonate content of the Kiscell Clay is approximately 15% [13, 14].

Both formations were exposed during construction activities. Kiscell Clay was the host rock of the Metro line 4 [15, 16], while the Buda Marl was the host rock of many different underground garage projects, such as Castle garage and Castle Bazar [17].

These two rock formations are not uniform. The upper layers are weathered and the beds behave like clayey material. In the cover zone of the rock beds, carbonate is leached and pyrite and other iron-containing minerals are oxidized to limonite so the gray color turns to yellow or brown.

Fig. 4. shows the difference between the yellow weathered and grey, freshly exposed marl.

Figure 4. Upper weathered yellow beds and grey non-weathered parts of Eocene Buda marl

Under the weathered zone, a jointed layer can be found and finally the intact part of the strata. These lower layers are always grey in color.

The Buda Marl Formation forms a part of the Hungarian Eocene system (Fig. 5.).

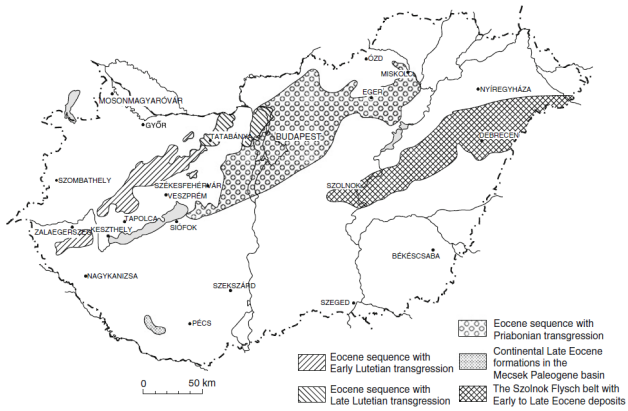

Figure 5. Distribution of the Eocene depositional systems in Hungary. Buda marl is found within the Priabonian transgression system marked by circled pattern (after Haas [18])

The core samples from Budapest contains mostly calcareous marls, marls and clayey marls. The main properties of the dataset from the Budapest area are given in the Table 3.

The tested Buda marl is a low to moderate strength rock. It has around two times higher average uniaxial compressive strength than the Dalmatian marls, but the average Young's modulus is almost the same in both cases.

Table 3. Properties of the Buda Marl

		Min	Max	Mean	No. Samples
γ_d	(kN/m^3)	19.98	25.90	24.49	256
UCS	(MPa)	0.34	105.16	38.27	207
BTS	(MPa)	0.62	10.12	4.09	174
E_s	(GPa)	0.01	20.00	5.76	143
v_p	(m/s)	130	3860	2540	97

γ_d - dry unit weight; UCS - uniaxial compressive strength; BTS – brazilian tensile strength; E_s – static Young's modulus; v_p – ultrasonic longitudinal pulse wave velocity

3. Analysis methods

Since the database covers a wide range of sedimentary rock types, the collected data was first divided based on the material type. The data referring to marly materials were extracted and then analyzed.

As it was already mentioned, the data was not collected systematically and not all samples have the same parameters tested. Consequently, the number of data in different analysis varies. The most common parameters in the database are: calcium carbonate content ($CaCO_3$), uniaxial compressive strength (UCS), dry unit weight (γ_d), water content (w_0), static Young's modulus (E_s) and point load strength ($I_{s(50)}$). The value of porosity (n) was derived from the known density values.

After data sorting, the regression and correlation analysis were conducted in order to obtain correlations between the properties, starting from the correlations already obtained by different authors as described in section 4.1.

The analysis was performed in statistical analysis software *NCSS 2019* [19], using linear and non-linear simple regression analysis options.

The starting point in the regression and correlation analysis is the definition of the scatter plot and the calculation of the coefficient of determination (R^2). The shape of the scatter indicates the existence of correlation between the variables and the type of the correlation (linear or non-linear), whereas the correlation coefficient value R indicates the strength of the correlation. The values above 0.40 indicate significant correlation and the values above 0.70 indicate strong correlation between the variables.

The regression model is an analytical expression of the correlation between two or more variables and it is a result of regression analysis. In this research two regression models were analyzed:

- simple linear regression model

$$y = B_0 + B_1 x + \varepsilon \quad (1)$$

- simple non-linear regression model

$$y = f(x) + \varepsilon \quad (2)$$

where: y = dependent variable;
x = independent variable;
B_0, B_1 = regression coefficients resulting from the least square method;
ε = error.

4. Correlations of properties

4.1. Overview of the previous research by different authors

Complex behavior of soft rocks and problems related to their classification, sampling and testing, lead to a great need of better understanding the soft rock properties and finding adequate solutions for the related problems. Therefore, many authors have previously dealt with soft rocks problems and the correlations between their properties.

Kanji and Galvan [20] have collected and analyzed data from more than 200 publications concerning soft rock behavior. Based on that data, they have considered relationships between porosity and absorption, porosity and density, porosity and *UCS*, density and *UCS* and „modulus of deformability“ and *UCS*. Obtained relationships show that absorption, porosity and density are very well correlated. The correlation between the *UCS* and porosity shows that the lower the porosity the higher the strength of the material, which allows prediction of the *UCS* value based on the porosity. Modulus of deformability and *UCS* relationship shows that higher material strength indicates higher values of modulus.

Relating the Dalmatian marls, Šestanović [1] has identified the existence of a relationship between calcite content ($CaCO_3$) and *UCS*, and consequently with marls tendency to weathering.

Kanji [2] also indicates the possibility of applying ultrasonic pulse wave velocity test methods based on the correlation between the dynamic modulus of elasticity (E_{dyn}) and static (Young) modulus. Faim, Andrade and Figueiredo [21] have obtained correlations between ultrasonic pulse wave velocity (v_p) and uniaxial compressive strength (*UCS*), as well as between v_p and point load strength ($I_{s(50)}$), on dolomitic limestone samples in Coimbra (Portugal).

According to the Sharma nad Singh [22], there are a number of factors that influence the P-wave velocity in rocks, such as lithology, density, porosity, anisotropy, pore water, confining pressure and temperature as well as the properties of the rock as a mass. Vasanelli et al. [23] have evaluated the effect of anisotropy and water presence on ultrasonic pulse wave velocity of a highly porous building limestone and how the presence of those factors affects the correlations between the ultrasonic pulse wave velocity and other physical and mechanical properties of the material. Since the samples used in this research were not collected and tested for the research itself, but mostly for the purpose of geotechnical design, there are no detailed information about the homogeneity of the tested samples. Therefore, future research should be focused on exploring the effect of aforementioned sample properties on the results of ultrasonic pulse wave velocity test, as well as on the correlations listed hereafter.

It should also be noted here that the tests carried out relate to the laboratory testing and therefore to the intact rock, which means (by definition of the intact rock) that the test specimens represent the whole drill core not affected by the gross structural discontinuities. Therefore, the samples can be considered as homogeneous as possible, and the results obtained should not be assigned to the whole rock mass, but the rock mass properties must in particular be determined for each project, taking into account both intact rock properties and discontinuity characteristics within the geological and geophysical surveys at the site.

4.2. Obtained correlations

For this research, around 30 regression analyses (linear and non-linear) were performed between 14 different material properties. The starting point of the regression analysis were correlations between the properties previously obtained by different authors.

The best-fit correlations for the analyzed data, with moderate and high coefficient of determination value, are shown in Table 4.

Hereafter, graphical representation of the obtained correlations is given and complemented with Budapest area data values.

Table 4. Overview of the obtained correlations

Regression type	Independent variable (x)	Dependent variable (y)	Data number	Coefficient of determination R^2	Equation
Simple linear regression Dalmatian marls	v_p	n	11	0.81	$n = 18.8880 - 0.0038\ v_p$
	v_p	UCS	13	0.52	$UCS = -14.5304 + 0.0142\ v_p$
	v_p	E_s	13	0.84	$E_s = -9.1709 + 0.0056\ v_p$
	E_s	UCS	188	0.60	$\sqrt{UCS} = 3.0024 + 0.2727\ E_s$
	E_{dyn}	E	9	0.53	$\sqrt{E_s} = 1.8447 + 0.0675\ E_{dyn}$
Simple linear regression Buda marl	v_p	γ_d	95	0.61	$\gamma_d = 0.0008\ v_p + 22.24$
	v_p	UCS	45	0.51	$UCS = 0.0065\ v_p - 1.8378$
	v_p	E_s	62	0.32	$E_s = 0.0011\ v_p - 0.6401$
	E_s	UCS	192	0.75	$\sqrt{UCS} = 0.3261\ E_s + 3.5658$
Simple non-linear regression Dalmatian marls	γ_d	UCS	315	0.79	$UCS = 2 \cdot 10^{-6}\ e^{0.653\gamma d}$
	n	UCS	314	0.79	$UCS = 58.121\ e^{-0.172n}$
Simple non-linear regression Buda marl	v_p	γ_d	95	0.74	$\gamma_d = 15.738\ v_p^{0.0563}$
	v_p	UCS	45	0.72	$UCS = 1.0483\ e^{0.0009\ vp}$
	E_s	UCS	192	0.82	$\sqrt{UCS} = -0.181\ E_s^2 + 0.6398\ E_s + 2.7566$
	γ_d	UCS	315	0.79	$UCS = 3 \cdot 10^{-5}\ e^{0.5669\gamma d}$
	v_p	E_s	49	0.68	$E_s = 0.0495\ e^{0.0012\ vp}$

Porosity (n) and ultrasonic pulse wave velocity (v_p) of the Dalmatian marls show very high correlation with the coefficient of determination R^2=0.81 (Fig. 6.). Better correlation could be obtained by increasing the number of data, i.e. increasing the application of ultrasonic pulse wave velocity tests in practice. For the Buda marl the correlation between dry density and ultrasonic pulse velocity resulted almost the same R^2 value like the previously described porosity – US wave relation for the power function. The value of the coefficient of determination is R^2=0.74, but for linear regression the R^2 value is smaller: R^2=0.61 (Fig. 7.).

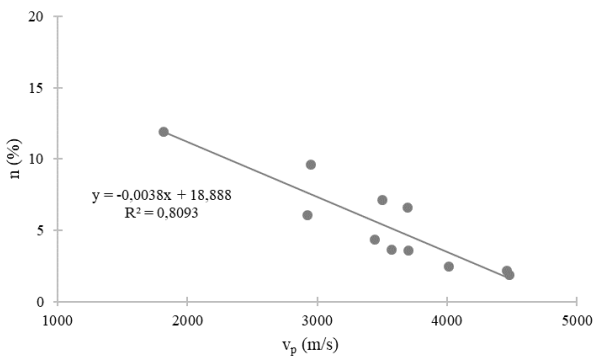

Figure 6. Porosity and ultrasonic pulse wave velocity relationship (Dalmatian marls)

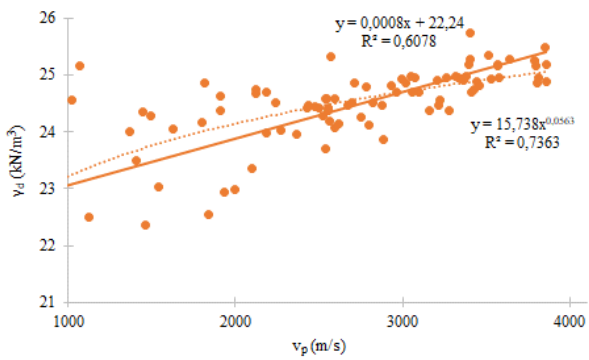

Figure 7. Density and ultrasonic pulse wave velocity relationship (Buda marl)

Uniaxial compressive strength (UCS) and ultrasonic pulse wave velocity (v_p) show significant correlation in both cases. The coefficient of determination for linear regression is almost the same for both – R^2=0.52 for the Dalmatian marl and R^2=0.51 for the Buda marl, but the slopes of the lines are very different. Presence of few outliers is noted on the scatter plot on Fig. 8.

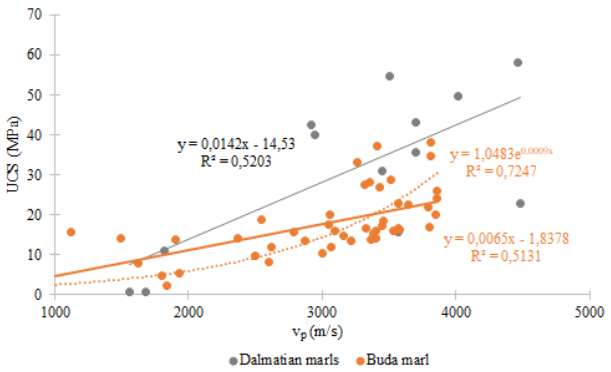

Figure 8. Uniaxial compressive strength and ultrasonic pulse wave velocity relationship

By omitting the outliers, better correlation is obtained. In this case, dropping the outliers is not reasonable. Therefore, obtained correlation is kept as it is. For the Buda marl non-linear regression was checked as well. The correlation with exponential equation shows better coefficient of determination R^2=0.72 compared to the linear one (Fig. 8.).

Static Young's modulus (E_s) and ultrasonic pulse wave velocity (v_p) show very high correlation in case of the Dalmatian marls with the R^2=0.84 (Fig. 9.). However, for the Buda marl the linear regression did not provide a good relation between the two parameters (R^2=0.32). Therefore, the data were also analyzed by nonlinear regression. An exponential equation was used to describe the correlation between the ultrasonic pulse wave velocity and static Young's modulus for the Buda marl and the R^2 value of 0.62 was obtained, which is considerably higher than the previous result for the linear correlation (Fig. 9.).

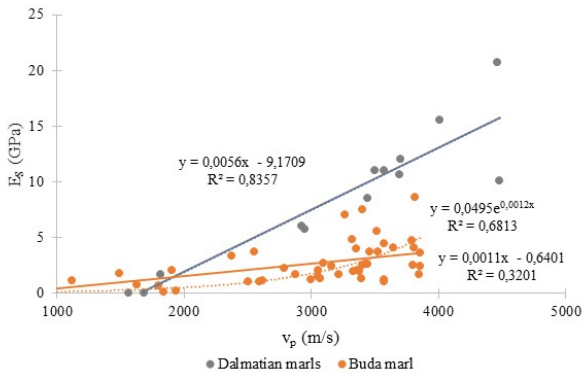

Figure 9. Static Young's modulus and ultrasonic pulse wave velocity relationship

For the correlation of uniaxial compressive strength (*UCS*) and static Young's modulus (E_s), transformation of *UCS* as a dependent variable was used in order to fulfill the normality condition of the statistical analysis. Therefore, a square root of *UCS* was used as dependent variable. Transformed $\sqrt{UCS}$ and E_s show significant correlation with the coefficient of determination R^2=0.60 for the linear correlation for the Dalmatian marls. The analysis of the dataset of the Buda marl resulted in higher R^2 for the linear regression (R^2=0.75). The shape of the scatter indicates also a possibility of non-linear parabolic correlation with the R^2=0.67 for the Dalmatian marls and R^2=0.82 for the Buda marl (Fig. 10.).

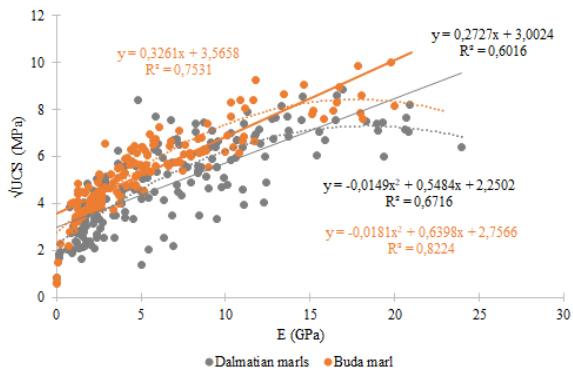

Figure 10. Uniaxial compressive strength and static Young's modulus relationship

The data on the scatter plot are quite dissipated and the given equation does not fit the data well enough and therefore it should be taken with caution. However, the value of coefficient of determination and the fact that the higher values of strength imply higher values of modulus, confirm the validity of the presumption that these variables are truly correlated.

For the static Young's (E_s) and dynamic (E_{dyn}) modulus of elasticity, which was analysed for the Dalmatian marls, it was also necessary to transform the dependent variable to fulfill the normality condition of the statistical analysis and the square root value of the static modulus (E_s) was used as a dependent variable.

Transformed $\sqrt{E_s}$ and E_{dyn}, calculated from the value of ultrasonic pulse wave velocity, show significant correlation with the coefficient of determination R^2=0.52 (Fig. 11.).

This correlation, as well as other obtained correlations with ultrasonic pulse wave velocity, show the importance of implementing this test method to standard use in sample testing. The advantage of this method is the fact that it is non-destructive, which is important when dealing with sensitive materials prone to weathering, such as soft rocks.

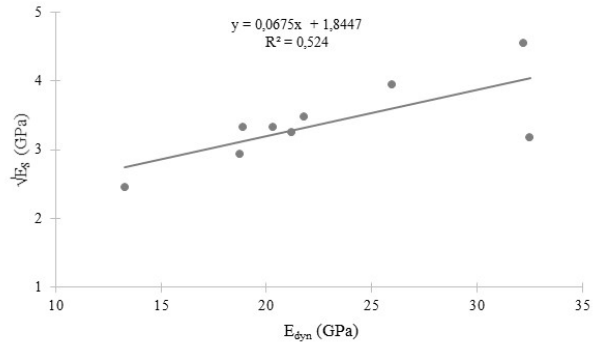

Figure 11. Static Young's and dynamic modulus of elasticity relationship for the Dalmatian marls

Uniaxial compressive strength (*UCS*) and dry unit weight (γ_d) relationship, as well as *UCS* and porosity (n), show non-linear behavior. Therefore, these relationships are described using simple non-linear regression as exponential functions. For the Buda marl only the uniaxial compressive strength and dry unit weight relationship was analyzed.

Both relationships show high correlations with the R^2 value of 0.79 for the Dalmatian marls (Fig. 12. and 13.).

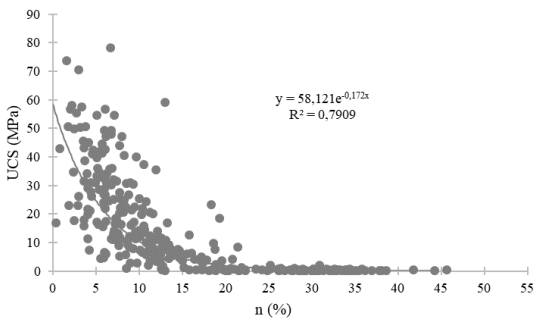

Figure 12. Uniaxial compressive strength and porosity relationship for the Dalmatian marls

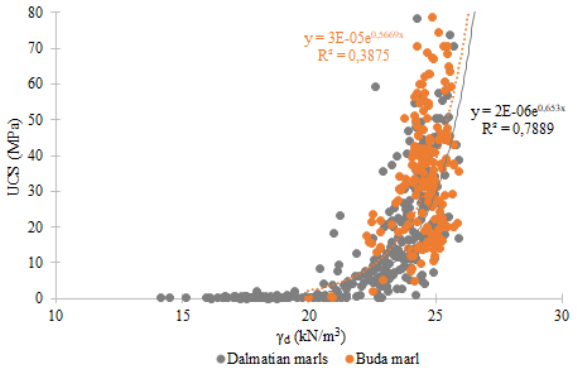

Figure 13. Uniaxial compressive strength and dry unit weight relationship

For the Buda marl this relation did not result in significant correlation, the coefficient of determination is only R^2=0.39 (Fig. 13.).

The Buda marl (orange dots on the scatter plot) has a smaller range of data, with the lowest density value of 19.98 kN/m^3. Therefore, the low R^2 value is an effect of the lack of lower range density and strength values. However, the Buda marl values complement the Dalmatian marl values perfectly.

5. Conclusion

Physical and mechanical properties of two types of marly rocks, the Dalmatian marls and the Buda marls, were compared and analyzed. Both types of rocks are a part of Eocene formations in two different regions – Croatia (Dalmatia) and Hungary (Budapest area). Physical properties of both types of rocks depend on the mineralogical composition, especially the carbonate ($CaCO_3$) content.

This paper is a first step of a complete, parallel geostatistical analysis of the Croatian and Hungarian marl properties. Apart from the scientific progress in the field of soft rock behavior, these correlations also have a practical application, since resolving slope instability problems in marly materials presents a big issue in both countries [24].

The dry unit weight, porosity, ultrasonic pulse wave velocity, uniaxial compressive strength and Young's modulus of both types of intact rock were statistically analysed using linear and non-linear simple regression analysis. Based on the regression analysis, correlations between the properties were obtained.

The analysis of the ultrasonic pulse wave velocity correlation to different material properties, such as density, porosity, uniaxial compressive strength and Young's modulus pointed that the ultrasonic pulse wave test is an important and useful non-destructive test method. The best correlations were obtained for the porosity and the ultrasonic pulse wave velocity and the density and ultrasonic pulse wave velocity.

The strength and deformability parameters (uniaxial compressive strength versus Young's modulus) show very good correlation with a high coefficient of determination in terms of linear regression analysis, whereas the application of non-linear correlation improves the value of the coefficient of determination. The uniaxial compressive strength values of the Buda marl are usually higher than the Dalmatian marls, while there is not significant differences between the Young's modulus values of the marls with different location.

Finally, the relation between the uniaxial compressive strength and dry unit weight and porosity was analysed. The results of the statistical analysis for these properties were slightly different for the Dalmatian marls and the Buda marls. However, the Buda marl data complement the Dalmatian marl dataset perfectly. The range of the Dalmatian marls is wider, while there are no dry unit weight values bellow 20 kN/m^3 of the Buda marl.

Conflicts of interests statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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