Correlation between various mechanical properties of porous limestones from Hungary

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Abstract. This study focuses on the mechanical parameters of Miocene limestones from Hungary. Four different lithotypes of porous limestone from two localities were analysed in laboratory conditions. These lithologies have been widely used for centuries as construction material in Central Europe. One type of the Badenian Leithakalk limestone, which is a bioclastic grainstone containing molluscs, foraminifera and Lithothamnium and three types of Sarmatian porous limestone; a fine-grained, medium-grained and a coarse-grained bioclastic lithotype were compared in laboratory conditions. Bulk density, water absorption, apparent porosity, uniaxial compressive and tensile strength tests were performed to obtain data set for correlation analysis. With water saturation under atmospheric pressure, the uniaxial compressive strength and tensile strength of all studied lithotypes were reduced significantly. A good correlation between dry bulk density and apparent porosity was found for two lithotypes; meanwhile, for the two other lithotypes a less significant relationship was found. Bulk density correlates with uniaxial compressive strength and with tensile strength for all lithologies. However, a significant difference was found in the coefficients of determination of the different lithotypes. The coefficients in air-dry conditions were over 70%, but they became smaller after water saturation. According to these results, microstructure, porosity, and water saturation influence porous limestones’ damage mechanism.

1. Introduction

In this study, two porous limestones from Hungary have been analysed to describe the variations in mechanical properties as a function of textural characteristics. The selected stone types have been widely used as ornamental and building stone in the Central-European region until the 20th century. Numerous emblematic monuments in Budapest and Vienna were constructed from this Miocene porous limestone.

In previous studies, it has been demonstrated that water content reduces the mechanical properties of stones. Rossana and Paola in [1] found that this can be observed even in low porosity rocks since an increase in water content causes a measurable decrease in flexural strength. A few per cent of moisture content significantly reduces the shear strength of sandstones and mudstones [2]. Stones with high porosity absorb a high amount of water, and the reduction of the strength due to water saturation can be very high, such as the uniaxial compressive strength and flexural strength measured in tuffs [3]. Tensile strength is also reduced besides uniaxial compressive strength linked to water saturation at porous limestones (Tuffeau and Sebastpol limestone, [4]).
Similar porous Miocene limestones were studied by [5]. The variety analysed from St. Margarethen (Austria) were among the low-strength lithotypes, and according to the laboratory tests, the uniaxial compressive strength decreased after water saturation. Vásárhelyi in [6] found correlations between petrophysical parameters of some Miocene porous limestone from Hungary, without emphasising the differences in textural characteristics. Rozgonyi [7] investigated the weathering effects of Sarmatian Miocene porous limestones with 3 different grain size (fine, medium and coarse grained) due to freeze-thaw and salt crystallisation. The changes of tensile strength and longitudinal wave velocity were measured on 3 types of porous limestone (fine grained bioclastic ooid packstone and medium grained ooid grainstone from the Sarmatian and bioclastic intraclastic grainstone from Fertőrákos) after water saturation, 10 freeze-thaw cycles and thermal effect [8]. A linear regression was found between the dry density and the porosity or between tensile strengths in dry and saturated conditions, but between the tensile strength in dried condition and after 10 freeze-thaw cycles was the correlation not linear.

In this study, a new approach is used; the textural characteristics are also considered in the statistical evaluation of mechanical parameters. Our aim was to find a correlation between air dry mechanical properties and porosity to assess the strength changes due to water saturation.

2. Materials and Methods
Two Hungarian Miocene limestone formations, the Badenian Leithakalk limestone from Fertőrákos and the Sarmatian oolitic limestone from Sósút, were analysed and compared in this study. The studied limestones were deposited during the Miocene period. The Badenian Leithakalk limestone is older, while Sarmatian limestone is a younger deposit. Both carbonates represent nearshore oolitic or bioclastic deposits. The studied limestones are porous and easy to cut and carve, but Sósút limestone’s porosity is uniformly high, while Leithakalk lithotypes can have lower porosities. The textural properties are similar; however, grain size, carbonate particles such as bioclasts are different in various lithotypes. Distinguishing the two lithologies by the naked eye is might be difficult [9]. Badenian Leithakalk occurs in several countries marking marginal sediments of the Pannon Sea: East-Austria, West Slovakia [5], Southern Czech Republic [10], West Hungary, while the Sarmatian oolitic limestone mostly found near Budapest (figure 1).
The most important quarry of the Badenian limestones in Hungary is found near Fertőrákos, where Rákos Limestone Formation deposits are exposed (figure 2a). The quarries of this region provided the construction materials of Vienna and Sopron [11]. Sarmatian oolitic limestone forms thick banks near Budapest and within the city, while major quarry sites are near Budapest in Sóskút (figure 2b). The Badenian Leithakalk is a bioclastic grainstone containing molluscs, foraminifera and Lithothamnium (figure 3a). It is also considered calcarenite or calcareous sandstone [12]. The Sarmatian oolitic limestone is a Cerithium-bearing [12], oolitic, porous limestone. Its prevailing microfacies are oolitic grainstone or bioclastic grainstone packstone. Three different lithotypes were tested: fine-grained, middle-grained and coarse-grained bioclastic varieties (figure 3.b,c,d).

To assess the mechanical properties of the four studied lithotypes, bulk (EN 1936:2007), water absorption at atmospheric pressure (EN 13755:2008), apparent porosity, uniaxial compressive (UCS) and indirect tensile strength (EN 1926:2007 and ASTM D3967), tests were made on cylindrical test specimens. Apparent porosity was calculated in V/V% based on the results of water absorption under atmospheric pressure. The water absorption experiments were performed until the specimens' constant mass (water saturated condition).

Statistical analysis of physical parameters is also presented in this study. Linear regression analysis was applied to estimate the relationship between dry bulk density vs apparent porosity and dry bulk density vs dry uniaxial compressive, tensile strength and water-saturated bulk density vs water-saturated uniaxial compressive, tensile strength. Relationships between these parameters were evaluated based on the coefficients of determination ($R^2$).
3. Results and discussion

The apparent porosity as a function of bulk density shows significant differences when the four studied lithotypes are compared (figure 4). The best correlation was found for Fertőrákos limestone, and the parameters of fine-grained limestone from Sóskút shows some correlation, while the porosity and bulk density of the coarse-grained limestone of Sóskút seem not to correlate ($R^2=0.0226$). This poor correlation between density and open porosity can be linked to very large and irregular pores. The coarse-grained stone specimens have huge amount of great pores in the size of few mm (figure 3). The apparent volume of the samples was calculated based on the measured dimensions of the specimens (Standard EN 1936:2006). Porosity was determined with water saturation by weighing the saturated samples, but the water flowed out from the large pores of the coarse-grained samples, so this phenomenon resulted in a poor correlation between apparent porosity and air dry bulk density. The coefficients of determination of medium-grained limestone from Sóskút was under 0.5 and the green symbols formed 2 separated groups on the figure 4.

The good correlation of the data of Fertőrákos limestone ($R^2=0.9932$) compared to the poor correlation of Sóskút limestone data is interesting since its bulk density varies in a larger range (1629-2441 kg/m$^3$) than the bulk density of Sarmatian limestone (1398-1896 kg/m$^3$). The lowest porosity (4.4 V/V%) was measured at Fertőrákos limestone that correlates with the highest density (2441 kg/m$^3$). Nevertheless, the slope of the regression line of Fertőrákos limestone and medium-grained limestone of Sóskút is very similar (figure 4). The point of intersection of the regression line and the $y$-axis should give the material density of the main mineral of the stones (calcite), which is known as 2710 kg/m$^3$. From equations of the regression lines it can be seen that the four studied lithotypes have different amount of closed pores. The intersections of the regression lines of the Fertőrákos limestone and the medium-grained limestone from Sóskút are close to 2710 kg/m$^3$ while the correlation lines of the other two limestone types intersect the air dry bulk density axes at 2217 and 1418 kg/m$^3$. This suggests that there are different amounts of pores that can not be measured by water absorption.

![Figure 4. Relationships between apparent porosity vs air dry bulk density of porous limestones from Sóskút and Fertőrákos.](image)

The regressions lines of air dry bulk density vs air dry uniaxial compressive strength and tensile strength are presented in figure 5 and 6, respectively. The coefficients of determination were higher
than 70% in air-dry condition. The smallest regression was found between tensile strength and bulk density of Sóskút limestone ($R^2=0.7162$, figure 6), while the most robust correlation is between uniaxial compressive strength and bulk density of Fertőrákos ($R^2=0.8662$, figure 5).

![Figure 5. Relationships between air dry bulk density vs air dry uniaxial compressive strength.](image)

![Figure 6. Relationships between air dry bulk density vs air dry tensile strength.](image)

The correlation between physical parameters of water saturated samples is generally smaller than that of the air-dry ones (figure 7 and figure 8). The smallest difference was found at Fertőrákos limestone where the coefficients of determination of density and UCS under dry and water saturated
conditions are nearly the same; namely $R^2$ equals 0.8662 and 0.9036 in air dry and water saturated conditions, respectively (compare figure 5 and figure 7). The regression coefficients show the same trend in water saturated condition as in air dry condition. The smallest regression was found between tensile strength results of limestone from Sóskút ($R^2=0.1778$), while the strongest between the uniaxial compressive strength results of limestone from Fertőrákos ($R^2=0.9036$).

![Figure 7](image_url)

**Figure 7.** Relationships between water saturated bulk density vs water saturated uniaxial compressive strength.

![Figure 8](image_url)

**Figure 8.** Relationships between water-saturated bulk density vs water-saturated tensile strength.
Our results showed a significant difference in the coefficients of determination of the limestones from the two localities. Leithakalk limestone parameters have a stronger correlation in all test conditions in air dry and water saturated one than Sarmatian porous limestone (Sóskút limestone). The weak correlation is due to the significant textural variation of Sarmatian porous limestone. Limestone from Sóskút shows considerable variety in textural properties, such as pore-size distribution and grain-size distribution, which is also visible even at the cut surface (figure 3). These textural differences have been described previously [7, 8]. Rozgonyi [7] has described two medium-grained limestones with different texture having the same density. This textural difference explains the low correlation between the physical parameters in our study too. Lower correlations were also documented for other limestones types [13].

Strength and its correlation to density decreased after water saturation for all lithotypes. Water saturation reduced uniaxial compressive strength by 35% for Leithakalk and by 30% for Sóskút limestone. Tensile strength also reduced due to water saturation. The decrease was 35% for Leithakalk and 40% for Sarmatian limestone. A similar trend and strength loss was also observed for French Tuffeau limestone [4]. They found an even higher loss in uniaxial compressive strength (58%) and tensile strength (68%). A similar lithology to Badenian Rákos Limestone Formation from Austrian and Slovakian quarries was studied by [5]. They found that the bulk density of tested limestone varies greatly (1984-2654 kg/m³) and seems to be higher than the results presented in this study (1629-2441 kg/m³). Concurrently, the porosity values were between 1.873 V/V% and 26.752 V/V% in Austrian limestones, while we found porosities between 4.44 V/V% and 28.16 V/V%. Extremely high uniaxial compressive strength values were measured in Austrian limestone up to 103 MPa, while the lowest value was 11 MPa which is more comparable with the uniaxial compressive strength values of Badenian Leithakalk from Fertőrákos. The uniaxial compressive strength test results obtained from the testing of St. Margarethen, Roemersteinbruch limestone (11.24-40.67 MPa, [5]) are very similar to our ones of Fertőrákos (8-41.6 MPa). The two deposits, two limestone occurrences in St Margarethen and Fertőrákos, are very similar in terms of texture, and they represent a similar depositional environment; thus, their physical parameters are very similar.

The coefficient of determination and the equation of the linear regression between dry bulk density vs apparent porosity for Miocene Limestone ([6], R=0.996) is similar to the ones of Fertőrákos Leitha Limestone and Miocene medium-grained limestone presented in this study (figure 4). Meanwhile, the fine-grained limestone of Sóskút does not fit in this trend, and the slope of linear regression is less. The coarse-grained variety of Sóskút has significant scatter in density and porosity data, but it is very probably linked to the presence of the high amount of closed pores.

4. Conclusion
Although all of them are considered porous limestone, the studied limestones show textural varieties that influence their physical properties. Even from one locality (Sóskút), we have identified three texturally different lithotypes with different physical parameters. Different correlations were found between apparent porosity, bulk density, uniaxial compressive strength and tensile strength for the studied limestone lithotypes. The bulk density and tensile strength of the Sarmatian oolitic limestone from Sóskút show a weak correlation in water saturated condition due to the textural heterogeneity. Despite that Fertőrákos limestone has a broader range of density and porosity than Sóskút limestone, its physical parameters show good correlation. Badenian limestone of Fertőrákos has similar physical properties to St. Margarethen limestone that occurs in Roemersteinbruch (Austria), which can be explained with the similarities in the depositional environment. Our study shows that significant data on physical properties allow us to set up correlations between physical parameters. Still, these correlations have some limitations, depending on the textural variety of the limestone. Our results showed that limestones deposited in the same geological age (Miocene) and at the same depositional settings (shallow marine shoal deposits) could have very different physical, mechanical properties and correlations. It is known that the microstructure, porosity and water saturation influence the
damage mechanism of porous limestones; hence the presented parameters can be used to assess the sensitivity of the limestone to weathering.

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