Petrophysical and mechanical properties of the Struganik limestone (Vardar Zone, western Serbia)

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Abstract. The Struganik limestone has been increasingly popular in recent years for interior and exterior building applications, due to easy workability, low cost and multi purpose suitability. The quality of limestone is determined by its mineralogical and textural characteristics and physico-mechanical properties. The Struganik stone corresponds to marl, clayey limestone and limestone (micritic and allochemical). The limestone is commonly layered, either thinly bedded or banked. Chert concretions are present in all varieties. The Upper and the Lower Campanian age were deduced by the abundant foraminifers. Micrite limestone is an autochthonous rock generated in a deep marine environment, whereas allochemical limestone is related to a shallow marine environment but subsequently brought into a deep-water system.

The mass quality of the Struganik limestone is controlled by variability of lithology and layering. The values of physico-mechanical properties, such as density, porosity, water absorption and strength, were statistically analyzed and the obtained data were used to assess the rock quality in the quarry. The relationship among the quantified properties is described by regression analyses and the equations of the best-fit line.

The Struganik limestone was qualified by its petrological and engineering properties coupled with statistical analysis. It satisfies the majority of the requirements of the Main National Standard as a decorative stone, but with a limiting factor regarding abrasive resistance.

Key words: Struganik limestone, western Serbia, petrology, physico-mechanical properties, correlation, rock quality.

Апстракт. Интересовање и примена струганичких кречњака како у екстеријеру, тако и у ентеријеру је у порасту последњих година, посебно у западној Србији, због њихове лаке обраде, ниске цене и могућности различите примене. Квалитет кречњака зависи од његових минералошких и текстурних, као и физичко-механичких својстава. Петролошки, струганички кречњаци одговарају лапорцима, глиновитим кречњацима и кречњацима (микритски и алохемијски). Обично су слојевити, танкоплочасти или банковити. У свим варијететима јављају се конкрециони рожнаци. На основу бројних фораминифера ови седименти су сврстани у доњи и горњи кампан. Микритски кречњаци су аутохтоне стене настале у дубоководној маринској средини, док је порекло алохемијских кречњака везано за плитку морску средину, одакле су принети у дубоководни систем.

Квалитет струганичких кречњака је условљен литолошким саставом и типом слојевитости. Вредности физичко-механичких својстава, као што су густина, порозност, упијање влаге и чврстоћа, статистички су анализирани, а добијени резултати су коришћени као показатељи квалитета стенске масе каменолома. Односи између испитиваних својстава су испитани регресионом анализом и изражени једначином "best-fit line". Петрографска и техничка својства заједно са резултатима статистичке регресионе анализе која је примењена у овом раду, указују да струганички кречњаци по свом квалитету испуњавају већину захтева сходно главном националном стандарду за примену архитектонског камена, а да је ограничавајући фактор њихова отпорност према хабању.

Кључне речи: струганички кречњак, западна Србија, петрологија, физичко-механичке особине, корелација, квалитет кречњака.

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Introduction

Natural stone is one of the most common construction materials. Dimension stone is used in areas where the aesthetical properties (color, design), soundness of the deposit and market demand are crucial factors (Luodes et al. 2000). To be used for the interior and exterior of buildings, a natural stone must satisfy standardized physical and mechanical requirements strictly (Yagiz 2010). Petrophysical and mechanical properties of sedimentary rocks are influenced by the size, shape, packing of grains, porosity, cement and matrix content, depending strongly on depositional fabric and post-depositional processes (Andriani & Walsh 2002). These properties are measured in laboratories by standardized, relatively simple methods but they are time consuming and expensive and require a well-prepared rock sample. For this reason, the modern world trend in geological and civil engineering prac-

1972; Ollson 1974; Bieniawski 1967, 1975; Hugman & Freidman 1979; Gunsallus & Kulhawy 1984; Fredrich et al. 1990; Wong et. al. 1996; Hoffman & Niesel 1996; Hatzor et al. 1997, 1998; Turgul & Zarif 1999; Palchik et al. 2000, 2002).

Carbonate deposits with different lithology, age and quality are widespread in Serbia, making limestone the most excavated stone for building purposes. In the western part of Serbia, particularly in the Mionica area (Fig. 1), there are more than 70 quarries excavating limestone known as Struganik stone. The first written data related to the exploitation of this stone dates back to 1737. In 1861, Struganik stone was used for the building of the Vienna Opera House.

In the last two decades, the popularity of this limestone and its use as an architectural stone has increased rapidly due to its cost coupled with aesthetic value, quality and available reserves. It is still the main building material in this area, used for exterior and interior cladding but with limited application mainly due to insufficient investigations from geological and engineering aspects. Many authors investigated the stratigraphy of this area (e.g., Anđelković 1978), paleontological assemblages (e.g., Filipović et al. 1978) and tectonic features (Karamata et al. 1994, 2000; Dimitrijević 2001; Gerzina 2002; Robertson et al. 2009). Only a small number of recently published papers provide general information on the stratigraphy and lithology of stone in the Struganik area (Vasić et al. 2001; Rabrenović et al. 2002; Vasić et al. 2005; Gajić 2007; Djerić et al. 2009; Gajić & Vasić 2011). Unfortunately, petrological and technical features of the Struganik limestone, data of the depositional processes and problems of the quality and assortment of use have not yet been studied in detail. Insufficient data raised a necessity for an improvement of the exploration methodology of the Struganik limestone. Therefore, studies concerning the fabric of the Struganik limestone and its quality as a building stone have not only theoretical significance, but also practical importance for civil engineering.
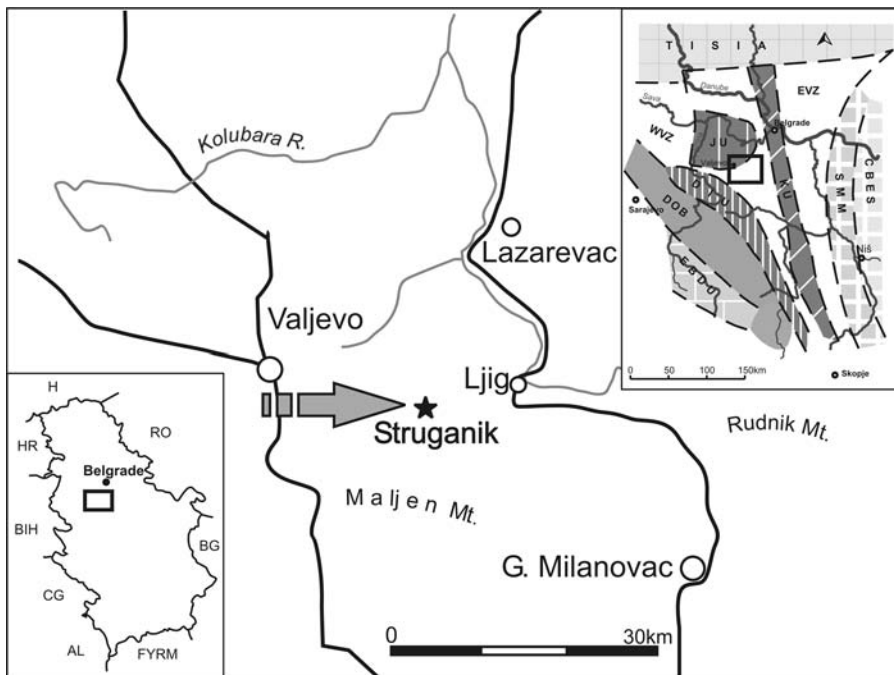

Fig. 1. Location of the Struganik limestone in western Serbia, central part of the Vardar Zone. Right: Terranes of the central part of the Balkan Peninsula (According to Karamata & Krstić 1996; Karamata 2006 and Robertson et al. 2009). Key (in alphabetic order): **CBES,** Eastern Serbian Carpatho–Balkanides; **DIU,** Drina–Ivanjica Unit; **DOB,** Dinaride Ophiolite Belt; **EVZ,** Eastern Vardar Ophiolitic Zone; **JU,** Jadar Unit; **KU,** Kopaonik Unit; **SMM,** Serbo–Macedonian Massif; **WVZ,** Western Vardar Ophiolitic Zone.

tice is the investigation of the relationship between complex mechanical and simple physical properties. The equations for estimating mechanical properties on the base of simpler, faster and more economical indirect tests have been presented by a great number of authors (Handlin & Hager 1957; D'Andrea et. al. 1964; Deer & Miller 1966; Broch & Franklin

The object of the present investigation was the oldest and largest quarry in the Struganik area, with the same name (Fig. 2), located about 100 km southwest of Belgrade (Fig. 1).

This quarry is irregular in shape, elongated in the NW–SE direction and opened at approximately 0.32 km² (KIJANOVIĆ 2007). The extraction in it, 30 years old, is constrained by bedding planes in limestone (Fig. 2). The extraction comprises the removal of large tiles and their cutting into natural-faced slabs usually 2–3 cm thick using a circular blade saw or hand tools. These products, with natural appearance, are packed on a palette and ready for use as external and interior cladding. Their limited application is mainly caused by insufficient investigations of their properties needed to meet the requirements of architectural stone.

Fig. 2. The "Struganik" quarry in the Struganik area.

The purpose of this study was a detail determination of the lithological, structural and textural properties, and the depositional processes and their link with physical and mechanical properties. This work provides new geological data for the Struganik limestone based on petrological field observations, optical and chemical analysis of the collected samples, as well as on results of a statistical analysis of the geomechanical characteristics and, finally, an assessment of the limestone quality as a building stone.

Geological setting

Geological setting of the Struganik area consists of Mesozoic formations of Triassic, Jurassic and Cretaceous age, and of Quaternary sediments to a lesser extent. According to ANĐELKOVIĆ (1978), the shallow Triassic sediments were deposited over the Permian. Complex and geotectonic processes during the Jurassic led to the formation of the ophiolite mélange (SCHMID et al., 2008). The Struganik area is part of the northern rim of the Maljen ophiolitic massif. This region is in the Vardar Zone Western Belt (Fig. 1; KARAMATA & KRSTIĆ 1996; KARAMATA 2006; ROBERTSON et al. 2009).

In the wider area, Cretaceous sedimentation commenced with the Albian transgression. Terrigenous-carbonate and carbonate sedimentation continued from the Albian to the Maastrichtian, while flysch ("Ljig flysch") sediments were deposited in the latest Senonian (FILIPOVIĆ et al. 1978).

According to data obtained during geological studies in the villages Osečenica, Brežđe and Struganik, MARKOVIĆ & ANĐELKOVIĆ (1953) considered the Struganik limestones as Senonian, i.e., as the latest Cretaceous products in this area. The Cretaceous sediments in the broader Struganik area were studied recently by VASIĆ et al. (2001), RABRENOVIĆ et al. (2002), GERZINA (2002), VASIĆ et al. (2005), GAJIĆ (2007), DJERIĆ et al. (2009), GAJIĆ & VASIĆ (2011). FILIPOVIĆ et al. (1978) distinguished within the Cretaceous sediments the following members: detrital limestones, claystones and sandy marlstones of Albian age, conglomerates and limestones of Albian–Cenomanian age, Cenomanian conglomerates, limestones, marlstones and sandstones, organogenic-detrital limestones and marlstones of the Cenomanian–Turonian, a limestone and limestone–marlstone series of Turonian–Senonian age and Campanian–Maastrichtian flysch (Fig. 3).
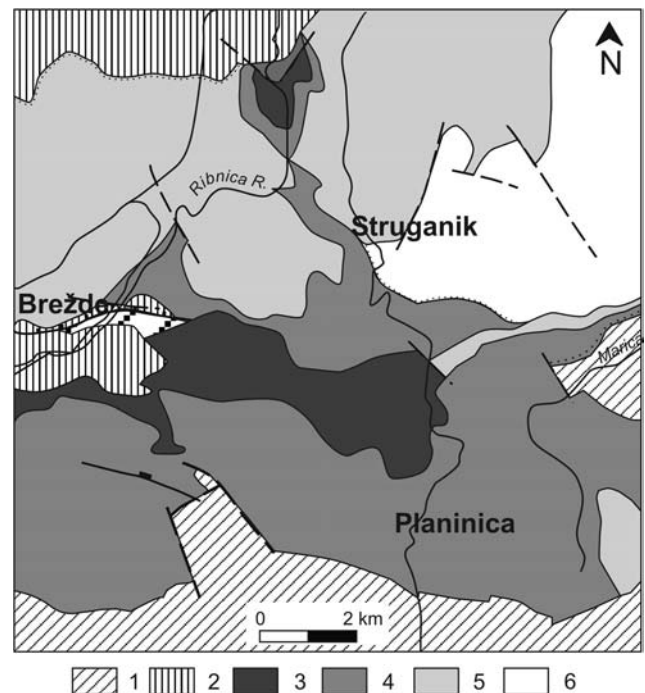

Fig. 3. Simplified geological map of the Struganik area based on the Basic Geological map sheet Gornji Milanovac 1:100000 (FILIPOVIĆ et al. 1976). Legend: **1,** Jurassic ophiolite mélange; **2,** Triassic shallow sediments; **3,** Conglomerate and limestone of Albian–Cenomanian age; **4,** Cenomanian sediments; **5,** Limestone and limestone–marlstone series of Turonian–Senonian age; **6,** Campanian–Maastrichtian flysch.

The Turonian–Senonian age of the Struganik limestone is documented by the microfossils: *Praeglobotruncana helvetica*, *Rotalipora sp.*, *Globotruncana lapparenti coronata*, *etc*. (Filipović *et al*. 1978). A recent micropaleontological analysis, *i.e.,* the association of pelagic globotruncanas, indicates that these sediments are of Campanian age (Gajić 2007). The age of radiolarians from the layer of smectite clay within the micrite limestone of the Struganik was defined as the Coniacian (Vasić *et al*. 2005; Djerić *et al*. 2009).

Material and methods

Determination of petrological properties of the Struganik limestone commenced with field observations in the quarry and preparation of a detailed lithological column. A total of 33 samples were collected from the lowest level of the quarry for further laboratory testing in order to assess the structural and chemical composition of the limestone (Fig. 2). A microscopic analysis of thin sections by optical microscopy was used to characterize the mineral composition, microtextural features (size and kind of allochem, grain orientation, *etc*.), and content and type of microfossils. Based on the field inspection and the results of a petrographic (optical) investigation, the rock samples were classified according to the Folk (1959) and Dunham (1962) classification scheme. In the same samples, the contents of CaO and MgO were determined by the complexometric method (EDTA titration) using a standardized solution of 1 M EDTA as the titrant.

In order to examine the quality of the Struganik limestone as a building stone, the physical (bulk and apparent density, porosity, water absorption, frost resistance) and mechanical properties (compressive strength, abrasive resistance) of a total of 18 samples from the quarry were determined. The laboratory tests were performed according to the national standards (Unification of Serbian Standards) at the Laboratory of the Highway Institute of in Belgrade. The bulk density is given as mass per unit of apparent volume. The volume was determined by hydrostatic weighing of the specimens soaked and suspended in water under atmospheric pressure (according to SRPS B.B8.032). On powdery samples, the real densities were determined using a pycnometer with water as the displacement fluid. From the values for real and bulk density, the total porosity was calculated (according to SRPS B.B8.032).

The specimens that were used for the determination of the bulk density were also used for the determination of the water absorption, which was determined by measurement of the mass of water absorbed by the sample after immersion for 48 h at atmospheric pressure. It is expressed as a percentage of the initial mass of the sample previously dried at 105 °C to constant weight (SRPS B.B8.010). The resistance to frost was determined by 25 cycles of freezing to –25 °C and thawing according to SRPS B.B8.001. The freeze–thaw tests were performed on cubic samples to assess the durability of the limestone samples by determining their strength and mass loss after 25 freeze–thaw cycles. The test procedure involved repeating of cycles where one cycle involved placing a water-saturated sample in a freezing chamber for 4 h, after which the sample was totally immersed in water in a thawing tank for 2 h.

The limestone samples were tested for their mechanical properties (compressive strength and abrasion resistance). The uniaxial compressive strength tests (SRPS B.B8.012) were performed on both dry and water-saturated limestone samples (5×5×5 cm cube) and on samples that had been subjected to the freeze–thaw test. According to SRPS B.B8.015, cubic samples of 7 cm in size were used for determination of the Böhme abrasion resistance. The test procedure involved 440 cycles of sample abrasion using abrasion dust (crystalline corundum) on a rotating steel disc under an applied stress of 300 N.

In order to evaluate the relationships between the physical and mechanical properties, different statistical analysis techniques (basic descriptive statistics, correlation, bivariant regression analysis, *etc*.) were performed using the SPSS computer program. All the measured values of the technical properties were statistical analyzed at the level of significance (α) of 0.05. The descriptive statistical parameters included the mean, minimum and maximum value, standard deviation, median, standard error, range, quartiles, standardized skewness, kurtosis, *etc*. The Kolmogorov-Smirnov (non-parametric test for normality) was used with the level of significance set at 0.2.

Subsequently, the results of the laboratory measurements were correlated using the method of least squares regression. Linear regression ($y = ax+b$) were performed and the equations of the best-fit line, the regression coefficient (R^2) and the 95 % confidence limit were determined for the regressions.

Validation of the regression analyses was confirmed by the Student *t*-test and by the test of variant analysis (the *F*-test).

Petrological properties of the Struganik limestones

Struganik limestones are the latest Upper Cretaceous sediments in this part of western Serbia. The limestones are best uncovered in the village Struganik. Exploration were performed in the "Struganik" quarry and a lithological column about 10 m tall was constructed (Fig. 4).

The limestones are massive and compact. Their uniform grayish color throughout the entire deposit is
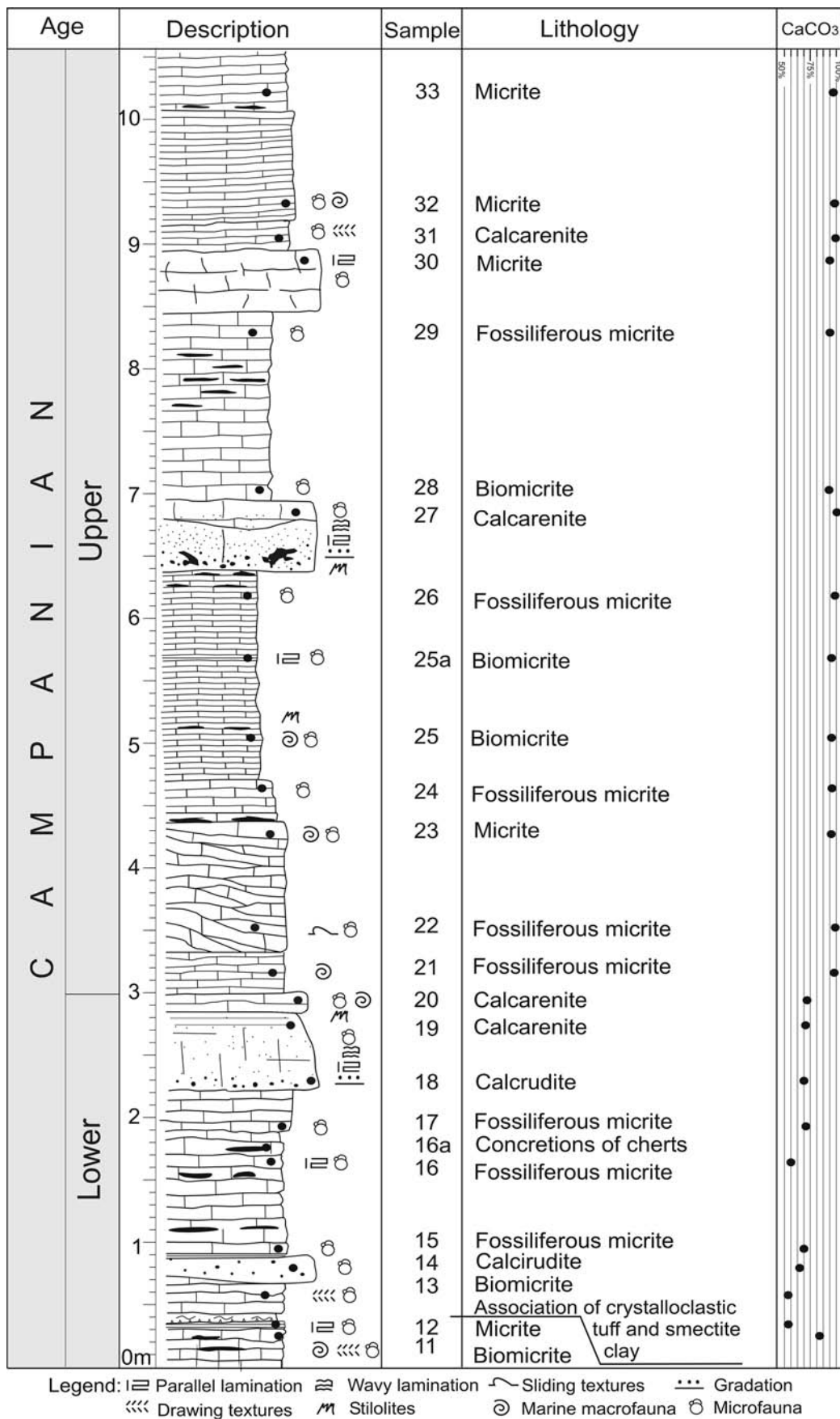
Fig. 4. Local lithological column of the lowest level in the "Struganik"quarry.
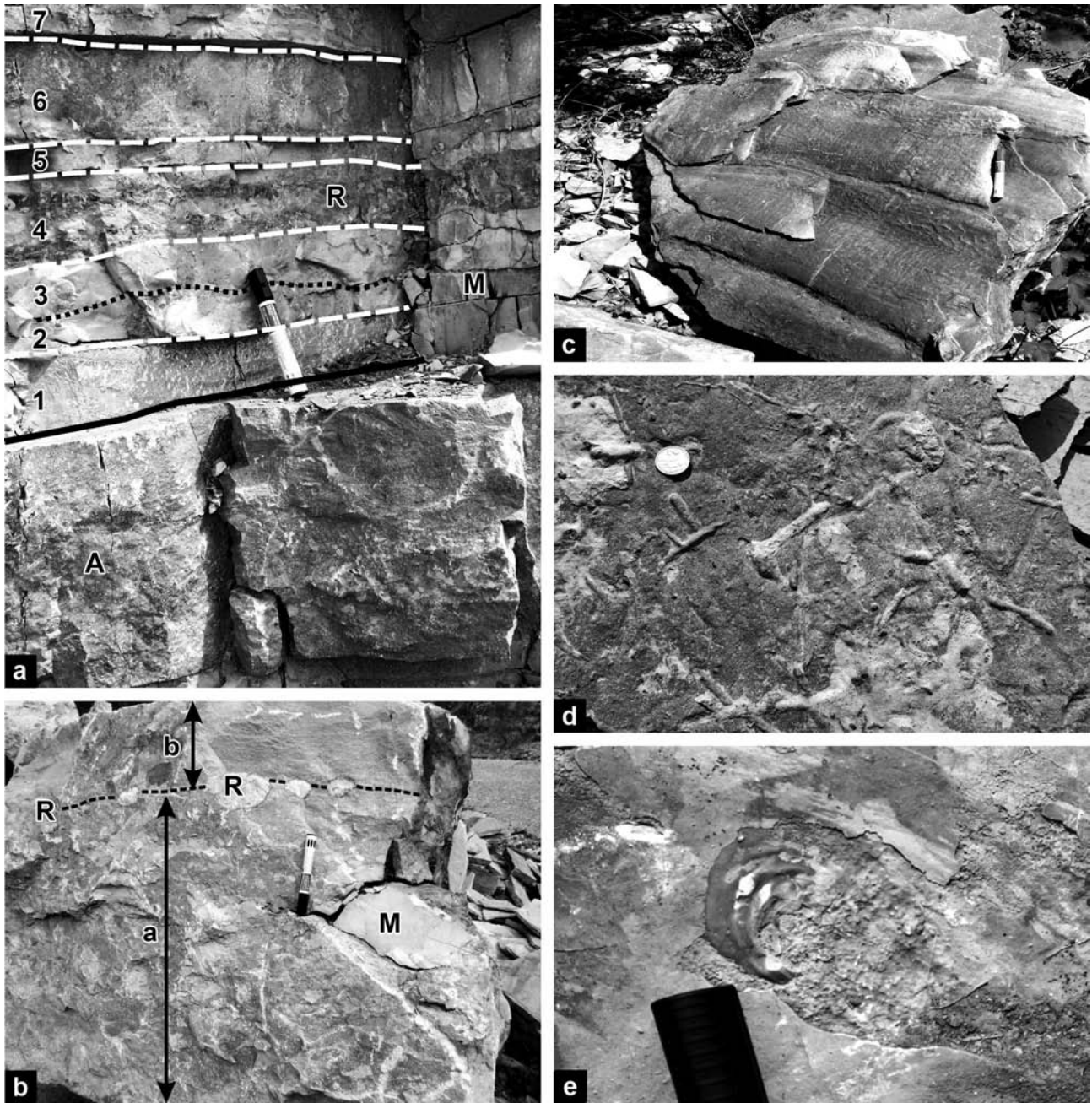
Fig. 5. The appearance of the Struganik limestone. **a,** Beds of Struganik limestone. Thick bed of the allochemical-sparite limestone with gradation (A). Beds of the micrite limestone (1, 2, 3, 4, 5, 6 and 7). Stylolitic boundary surface between beds 2 and 3. Concretional interlayer of black chert in bed 4; **b,** Bank of the allochemical limestone with well-developed Bouma intervals a & b. Interval "a" is calcrudite with fragments of the micrite limestone (caught by turbidity flow). Interval "b" is calcarenite. Along the boundary between a & b whitish concretional chert is developed; **c,** Upper bedding plane with ripple marks in fine-grained calcarenite; **d,** Grouped tracks of life activities on the lower bedding plane in the Struganik limestone (obscured origin); **e,** Test of Inoceramus in the micrite limestone.

sporadically disturbed by the presence of dark gray, grayish blue or whitish chert concretions.

The main lithological member is micrite limestone, which represents the autochthonous rock of deep water, marine carbonate sedimentation (Fig. 5). Micrite limestones are layered in thick beds (Fig. 5a). The distinctive beds display notable horizontal lami-nation. Allochemical limestone, the second lithologi-cal member, is related to a shallow marine environ-ment. Subsequently, the shallow water allochems were transported into a deep-water environment by turbidity currents to produce either beds or banks (Fig. 5a) or sporadic packages composed of two or three beds. Allochem limestone carries textures that

are characteristic for the turbulent transport (particular intervals of the Bouma Sequence within the layers, Fig. 5b).

Mechanical and biogenic textures are common on the bedding planes in the Struganik limestone (Fig. 5c, Fig. 5d). Bedding planes in both of the mentioned limestones are often stylolitic (Fig. 5a). On the upper bedding planes in micrite limestones, Inoceramus can be found abundantly (Fig. 5e).

The third lithological member, concretional cherts, was produced by silification during diagenesis. The chert concretions are notable textural, as well as being a petrological feature of the Struganik limestone. The chert concretions are uniformly distributed throughout the whole column in both micrite and allochem-sparite limestone (Fig. 5a, Fig. 5b).

The paleontological study of the microfauna (many foraminifers) indicates to Campanian age of the Struganik limestone (GAJIĆ 2007). According to the observed association, the first three meters of the column correspond to the Lower Campanian, whereas the remaining 7 m of the column corresponds to the Upper Campanian.
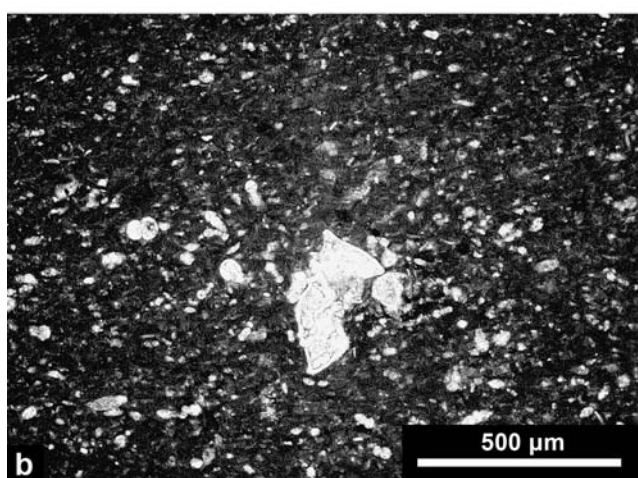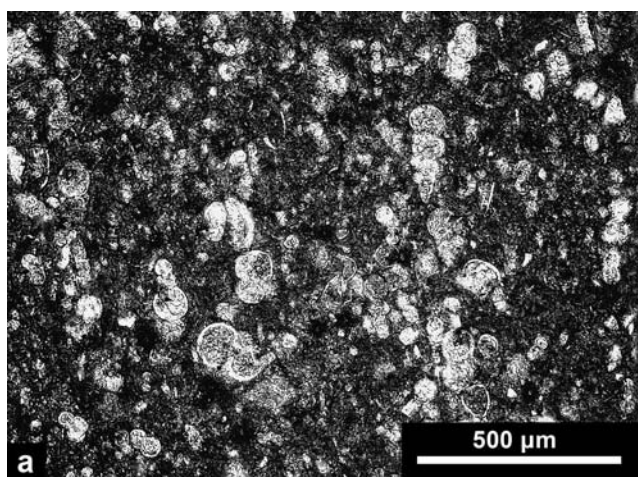

Fig. 6. Photomicrographs of the micrite limestone: **a,** Biomicrite; **b,** Fossiliferous micrite with globotruncana in the middle.

Micrite (orthochemical) limestone

The micrite limestone is mainly composed of microcrystalline calcite – micrite. Non-carbonaceous compounds are clay minerals, organic matter and subordinated silty material. According to the $CaCO_3$ content, micrite limestone refers to pure limestone, clayey limestone and marlstone (Fig. 4). The least amounts of $CaCO_3$ were determined inside the Lower Campanian rocks (marlstone - 55–60 % and clayey limestone - 70–85 %). This is, beside their micro paleontological characteristics, identifiable feature in respect to the Upper Campanian rocks (86–94 %). The allochem (biogenic) component is represented by well-preserved moulds of microorganisms. Pelagic foraminifers (globotruncana) are prevailing, but some calcispheres and radiolarians were also registered. The micrite limestone could be defined by the amount of biogenic component, defined either as micrite and fossiliferous micrite (less than 10 % of biogenic allochem, Fig. 6a), or as biomicrite (biogenic allochem exceeding 10 %, Fig. 6b). According to the DUNHAM classification (1962), the micrite limestone belongs to Mudstone and Wackestone.

Allochemical limestone

The allochemical limestones are represented by alternation of very coarse-grained rudites to fine-grained calcarenites, regarding their textural features, *i.e.*, the coarseness of the particles and the allochem component.

The allochem and orthochem types, the bio-intra-spar varieties are the commonest (Fig. 7.). Among the sparry varieties, intrasparrudite, biosparrudite, intra-biosparrudite, biosparite and intrabiosparite may be distinguished.

The biogenic allochem compounds include fragmented moulds of shallow-water organisms (mollusks), moulds of benthos and planktonic microorganisms as well as algal fragments (Fig. 7.a.). Intraclasts might be simple or composite. The simple intraclasts usually occur within the medium and fine-grained calcarenite varieties (Fig. 7.b), while the latter were registered in the coarse-grained varieties of calcarenite of the allochemical limestone. The amount of $CaCO_3$ (calcite) in these limestones is in general higher than in the micrite varieties (Fig. 4), attaining from 67 to 96 %.

Depositional environmental

The Pelagic sediments, represented by marlstone, clayey limestone and limestone, were deposited in the deeper parts of an Upper Cretaceous sea. All the mentioned sediments contain chert concretions, just like the Struganik limestone. The autochthonous sedi-
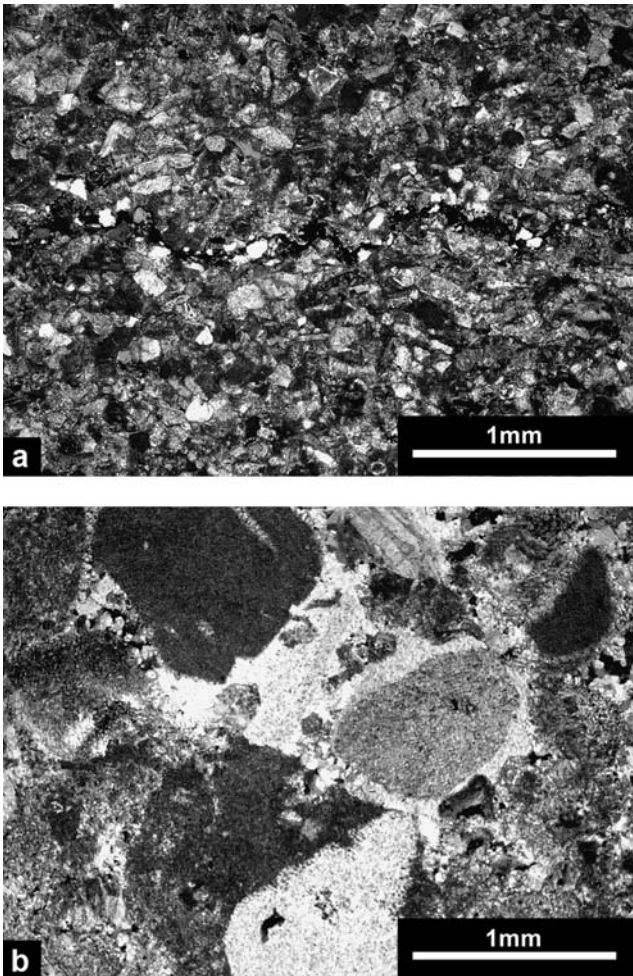
Fig. 7. Photomicrographs of the allochemical limestone: **a,** Fine-grained intrabiosparite. In the middle of the photo is a stylolite seam marked with the accumulation of a sandy component; **b,** Coarse-grained biosparite.

ments are marly limestone and marlstone of micrite and biomicrite composition. The presence of weakly preserved radiolarians and silica sponges in these rocks indicates to their formation at depths deeper than 200 m, while the partial replacement of the siliceous skeletons with calcite implies an alkaline environment, most probably with pH 8 during diagenesis. The presence of concretional cherts indicates the presence of organogenic siliceous remains. The association of rocks and fossil remains is indicative of sedimentation related to a deep marine environment. The presence of layers and banks of allochemsparite, calcarenite and calcrudite with characteristic textures from the Bouma sequence suggests an intermittent supply of shallow-water material by turbid flows along the continental slope, *i.e.*, through the Bathyal Zone.

It could be concluded that the Struganik limestone was derived in a deep marine environment, through deposition on a continental slope.

Physico-mechanical properties of the Struganik limestone

The results obtained from the statistical analyses of the physico-mechanical values of the Struganik limestone are given in Table 1. The real density of a rock is one of its basic properties. It is influenced primarily by the density of the minerals, their content and amount of void space inside the rock (Bell & Lindsay 1999). In the investigated samples of Struganik limestone, the real density displayed little variation and range from 2700 to 2720 kg/m^3, with a mean value of 2710 kg/m^3. The bulk density also varied slightly due to the low amount of void space and was in range 2610 to 2680 kg/m^3, with a mean value of 2650 kg/m^3. All of the tested samples had a moderate density according to Bilbija & Matović (2009). The values of the absolute porosity varied from 1.10 to 3.30 %. Central tendency parameters indicated a negative asymmetrical unimodal distribution of the porosity, with the most frequency class (1.0–1.5 %) of 43 %. According to the mean value of 2.0 %, these limestones generally have a low porosity, although in some samples a moderate porosity was detected (Bilbija & Matović 2009). The obtained values of water absorption (from 0.17 to 0.67 % with an average value of 0.4 %) indicate a very low water absorption by the Struganik limestone. All the investigated limestone samples were resistance to frost. The mass loss after freezing and thawing was low due to the low porosity of the Struganik limestone.

The values of the central tendency for all the physical parameters were similar and indicate to a symmetric, unimodal distribution conforming closely to a Gauss curve. The statistical parameters of the Kolmogorov-Smirnov test confirmed that all the tested samples had a normal distribution of the measured values of the physical properties ($D_{max} > D_{cr}$, Table 1).

The dry unconfined compressive strength values of the limestones varied between 48 and 189 MPa, with a mean value of 134 MPa (Table 2). Most of the tested samples were very strong (strength > 150 MPa), while over a quarter of the samples were moderately strong according to the proposed strength classification of Bilbija & Matović (2009). The values of the saturated compressive compression strength were between 41 to 177 MPa, with an average value of 120 MPa. The mean of the water saturated samples was 10 % lower than that in the dry state, while after 25 freeze–thaw cycles, it had decreased by 4 % to 129 MPa (mean value), indicating that the Struganik limestone is durable to freezing and thawing. The negligible decrease in the unconfined compressive strength reflects that the amount of saturated water is not an important factor for the strength reduction. A significant reduction in the strength appeared when the porosity of the limestone exceeds 3 % (the reduction was about 30 %). The values of volume loss on wear (Böhme abrasion

value) varied from 13.5 to 23.2 cm³ per 50 cm². In terms of the mean value, this limestone is a hard to moderately hard rock (BILBIJA & MATOVIĆ 2009).

The results of regression analysis indicate to a prominent relationship between the dry compressive strength (σ_s) and the water equivalent (σ_v). The trend

Table 1. Statistical parameters of physico-mechanical properties of the Struganik limestone. Legend: n, number of samples; $\bar{X}$, mean; V_{min}, Minimum values; V_{max}, maximum value; $PX_{-95\%}$, confidence intervals for the mean; M, median; Md, Mod; R, range; Q_i, quartile range; Q_1, lower quartile; Q_2, upper quartile; S^2, variance; S, standard deviation; As, Skewness; Kt, Kurtosis; SE, standard error; D_{max}, value of the largest absolute difference between the observed and the expected cumulative distributions; p, confidence interval; D_{cr}, critical value; α, probability level.

	Technical properties							
statistical parameters	Bulk density (ZSP)	Real density (ZBP)	Porosity (P)	Water absorption (Uv)	Strength dry (σ_s)	Strength water (σ_v)	Strength frost (σ_m)	Wear abrasive (H_b)
n	18	7	7	16	18	18	7	18
$\bar{X}$	2650	2710	2,0	0,40	134	120	129	19,36
V_{min}	2610	2700	1,1	0,17	48	41	52	13,5
V_{max}	2680	2720	3,3	0,67	189	177	174	23,15
$PX_{-95\%}$	2640	2700	1,35	0,32	109	96	91	17,9
	-2660	-2720	-2,78	-0,48	-159	-144	-168	-20
M	2650	2700	2,3	0,40	152	138	148	19,29
Md	2650	2700	2,3	0,50	156*	146*	148	22,2
R_i	70	20	2,2	0,50	141	136	122	10
Q_1	30	20	1,17	0,21	99,75	88	58	3,55
Q_2	2640	2700	1,4	0,28	85	68	102	18,22
Q^2	2670	2720	2,57	0,50	181	156	160	21,77
S	365	114,28	0,59	0,02	2503	2323	1729	7,637
S	19,11	10,69	0,77	0,14	50,03	48,20	41,58	2,76
As	-0,60	0,37	0,32	0,02	-0,626	-0,477	-1,19	-0,74
Kt	0,05	-28	-0,74	-0,59	-1,181	-1,355	1,18	-0,06
SE	4,50	4,04	0,29	0,03	11,79	11,36	15,71	0,65
Kolmogorov-Smirnov test of normal distribution (D_{max}) α=0.20								
D_{max}	0,135	0,360	0,197	0,077	0,166	0,184	0,240	0,168
p	0.893	0.324	0.949	0.996	0.699	0.571	0.814	0.683
D_{cr}	0,244	0,381	0,381	0,258	0,244	0,244	0,381	0,244
Distrib.	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal

Regression analysis

Regression analysis was applied to obtain relationships between the mechanical and physical properties of the Struganik limestone. Some of these relationships and the best-fit curves between the different parameters are shown in Fig. 8. The relationships show fairly higher correlations between the bulk density (*ZSP*) and the porosity (*P*). The relationship between them is highly significant with a correlation coefficient of –0.929 and a Students *t*-value of –5.598 (p < 0.05; Fig. 8a). The cross plot of porosity and bulk density shows a general trend of increasing bulk density with decreasing absolute porosity. The plot suggests that the bulk density may be used to obtain the value of the porosity.

is positive and clearly linear with a regression coefficient R^2 = 93 % and a Students *t*-value of 14.717 (Fig. 8b). Comparing the value of the dry strength (σ_s) and that after the freeze–thaw cycles (σ_m), the correlation is positive and high statistically significant with a regression coefficient R^2 = 78 % (*t* = 4.159; Fig. 8c). Low correlations with no significant Pearson coefficients were obtained for all the other physico-mechanical properties.

Validation of this model was confirmed by the *t*-test and analysis of the variance (Table 2). As can be seen in Table 2, all the regression coefficients are significant at the 95 % confidence level. The computed *t*-values are greater than the tabulated critical *t*-values of ±2.36 and ±2.10 for the obtained models. The analysis of variance follows an *F*-distribution with degrees
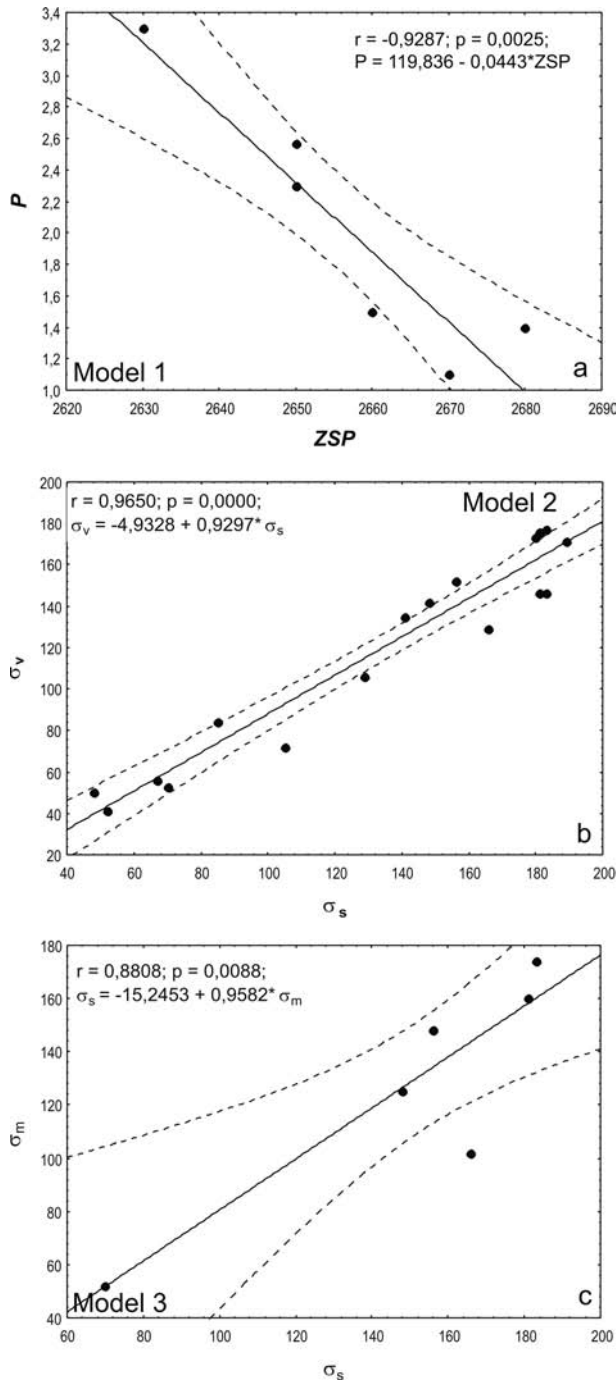
Fig. 8. Relationship between physico-mechanical properties: bulk density *vs*. porosity (a); compressive strength dry *vs*. water equivalent (b); compressive strength dry *vs*. the after freezing equivalent (c).

of freedom $df_1 = 1$ and $df_2 = 5$ for models with samples number of 7, therefore the critical region consists of values exceeding 6.61. For the model with a sample number of 18 ($df_1 = 1$ and $df_2 = 16$), the corresponding critical F value is 4.49. All the computed F values were greater than those tabulated; thus, the null hypothesis can be rejected and it can be concluded that all equations are significant according to the F-test.

Discussion and conclusions

The presence of two lithological types of limestone, *i.e.*, micrite and allochemical, was emphasized. Micrite limestone is the autochthonous rock of a deep water, marine environment. In the original terminology (FOLK 1959), these limestones are considered as orthochemical. The allochemical limestones were derived from shallow-water material that was brought by turbidity currents into the system. The Struganik limestone represents a series of marlstone, clayey limestone and limestone. Concretional cherts and many microfauna are present in all the distinguished varieties. Among the macrofaunal remains, inoceramus is the most frequent.

Generally, the values of physico-mechanical properties indicate the good quality of Struganik limestone as a dimensional stone. Their quality and way of exploitation are directly governed by their petrological properties. Pronounced layering in the micrite varieties results in their exploitation in the form of thin plates and simultaneously determines the dimensions of the final products. As Struganik limestone is used as natural-faced slabs, this texture is undoubtedly a significant economic factor in that it simplifies the process of final shaping. Allochemical, banked limestone, is used to a lesser extent due to its mode of appearance and economic interests. The petrological heterogeneity of the Struganik limestone, including its textural and structural characteristics, has an impact on the numerical values of its physico-mechanical properties. Statistical analysis showed notable variation in important mechanical parameters, *i.e.*, in major criteria, for the application of the stone. This is the consequence of not only the natural heterogeneity of the rock mass, but also probably partially of the fabric and structural differences between the investigated samples. The results of the regression analysis presented in this paper imply that the porosity could be deduced from the bulk density values. Similarly, using the regression equation, the values of the strength of a water-saturated sample or a sample after freezing could be accurately determined using values of the strength in the dry state that was estimated in the laboratory.

However, other properties cannot be estimate with any confidence due to low regression coefficient. It should be emphasized that the analysis was performed on a statistically small number of sample, which additionally affected the obtained results. The real density of limestone is relatively constant as was to be expected due to the uniform mineral composition. The bulk density had a value range of 70 kg/m³, which is probably related to small range in the porosity of this limestone. However, the inverse relationship between the porosity and the bulk density was predicted. Generally, these limestones have low interparticle and intraframe (intraskeletal) porosity, which results from

Table 2. Data on validation of regression models.

| Model | t-test | t-critical | degree of freedom | | F-test | p (α=0.05) | F-critical |
			df_1	df_2			
1	-5.598	±2.36	1	5	31.33	0.003	6.61
2	14.717	±2.10	1	16	216.18	0.000	4.49
3	4.160	±2.36	1	5	17.30	0.009	6.61

the depositional process. However, some higher values of porosity (secondary type: stylolite and micro fissures) are probably caused by post depositional processes. The very low value of water absorption is in agreement with that of their porosity. Even in samples with a porosity value of 3 % or higher, the water absorption was very low (under 0.4 %). This means that these rocks contain isolated, unconnected pores or micro-cracks unable to receive and retain water. The low values of water absorption indirectly imply limestone resistance to frost.

The mechanical properties data of the Struganik limestone point to its variable quality, which is in accordance with the petrological heterogeneity of the rock mass. The same part of the rock mass is strong to moderately strong regarding the unconfined compressive strength. Simultaneously, it is hard to moderately hard rock concerning its wear abrasive. Samples with high values of strength (over 150 MPa) and lower values of abrasive resistance (below 18 cm^3 per 50 cm^2) probably correspond to micrite, fossiliferous micrite or biomicrite. On the other hand, layers/banks of bio-intra-spar varieties as well as layers with a higher clay content (marly limestone and marlstone) are present in the quarry. This may be the main cause for the very low strength values (below 70 MPa) and poor resistance to wear (over 22 cm^3 per 50 cm^2). Additionally, the presence of chert concretions, variable layer thickness, lamination, stylolite and other textural forms are reasons for the variable technical properties.

All the mentioned parameters are limiting factors for the use of the Struganik limestone as a dimension stone. Namely, the thickness of the final slabs is naturally defined by the layering, whereas the pronounced petrological heterogeneity requires selective exploitation. The statistically analyzed data confirmed that the average values of the technical properties satisfy the majority of the requirements of the national standard for stone slabs (SRPS B.B3.200 national standard without obligatory use). Unfortunately, the average value of the abrasive wear is higher than the limit for some applications of building stone and actually represents the main limiting factor. According to this standard, in the case that the tensile strength has been previously determined, the Struganik limestone may be used for:

– Pavement of interior vertical surfaces and horizontal surfaces with intensive and moderate trailer traffic;

– Pavement of exterior vertical surfaces up to 30 m in height in objects;

– Pavement of exterior horizontal surfaces with moderate trailer traffic (if the value of the wear abrasive is max. 18 cm^3 per 50 cm^2 or lower).

Compact, thinly bedded micrite varieties of chemically pure limestones entirely fulfill the requirements for the above-listed purposes, whereas the banked allochemsparite varieties or beds with an elevated content of clayey components should be avoid as dimensional stone.

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Резиме

Петрофизичке и механичке особине струганичких кречњака (Вардарска зоне, западна Србија)

Природни камен је највише коришћен грађевински материјал на свету, како за унутрашња тако и за спољашња зидања. Да би се користио у грађевинарству, камен треба да поседује добар квалитет односно физичко-механичка својства која задовољавају захтеве стандарда у грађевинарству. Карбонатне наслаге различите литологије, старости и квалитета су широко распрострањене у Србији па су и кречњаци најчешће коришћен грађевински камен. У индустрији архитектонског камена значајно место заузима струганички кречњак, најпознатији украсни камен западне Србије чија је експлоатација започела још у 18. веку. Данас, више од 70 каменолома обавља активну експлоатацију кречњака у области Струганика и шире, али услед недовољне геотехничке истра-

жености ове стене имају још увек ограничену примену у грађевинарству. Рад представља синтезу резултата детаљних петролошких и технички испитивања кречњака из најстаријег и највећег површинског копа „Струганик“, интерпeрeтацију депозиционе средине стварања кречњака, као корелацију физичко-механичких карактеристика тј. утицај петролошких карактеристика на квалитет стенске масе.

Према петрлошким карактеристикама, минералном и хемијском саставу, стенску масу површинског копа „Струганик“ граде лапорци, глиновити кречњаци и кречњаци. Стратиграфски они припадају доњем и горњем кампану, а нова открића асоцијације пелашких глоботрунканида потврђују њихову кампанску старост (Гајић 2007). Кречњаци су једри, компактни са хомогеном сивом бојом коју делимично нарушава присуство тамносивих конкреција рожнаца. Основни текстурни облик појављивања кречњака је слојевитост са доминантном дебљином од 5–15 cm. Слојне површи су равне или стилолитске, а на горњим површинама се налазе и бројни биогени текстурни облици и трагови богате животне активности. Од интерних текстурних облика јављају се хоризонтална ламинација, стилолитски шавови и веома карактерстична конкрециона тела рожнаца. Палеонтолошка анализа микрофауне показала су да доњи део литолошког стуба стратиграфски припада доњем кампану а преосталих седам метара – горњем кампану. Према структурним карактеристикама издвајају се два основна литотипа кречњака: микритски – ортохемијски, аутохтони кречњаци (Mudstone, Wackestone) и алохемијски кречњаци, био-интра-спар варијетети (Grainstone, ретко Rudstone). Основу микритских кречњака гради микрокристаласти калцит док некарбонатни део чине минерали глина, органска материја и алевритска компонента. Биогена компонента је представљена добро очуваним љуштурицама пелашких фораминифера *(Globotrunkanide)* и у зависности од њиховог садржаја разликују се микрити, фосилиферни микрити и биомикрити. Садржај $CaCO_3$ у овим стенама варира од 55 до 94 %. Банковити био-интра-спар варијетети (интраспаррудити, биоспаррудити, биоспарити, интрабиоспарити) су изграђени од разноврсног биогеног алохема (фрагменти љуштура плитководних организама, љуштурице бентоских и планктонских микроорганизама, фрагменти алги) и простих до сложених интракласта. Природа транспорта којим је материјал принешен у басен омогућила је развој интерних текстура карактерстичних за Боумину секвенцу. Садржај $CaCO_3$ у овим стенама варира од 86 до 98 %.

На основу петролошких показатеља утврђено је да су аутохтони микритски варијетети пелашки седименти таложени на континенталној падини у

дубоководној средини горњокредног мора, док присуство слојева и банака алохемоспаритских калкаренита и калкрудита указују на повремени принос плитководног материјала турбидитним токовима низ континенталну падину.

Квалитет струганичког кречњака као украсног камена у функцији је његовог минералног састава, склопа и физичко-механичких својстава. Према статистичким показатељима испитивани кречњак припада категорији умерено тешког, компактног и тврдог камена са врло малим упијањем воде, средње до високе чврстоће према притиску. Квалитет и начин експлоатације предодређени су екстерним и интерним текстурним облицима. Изражена слојевитост микритских варијетета условила је: експлоатацију у облику танких плоча, димензије готових производа; равни слојевитости су природне, али и финалне површи ове врсте архитектонског камена. Петролошка хетерогеност стенске масе условила је велику варијабилност нумеричких вредности физичко-механичких карактеристика тј. главних критеријума за примену камена. Густина кречњака је релативно константна што је и очекивано с обзирома на уједначени минерални састав. Запреминска маса показује мали опсег варирања – последица релативно уједначене порозности. Струганички кречњак има ниску интерпартикуларну и интерскелетну порозност која је резултат депозиционих процеса. Ниске вредности упијања воде индиректно указују на

отпорност кречњака на агресивно дејство мраза што је потврђено и лабораторијским анализама. Чврстоћа на притисак и отпорност на хабање су технички параметри са највећим варирањем вредности. Узорци кречњака са високим вредностима чврстоће на притисак (изнад 150 MPa) и високом отпорношћу према хабању брушењем (<18 cm^3/50cm^2) одговарају микритским варијететима док био-интра-спар варијетети и варијетети са високим садржајем глиновите компоненте одговарају стенама умерене чврстоће, а њихова нижа абразивна отпорност је и главни ограничавајући фактор примене. Резултати регресионе анализе приказани у раду, показују да су порозност и запреминска маса у директној линераној зависности са високим статистички поузданим коефицијентом регресије. Високу међусобну линеарну зависност показују и параметри чврстоће на притисак у сувом, водозасићеном стању у после дејства мраза. Остала физичко-механичка својства, услед ниског регресионог коефицијента немају статистички значајне функције зависности.

На основу резултата статистичке анализе физичко-механичких својстава може се закључити да квалитет струганичког кречњака задовољава већину захтева националног стандарда за примену плоча за унутрашња и спољашња, вертикална и хоризонтална облагања. Отпорност на хабање је једини фактор који лимитира примену кречњака као украсног камена.