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ORIGINAL PAPER

Mesozoic carbonate rocks in Serbia used as dimension stone

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Abstract The building industry in Serbia uses, to a great extent, imported natural stone for architectural purposes. The significance of local deposits, particularly limestones, is not adequately perceived despite the country's abundance of these valuable resources. Therefore, this study focuses on Serbia's Mesozoic carbonate rocks, specifically on the deposits of four selected quarries: Klisura, Skrzut, Struganik, and Tisnica. The quality and prospects of the application of these limestones has not yet been the subject of a detailed, comprehensive investigation. Therefore, this research is primarily concerned with the examination of their petrological and physico-mechanical properties in order to propose their scope of application further as dimension stone. According to the petrological features, different carbonate microfacies are observed: biolithites, pure orthochemical micrites, allochemmicrites, and allochemsparites. Physico-mechanical characteristics confirmed that the investigated carbonate rocks are of high bulk density, compact or of low porosity, of very low water absorption, hard, and with high to moderately high values of compressive strength. The scope of use is established according to a comparison of statically analysed engineering properties with the technical requirements necessary for a suitable reference of natural stone products. The results demonstrate that the examined rocks are suitable for use as slabs for architectural cladding and paving, whereas the occurrence of bedding and occasional tectonic fissures (fractures) is considered to be a limiting factor of exploitation.

Keywords Dimension stone · Mesozoic · Limestone · Serbia · Petrography · Physico-mechanical properties

Introduction

Stone was and still is the most important building material in civil engineering; it is used in the architecture of old cities or modern buildings, in monument heritage sites, and in the memorial industry. With regard to its aesthetic properties, workability, and durability, stone is a favourite material of sculptors as well. In addition to the desired properties for its intended purpose (physico-mechanical properties and durability), the main criterion for choosing ornamental stone is its appearance. The aesthetic properties of stone are determined by colour and texture.

Although a uniform colour is recommended for the use of stone in façade cladding or tombstones, in other areas, such as in the production of countertops or home accessories, exotic colours and textures are decisive factors in determining stone type. The other crucial criterions for the profitable production of dimension stone are the soundness of the deposit (possibility of block production of a suitable size) and market demand (Luodes et al. 2000).

Despite the fact that concrete and glass were the principal materials in architectural design during the 1970s and 1980s, in the last three decades, the demand for dimension stone has continuously increased (Siegesmund and Snethlage 2011). This trend is a result of the aesthetic

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appearance, surface processing possibilities, durability, wide variety of use, and easy maintenance of stone (Siegesmund and Török 2011). New technologies, leading to substantial advances in excavation and processing, further extend modern design possibilities.

Today, the global leaders in dimension stone production are Asia (50 % of world production in 2004) and Europe (~38 %) (Montani 2005). With 11.8 Mt exported in 2008, China is the leader in stone exportation. Along with Italy, India, Spain, Brazil, and Portugal, China sold more than 1 Mt of material on the international stone market (Siegesmund and Török 2011). Some of these countries also import considerable quantities of raw materials and semi-finished products and are positioned as leading importers on the world stone market. The high production and processing capacities, along with low labour costs, in countries such as China, India, Brazil, or South Korea, are out-competing the local stone industries of other countries with a wide range of exotic and cheap decorative stone (Terezopoulos 2004; Snethlage 2011). This fact is perhaps the main cause of the stone production decrease in many European countries, especially small and economically undeveloped countries of the Balkan region. This is also the case in Serbia, where limestones were traditionally quarried as dimension stone.

The widespread, satisfactory engineering properties confirmed in praxis, and cost-effective exploitation and processing of limestones has resulted in active quarries of dimension stone being opened primarily in the Mesozoic carbonate rocks of Serbia. Their geological characteristics have been studied by numerous authors (Sučić 1961; Antonijević et al. 1970; Grubić and Jankićević 1973; Andjelković 1975a, b, c; Mojsilović et al. 1978; Kalenić et al. 1980; Sudar 1982, 1985, 1986, 1996; Dimitrijević and Dimitrijević 1986, 1996; Andjelković and Sudar 1990; Matović 2009; Gajić et al. 2011; Sudar et al. 2013), but a detailed investigation of quality in terms of the possibility of use has not yet been conducted. Although some individual limestone quarries have deposits of more than a million cubic metres, with the potential production capacity of approximately 10,000 m^3 of blocks and 15,000 m^2 of panels per year, their market demand is very low. The fact that the significance of these local deposits is not adequately perceived contributes to the low market demand. Therefore, we proposed to investigate the quality indicators of limestones deposited in four active quarries and compared them to a suitable usability reference.

This work presents petrographic properties, along with physical and mechanical features of selected limestones. The aim is to explore a substantiated overview of the limestones' scope of application as dimension stone–slabs for architectural cladding and paving for exterior and interior use—with the possible effect on Serbia's building and stone industry, and eventually the export market.

Study area

The study area includes four selected limestone quarries: Klisura (Fig. 1a), Skrzut (Fig. 1b), Struganik (Fig. 1c), and Tisnica (Fig. 1d). These are the only quarries in Serbia in which limestones were excavated as dimension stone.

At Klisura, the exploitation of stone for architectural purposes has occurred for over five decades. The quarry is situated in western Serbia, approximately 22 km south of the town of Uzice, within the territory of Sirogojno village (Fig. 1). The wide terrain, a hilly mountainous area with altitudes ranging from 800 to 1,000 m, belongs to the northeastern edge of the Zlatibor massif. The Klisura quarry occupies an area of 0.12 km^2 at a few exploitation levels (Fig. 1a). The thickness of the ore mass varies from 12.5 to 25.5 m. In geological terms, the rock mass is known as "Bulog limestone". It belongs to the Medium Triassic–Late Pelsonian to Middle/Late Illyrian age (Pantić-Prodanović 1996; Sudar et al. 2013).

The Skrzut quarry of natural stone was opened in 1960. It is situated in western Serbia, approximately 15 km from the town of Uzice. Similar to the Klisura quarry, the Skrzut quarry belongs to the northeastern edge of the Zlatibor massif (Fig. 1). It occupies an area of approximately 4,000 m^2. Natural exploitation levels follow planar bedding surfaces of limestone (Fig. 1b). The limestone ore body is elongated in a NW–SE direction, with variable thickness of 6.5–34.0 m (Lazarević 1994). The rock mass is built of Upper Cretaceous limestone, which belongs to the Cenomanian age (Dimitrijević 1996). Tectonically, the rock mass is fragmented into blocks by a system of faults and fractures that reduce the possibility of extracting blocks of commercial size.

The Struganik quarry has been exploited for architectural stone for over three decades. It is situated in western Serbia, within the territory of Struganik village, approximately 30 km from the town of Valjevo (Fig. 1). The area is part of the northern rim of the Maljen ophiolitic massif, located in the Western Belt of the Vardar Zone (Karamata and Krstić 1996; Karamata 2006). The wide territory is characterized by a complex morphology and is distinguished by two areas: the plain of the tertiary basin north of Struganik and the low-mountainous terrain of the Maljen (400 m) and Suvobor (500 m) mountains. The Struganik quarry is irregular in shape, elongated in a NW–SE direction, and occupies an area of 0.32 km^2. The maximum ore thickness is estimated to be 76 m (Kijanović 2007). The Upper Cretaceous (Turonian–Senonian) age of the Struganik limestone is documented using the microfossils: *Praeglobotruncana helvetica, Rotalipora* spp., and *Globotruncana lapparenti coronata,* among others (Filipović et al. 1978), whereas the association of pelagic globotruncanas, observed in a more recent micropaleontological

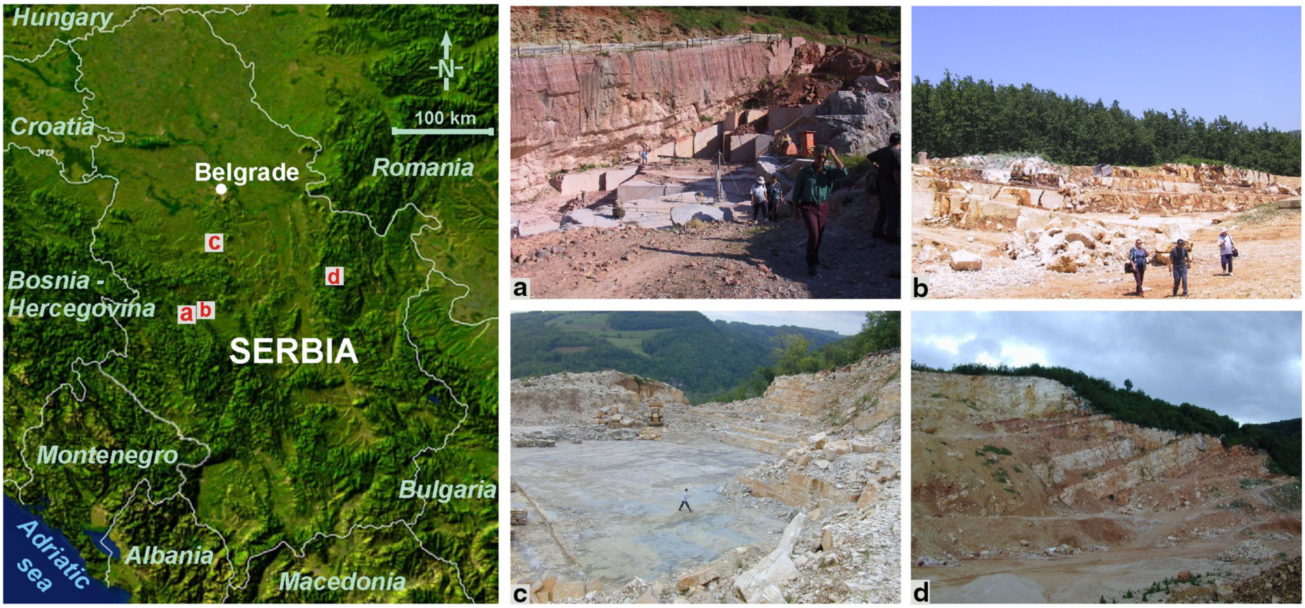

Fig. 1 Map of Serbia and the location of quarries of investigated limestone: **a** Klisura; **b** Skrzut; **c** Struganik; **d** Tisnica

analysis, indicates that these sediments are of Campanian age (Gajić 2007). Tectonically, the rock mass is characterized by the presence of longitudinal, parallel faults extending in a N–NW direction with an E–NE dip of 50°–60°. Limestone exploitation is performed along additional primary surfaces of mechanical discontinuity (bedding planes), whereas secondary surfaces—vertical tension fractures perpendicular to the bedding with a steep dip (80°–90°)—adversely affect the exploitation, reducing the usable percentage of the rock mass (Fig. 1c).

The Tisnica open pit quarry of natural stone is situated in Eastern Serbia, approximately 1 km from the town of Zagubica. The wide terrain, a hilly mountainous area, belongs to the northern edge of Beljanica Mountain (Fig. 1). The Tisnica quarry is composed of layered and banked limestone of the Lower Cretaceous age corresponding to Urgonian facies. Flowing in a N–S direction, the river Tisnica splits the deposit in two (Fig. 1d). The exploitation takes place at a few exploitation levels on both sides of the riverbed covering an area of approximately 0.12 km^2 (Živković and Paunović 2000).

Materials and methods

Carbonate rocks collected from four different locations in Serbia (quarries: Klisura, Skrzut, Struganik, and Tisnica) have been used to characterize the petrographic and technical properties of dimension stone. The determination of the petrological properties of the selected rocks began with field observations in the open pit and the creation of detailed lithological columns. In total, 81 stone samples were collected (Klisura—12 samples, Skrzut—six samples, Struganik—28 samples, and Tisnica—35 samples). Petrographic analyses of the rocks was performed on thin sections using a Leica DMLSP microscope for polarized light connected to a Leica DC 300 digital camera. The thin sections were used to determine the mineral composition and microtextural features (size and type of allochem) for the purpose of rock classification, according to Folk (1959) and Flügel (2004). The CaO and MgO contents were determined for the same samples, applying a complexometric method using a standardized solution of 1 M EDTA (ethylenediaminetetraacetic acid) as the titrant.

To determine the quality of the selected carbonate rocks, the physical and mechanical properties (bulk and apparent density, porosity, water absorption, frost resistance, compressive strength, and abrasive resistance) were examined for 52 collected samples. The laboratory tests were performed according to current national standards at two equally credible laboratories: the Laboratory of the Highway Institute (Laboratory for Stones and Stone Aggregates) and the Institute for Testing of Materials–IMS Institute (Laboratory for Stones and Stone Aggregates) in Belgrade. The bulk density was determined according to the standard method SRPS B.B8.032 (1980) (corresponding to European Committee for Standardization EN 1936:2006). On the same, but powdery samples, the real densities were determined using a pycnometer method. Considering the values of real and bulk density, the total porosity was calculated. The water absorption was determined according to the standard method SRPS B.B8.010 (1981) (corresponding to European Committee for Standardization EN 13755:2009). The resistance to frost was determined by subjecting the sample to 25 cycles of freezing to −25 °C temperatures and thawing according to SRPS B.B8.001 (1982). The strength characteristics in uniaxial conditions (dry, water sutured, and after frost) were determined following the test procedure defined in SRPS.B.B8.012 (1987) (corresponding to European Committee for Standardization EN 1926:2010). The Böhme abrasion resistance test was performed according to SRPS.B.B8.015 (1984) (corresponding to European Committee for Standardization EN 14157:2008).

To evaluate the physical and mechanical properties of the investigated carbonate rocks, basic descriptive statistics were performed using the StatSoft computer software. Statistical parameters (mean, minimum, and maximum value) are presented using box–Whisker diagrams. For the purpose of usability evaluation, the representative values (arithmetic mean or median) of physico-mechanical properties were compared to the technical requirements of a suitable national standard (SRPS B.B3.200 1994).

Results

Petrographic data of carbonate rocks

Petrological properties of the Klisura limestone

In geological practice, the Klisura limestone is known as "Bulog limestone", but its commercial name is also "Red Sirogojno" (varieties of red). Bedding is the main external textural form of this limestone, whereas nodular texture, lamination, and stylolitic seams appear as internal textural forms. The colour varies from dark grey and grey in the base of the lithological column, and pink and pinkish-red in the middle, to the intensive red of the highest layers of nodular limestone (Fig. 2a).

Preserved shells of various macrofossils (e.g., ammonites) further contribute to the aesthetic appearance. The homogeneity of colour is locally interrupted by cavernous spaces and fissures filled with greyish–white coarse crystalline calcite. The examined rocks belong to pure limestone ($CaCO_3$ varies from 92.93 to 99.94 %, with an average value of 97.61 %). The limestones of this quarry are represented by three types of microfacies (Matović 2009). Biosparite (Grainstone microfacies) occurs only in the base of the column and it is characterised by unsorted and densely packed bioclasts (up to 1 mm), rare intraclasts and oncoids arranged in sparitic cement. Dominant red nodular limestone, allochemmicrite (Packstone and Wackestone microfacies), builds the second and the third package of the column, and it is characterised by a high content of ammonites or is rich in different bioclastic materials (about 0.5 mm) within the micrite matrix. Stylolites and a high concentration of Fe-oxide/hydroxide commonly mark the borders between nodules and the matrix (Fig. 2b). Pure orhtochemical limestone, micrite (mudstone microfacies), occurs in all packages as a laminated interlayer at various distances, indicating discontinuity in sedimentation.

Petrological properties of the Skrzut limestone

These limestones are massive or thickly layered with frequent stylolites. Their presence makes the cutting of blocks difficult, reduces the useable percentage, and influences the final surface polishing. The homogeneity of colour in shades of light brown and preserved macrofossils contribute significantly to the aesthetic appearance and the decorative quality of the limestone (Fig. 2c). The amount of $CaCO_3$ in these limestones is high, from 97.46 to 99.96 %, and with a mean value of 98.76 %, they belong to pure limestones. With regards to textural features, coarseness and type of allochem, these limestones correspond to biomicrite/biomicrudite, i.e., rudstone, floatstone, and wackestone microfacies. They are abundantly accompanied by different types of macrofauna up to 2 cm (remains of benthic sessile organisms: shells, corals, etc.) and microfauna (mostly foraminifers from 0.5 to 2 mm). Macrofaunal remains are usually completely recrystallized (Fig. 2d).

Petrological properties of the Struganik limestone

The uniform greyish colour throughout the entire deposit is sporadically disturbed by the presence of dark grey, greyish blue, or whitish chert concretions (Fig. 2e). The main lithological member is micrite limestone layered in thick beds with bedding planes abundant with Inoceramus (Gajić 2007). The second member, allochemical limestone, occurs rarely, mainly in the form of beds or banks, and it is characterised by the texture of turbulent transport, particularly with intervals of the Bouma Sequence among the layers (Gajić 2007; Gajić et al. 2011).

The micrite (ortochemical) limestone–micrite, fossiliferous micrite, and biomicrite (mudstone and wackestone microfacies)—is primarily composed of microcrystalline calcite, whereas non-carbonaceous compounds include clay minerals, organic matter, and subordinated silty material. According to the $CaCO_3$ content, micrite limestone refers to pure limestone, clayey limestone (70–85 %), and marlstone (55–60 %) (Gajić et al. 2011). The allochem (biogenic) component is represented by well-preserved moulds of microorganisms. Pelagic foraminifers (globotruncana up to 0.5 mm) are prevailing, but some calcispheres and radiolarians were also registered (Fig. 2f). The allochemical limestones are represented by the alternation of bio-intraspar varieties: intrasparrudite,

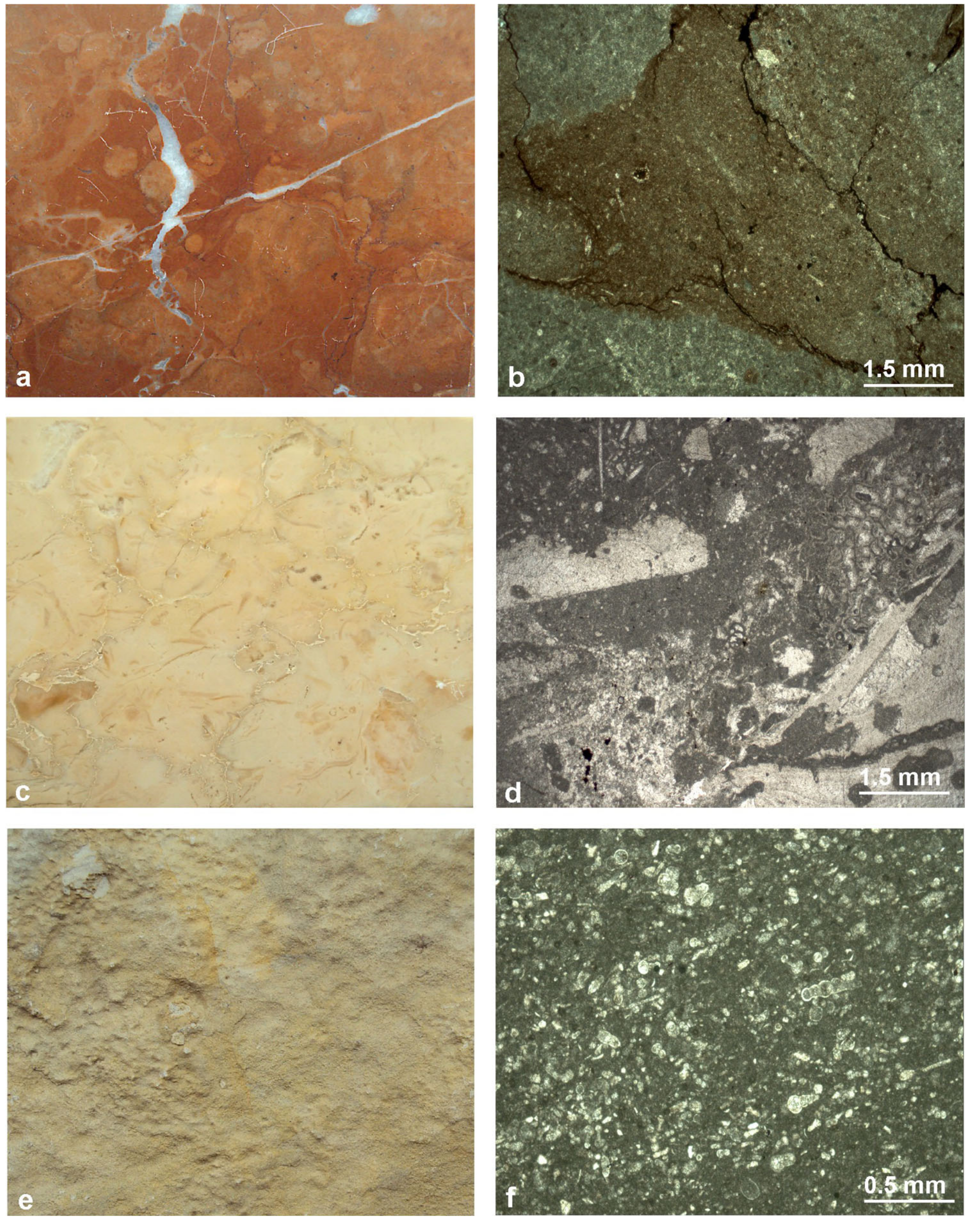

Fig. 2 The appearance and photomicrographs of the investigated limestones: **a** Klisura red nodular limestone (*polished surface*); **b** Klisura biomicrite; **c** Skrzut limestone (*polished surface*); **d** Skrzut biomicrudite; **e** Struganik limestone (*natural split surface*); and **f** Struganik biomicrite

biosparrudite, intrabiosparrudite (rudstone microfacies), biosparite, and intrabiosparite (grainstone microfacies). The allochem compounds (up to 1 mm) include fragmented moulds of shallow-water organisms (molluscs), moulds of benthos, and planktonic microorganisms, algal fragments as well as simple or composite intraclasts. The amount of $CaCO_3$ content in allochemical limestone is generally higher than in the micrite varieties and varies from 67 to 96 %.

Petrological properties of the Tisnica limestone

The Tisnica carbonate rocks are massive or bedded with frequent internal textures: stromatolites, fenestras, and stylolites (Fig. 3a). A diversity of colour along with textural features significantly contributes to the decorative properties of these rocks. The colour varies from grey, over pink, and orange, to bright red and light brown. Preserved macrofossil fragments (up to 4 cm) and spherical forms of reddish–pink oncoids further contribute to the aesthetic appearance (Fig. 3c). According to the structural and textural characteristics, four sedimentary packages with alternating microfacies were distinguished within the lithological column of the limestone (total height of 53 m). Stromatolite limestones (90–97 % $CaCO_3$), such as biolithite (Bindstone microfacies), are the most abundant members in the lithological column. Their common characteristic is the presence of the same type of LLH

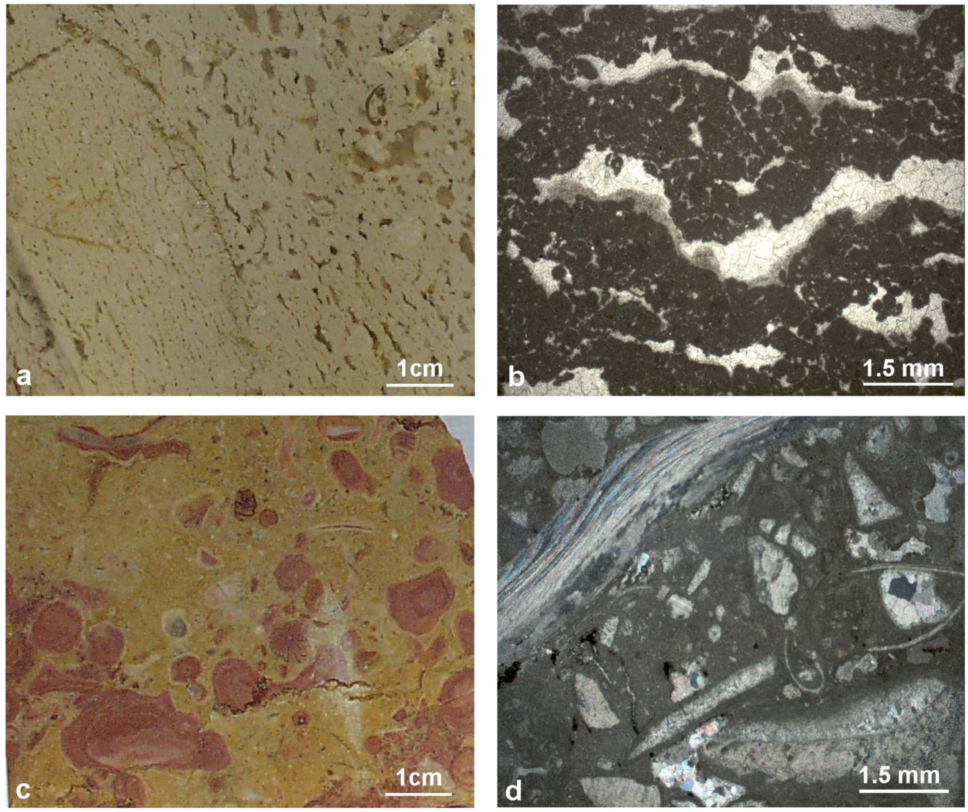

Fig. 3 The appearance and photomicrographs of the Tisnica limestone: **a** Stromatolite limestones (saw-plane surface); **b** Fenestral texture of biolitite with geopetal structural patterns; **c** spherical forms of reddish–pink oncoids in oobiomicrudite (saw-plane surface); and **d** Completely recrystallized macrofaunal remains of biomicrudite

stromatolites with wavy curved laminas at an approximate distance of 1–5 mm. Laminas consist of algal masses with the frequent occurrence of densely glued, grape-shaped accumulations of micrite and intraclasts. A general characteristic of the biolithite is its fenestral texture, which is characterised by irregular or lenticular voids that are completely filled by coarse-crystalline calcite or laminoid voids with geopetal structural patterns (Fig. 3b). Biomicrudites/oobiomicrudites with oncoids (floatstone microfacies; 90–95 % $CaCO_3$) consist of densely arranged oncoids (up to 1.5 cm), a diverse association of fragmented macrofauna (shells, gastropods, corals, brachiopods, etc.), and intraclasts and oolites with a well-preserved concentric fabric (Fig. 3c–d). Fossiliferous micrites, biomicrites, and micrites (mudstone and wackestone microfacies) characterise the layers of nodular limestone (78–87 % $CaCO_3$). The main feature of orthochemical limestone is the abundance of filaments and microfauna, which is mostly represented by foraminifers (up to 0.3 mm) placed inside the micrite orthochem. Microfauna are uniformly distributed in biomicrite and reduced to a minimum in pure micritic layers. The clayey matrix of nodular limestones has a variable amount of ferruginous matter that reveals various colours (from grey to red). Intrabiosparrudite (rudstone microfacies; 96–97 % $CaCO_3$) are made of simple and complex intraclasts and fossil fragments with the orthochem of sparry calcite. Bioclasts include shallow-water macrofaunal remains that are usually completely recrystallized. They are densely distributed around various-sized intraclasts. According to the content of the carbonate ($CaCO_3$) component, the majority of examined rocks belong to pure limestones.

Technical properties of observed limestones

As shown in the results of the physico-mechanical tests (Table 1) and basic statistical analyses (Fig. 4), all of the limestone samples exhibit relatively uniform values of mechanical properties, but some heterogeneity in terms of physical properties.

Because of the low amount of void space, the bulk density varies slightly and is in range of 2,650–2,690 kg/m^3 (Fig. 4a). The values of real density (2,700–2,712 kg/m^3) are in accordance with the mineral composition of these almost pure limestones (the main mineral is calcite with a density value of 2,710 kg/m^3; Fig. 4a). The constant real density values of the Tisnica limestone are probably the consequence of the small statistical sample.

The Klisura and Skrzut limestones are very compact rocks and they are characterised by consistency values of total porosity (mean is less than 1 %; Fig. 4b). Although Tisnica and Struganik limestones show a wide range of porosity values, their deviation is the inevitable result of textural heterogeneity (microfacies from mudstone to

Table 1 Technical properties of Klisura (KL), Tisnica (TI), Skrzut (SK), and Struganik (ST) limestone

No.	Bulk density (ZSP) (kg/m^3)	Real density (ZBP) (kg/m^3)	Porosity (P) %	Water absorption (Uv) %	Frost resistance (loss of mass) %	Compressive strength dry (σ_s) (N/mm^2)	Compressive strength water (σ_v) (N/mm^2)	Compressive strength frost (σ_m) (N/mm^2)	Wear abrasive (H_b) (cm^3/50 cm^2)
KL-1	2,679	2,720	×	0.1	0.0	117	94	95	18.86
KL-2	2,680	2,700	0.8	0.14	0.0	207	204	151	20.6
KL-3	2,700	2,720	0.8	0.09	0.0	218	199	198	17.9
KL-4	2,680	2,710	0.8	0.26	–	166	164	–	–
KL-5	2,690	2,700	0.8	0.29	–	188	137	–	–
KL-6	2,700	2,710	×	0.15	–	147	118	–	–
KL-7	2,710	2,720	×	0.16	0.0	227	203	194	13.9
KL-8	2,690	2,710	0.8	0.07	0.0	211	198	219	18.3
KL-9	2,680	2,720	1.1	0.16	0.0	130	110	157	20.5
KL-10	2,690	×	×	0.24	0.1	138	124	115	22.6
KL-11	2,690	2,710	0.7	0.07	0.0	185	160	156	14.9
KL-12	2,660	×	0.8	0.08	0.0	119	94	90	–
TI-1	2,680	–	–	0.37	–	141	128	–	21.5
TI-2	2,670	–	–	0.71	–	144	132	–	19.7
TI-3	2,680	2,700	0.8	0.37	0.0	141	128	119	21.5
TI-4	2,690	–	–	0.11	–	140	132	–	17.1
TI-5	2,690	2,700	0.4	0.11	0.0	140	132	132	17.1
TI-6	2,660	2,700	1.7	0.22	0.0	138	119	103	22.43
TI-7	2,630	×	1.1	0.49	0.1	116	83	66	15.98
TI-8	2,670	2,700	1.3	0.33	0.0	136	100	97	13.49
TI-9	2,690	–	–	0.29	–	156	150	–	14.1
TI-10	2,670	–	–	0.26	–	131	100	–	16.1
TI-11	2,660	2,700	1.5	0.29	0.0	140	120	101	15.49
TI-12	2,690	–	–	×	–	156	77	–	17.5
TI-13	2,640	–	–	0.68	–	138	98	–	16.34
TI-14	2,700	–	1.1	0.29	–	×	×	×	13.81
TI-15	2,700	–	1.9	0.39	–	187	172	–	13.96
TI-16	2,650	2,700	1.85	0.54	0.1	163	128	115	17.2
SK-1	2,670	2,700	1.1	0.25	0.0	138	140	90	15
SK-2	2,680	2,700	0.8	0.12	0.0	157	129	141	23.25
SK-3	2,680	2,700	0.8	0.1	0.0	148	135	108	17.77
SK-4	2,620	×	0.9	0.21	0.1	82	77	78	–
SK-5	2,650	2,700	0.8	0.28	0.0	117	84	113	13.11

Table 1 continued

No.	Bulk density (ZSP) (kg/m^3)	Real density (ZBP) (kg/m^3)	Porosity (P) %	Water absorption (Uv) %	Frost resistance (loss of mass) %	Compressive strength dry (σ_s) (N/mm^2)	Compressive strength water (σ_v) (N/mm^2)	Compressive strength frost (σ_m) (N/mm^2)	Wear abrasive (H_b) (cm^3/50 cm^2)
SK-6	2,690	2,710	1.1	×	0.0	182	168	142	13.35
ST-1	2,640	–	–	0.55	–	180	173	–	19.16
ST-2	2,610	–	–	0.67	–	141	135	–	18.24
ST-3	2,650	–	–	0.36	–	189	171	–	15.7
ST-4	2,660	–	–	0.48	–	183	146	–	18.42
ST-5	2,630	–	–	0.24	–	181	146	–	18.78
ST-6	2,630	2,720	3.3	0.4	0.7	166	129	102	18.5
ST-7	2,640	–	–	0.61	–	67	56	–	19.42
ST-8	2,680	2,720	1.4	0.33	1.6	70	53	52	21.67
ST-9	2,670	–	–	×	–	52	41	–	21.16
ST-10	2,660	–	–	0.38	–	85	84	–	20.46
ST-11	2,680	–	–	0.27	–	48	50	–	22.1
ST-12	2,675	–	–	0.41	–	129	106	–	21.38
ST-13	2,670	–	–	–	–	105	72	–	18.19
ST-14	2,650	2,700	2.3	0.5	0.2	156	152	148	22.2
ST-15	2,670	2,700	1.1	0.17	0.0	181	176	160	13.5
ST-16	2,650	2,720	2.57	0.19	0.0	183	177	174	23.15
ST-17	2,660	2,700	1.5	0.44	0.9	148	142	125	14.3
ST-18	2,650	2,700	2.3	0.5	0.2	156	152	148	22.2

× Omitted outliers and extreme values

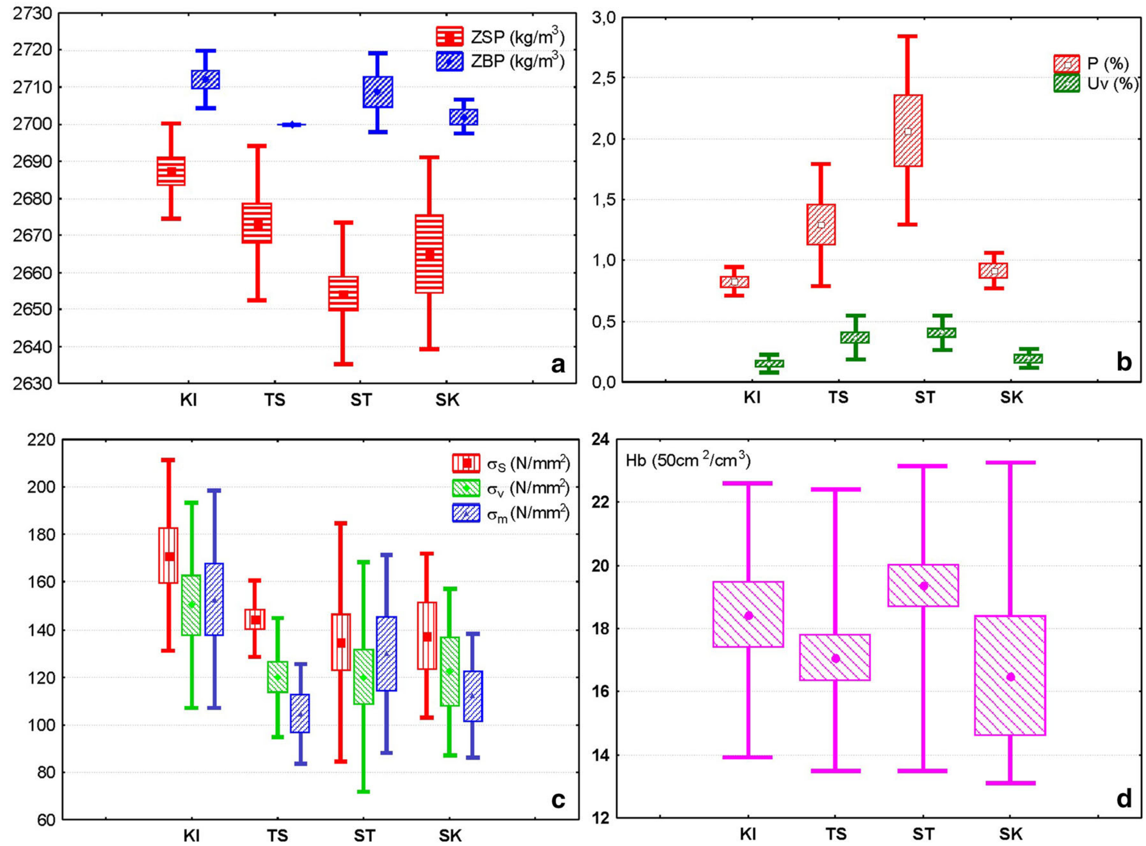

Fig. 4 *Boxplot* diagrams of physical and mechanical properties of limestones: **a** bulk density (ZSP) and real density (ZBP); **b** porosity (*P*) and water absorption (Uv); **c** compressive strength–dry, water saturated and after freeze–thaw cycling (σ); and **d** wear abrasive (Hb); legend: *Kl* klisura, *TS* tisnica, *ST* struganik, *SK* skrzut

rudstone). They also have a low porosity (1.3–2.0 %). All limestones exhibit similar behaviour in terms of water absorption (Fig. 4b). Concerning porosity, these rocks have very low absorption (<0.5 %). This fact contributes to their durability to weathering processes.

According to the arithmetic mean, the Klisura nodular limestone has the highest value of compressive strength (171 N/mm^2 in a dry state), whereas Cretaceous allochemical limestones are generally of moderately high compressive strength according to their arithmetic mean (Tisnica 144 N/mm^2, Struganik 134 N/mm^2, and Skrzut 135 N/mm^2; Fig. 4c). The values of compressive strength were 10–17 % lower in the water saturated samples, whereas after 25 freeze–thaw cycles they have decreased by 20–27 %. A small decrease in compressive strength of the Struganik limestone (after the frost test), compared to the expected decrease in strength in water saturated samples, may be due to the heterogeneity of the rock mass, i.e., tested samples. All observed limestones are resistant to frost with the mass loss being less than 2 % after 25 freeze–thaw cycles.

All investigated limestones are predominantly hard rocks (Bilbija and Matović 2009). They have equable means of abrasion wear (volume loss) that vary from 16.5 to 19.4 cm^2/50 cm^3 (Fig. 4d).

The petrographic features of the examined rocks initiated the differences of their technical properties. The highest compressive strength values of Klisura nodular limestones are the result of the dominant presence of micrite microfacies. The rocks of the other three quarries are characterized by lower compressive strength values and slightly higher water absorption values due to the presence of microfacies with sparitic cement as well as stylolites.

Discussion

The petrographic, physical, and mechanical properties of Serbian Mesozoic carbonate rocks were examined within the rock mass of four active quarries: Klisura, Skrzut, Struganik, and Tisnica. These limestones are of different ages, from the Traissic and Cretaceous, and belong to the carbonate platforms of eastern (Tisnica limestone) and western Serbia (all others).

In terms of the petrological properties, the basic textural form of examined rocks is bedding. Thin layers and banks,

Table 2 The scope of application of Klisura, Tisnica, Skrzut, and Struganik limestones

Limestone type	Interior surfaces				Exterior surfaces					
	Horizontal surfaces			Vertical surfaces	Horizontal surfaces			Vertical surfaces		
	IH-1	IH-2	IH-3	IV-1	EH-1	EH-2	EH-3	EV-1	EV-2	EV-3
Klisura		+	+	+			+		+	+
Tisnica		+	+	+			+		+	+
Skrzut		+	+	+			+			+
Struganik		+	+	+			+			+

+ Recommended application

IH-1 Paving of interior horizontal surfaces of very intensive pedestrian traffic areas (shopping malls, hotels, hospitals, public buildings, industrial buildings, cinemas, etc.)

IH-2 Paving of interior horizontal surfaces of intensive pedestrian traffic areas (shops, museums, residential buildings, restaurants, schools, etc.)

IH-3 Paving of interior horizontal surfaces of moderate pedestrian traffic areas (libraries, archives, book stores, waiting rooms, etc.)

IV-1 Cladding of interior vertical surfaces

EH-1 Paving of exterior horizontal surfaces of very intensive pedestrian and occasional vehicular traffic areas (squares, pedestrian areas, streets, etc.)

EH-2 Paving of exterior horizontal surfaces of intensive pedestrian traffic areas (parks, promenades, pedestrian areas around monuments, etc.)

EH-3 Paving of exterior horizontal surfaces of moderate pedestrian traffic areas

EV-1 Cladding of exterior vertical surfaces of architectural objects higher than 30 m

EV-2 Cladding of exterior vertical surfaces of architectural objects from 10 to 30 m high

EV-3 Cladding of exterior vertical surfaces of architectural objects up to 10 m high

along with fractured rock mass, limit the size of commercial blocks and reduce the usable percentage of the rock mass. Nodular texture, lamination, stromatolites, fenestrations, and stylolites appear as internal textural forms. A diversity of colour (grey, pink, orange, red, and brown) and shade, along with the frequent appearance of macrofossil fragments, contribute to the decorative properties of these rocks. According to the lithological characteristics for allochem and orthochem types, different carbonate microfacies are observable: biolithites, pure orthochemical micrites, allochemmicrites, and allochemsparites. According to the content of the carbonate ($CaCO_3$) component, which is generally high, the examined rocks are predominantly pure limestones (dolomitization is not observed). These limestones consist small amounts of isoluble residue (clay minerals and Fe-oxide/hydroxide). In general, the local appearance of clayey limestone, marly limestone, and marlstone in the form of very thin interlayers (observed in Struganik and rarely Tisnica quarry) does not affect the durability of these rocks.

Previously presented technical properties of the examined carbonate rocks further served as indicators of their usability. For the appropriate use of natural stone products, it is advisable to consult suitable technical requirements. The alignment of Serbian national standards with the standards of the European Union is in progress. The requirements concerning natural stone slabs for cladding and paving are already aligned in terms of their acceptance without alteration (SRPS EN 1469 2009; SRPS EN 12058 2009). These current standards are not obligatory and do not include limitations or guidelines for the proper application of natural stone products. Therefore, for the substantiated evaluation of usability we consulted the withdrawn national standard SRPS B.B3.200 (1994), which was also not obligatory, but had useful recommendations concerning the application of dimensional stone based on its technical properties. It is useful to say that the test methods involved in both the current and withdrawn standard are correlative. The scope of application was evaluated by comparing the representative (mean) parameters of the physico-mechanical properties to the prescribed technical requirements of the SRPS B.B3.200 (1994) standard, and the usability of the ore mass from the four selected quarries was determined.

It is shown (Table 2) that due to the abrasion wear values (>25 $cm^3/50\ cm^2$) the application of all observed limestones as horizontal interior surfaces is limited to intensive and moderate pedestrian traffic areas (SRPS B.B3.200 1994). The national standard proposes no constraints regarding interior vertical cladding; therefore, all of the mentioned limestones are applicable. According to the compressive strength values (<120 N/mm^2) of Skrzut limestone and the abrasion wear values (>18 $cm^3/50\ cm^2$) of Klisura and Struganik limestones, these rocks are applicable for paving exterior horizontal surfaces of moderate pedestrian traffic areas. Owing to both the strength and abrasion values, Tisnica limestone is restricted to the same application. According to the compressive strength values (<160 MPa) of Klisura and Tisnica limestones, these rocks are recommended for cladding exterior vertical surfaces of architectural objects up to 30 m high. Owing to the compressive strength values (<140 N/mm^2) of Skrzut and Struganik limestones, their use is restricted to the cladding of exterior vertical surfaces up to 10 m high.

Conclusion

According to the obtained results of the physico-mechanical properties, it can be concluded that the investigated carbonate rocks are of high bulk density, compact or of low porosity, of very low water absorption, hard, and of high to moderately high values of compressive strength. The statistically analysed data confirmed that the representative values of the technical properties satisfy the requirements of the withdrawn SRPS B.B3.200 (1994) used for reference in this research. Therefore, the examined rocks are suitable for use as dimensional stone, as natural stone slabs for architectural cladding and paving for exterior and interior use. With the actual national standards for natural stone products, designers and investors have lost the usability reference in evaluating stone quality.

The theoretical contribution of previous studies delivers a wider understanding of the petrological and physico-mechanical properties of Serbia's Mesozoic carbonate rocks, among those of which are rocks applicable as dimension stone. Essentially, this paper offers a substantiated overview of this material's recommended scope of use, proposing proper applications of natural stone products that can meet durability requirements. Research results could have further impacts on Serbia's building and stone industry, as well as the export market.

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