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Analysis and evaluation of dimension stone and crushed stone aggregate of Herzegovina (and beyond)

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Abstract: This paper is a continuation of papers published 10 years ago, which covered the tests results obtained during the period from 1997 to 2013. The paper presents the test results obtained during the period from 2013 to 2023. Based on scientific methodology, the use of relevant literature as well as laboratory test methods, the authors analyze and evaluate the obtained results of testing natural stone as a basic raw material for the production of dimension stone (DS) and crushed stone aggregate (CSA). Test results are based on applicable test methods. The paper presents natural stone deposits for the production of DS and CSA, as well as the results of testing their physical and mechanical properties as the basic evaluation criteria.

Keywords: dimension stone, DS, crushed stone aggregate, CSA, testing, Bosnia and Herzegovina, quarries

Analiza i vrjednovanje arhitektonsko-građevnog (AGK) i tehničko-građevnog kamena (TGK) Hercegovine (i šire)

Sažetak: Ovaj rad je nastavak radova objavljenih prije 10 godina koji su obuhvatili rezultate ispitivanja dobivene kroz razdoblje od 1997. do 2013. godine. Rad prikazuje rezultate ispitivanja dobivene kroz razdoblje od 2013. do 2023. godine. Autori temeljem znanstvene metodologije, korištenja relevantne literature kao i ispitnih laboratorijskih metoda analiziraju i vrjednuju dobivene rezultate ispitivanja prirodnog kamena kao elementarne sirovine za proizvodnju arhitektonsko-građevnog kamena (AGK) i tehničko-građevnog kamena (TGK). Rezultati ispitivanja temelje se na važećim ispitnim metodama. U radu su prikazana nalazišta prirodnog kamena za proizvodnju AGK i TGK, te rezultati ispitivanja njihovih fizikalno-mehaničkih svojstava kao osnovni kriterij za vrjednovanje.

Ključne riječi: arhitektonsko-građevni kamen, AG kamen, AGK, tehničko-građevni kamen, TG kamen, TGK, ispitivanje, Bosna i Hercegovina, kamenolomi

1. INTRODUCTION

Results of tests of dimension stone (DS) and crushed stone aggregate (CSA) from deposits in the areas of Herzegovina, central and southwestern Bosnia, which were conducted in the laboratory "IGH-Mostar" d.o.o. Mostar in the period from 1997 to 2013 were presented in the paper at the 1st Symposium "Herzegovina - Country of Stone" (2013).

This paper presents the results of physical and mechanical tests of the properties of DS and CSA conducted over the last 10 years (2013-2023) in the Central Laboratory of "IGH" d.o.o. Mostar, which is the successor of the company "IGH-MOSTAR", and continuously works to improve and increase the scope of laboratory services. The company has the status of being accredited according to *BAS EN ISO/IEC 17025:2018 - General requirements for the competence of testing and calibration laboratories*, with 22 accredited test methods out of a total of more than 80 of them. In the central laboratory, samples are tested of natural stone mainly from Herzegovina (from Grude in the west to Foča in the east), southwestern and central Bosnia, and quarries in the vicinity of Sarajevo. Samples of imported stone are also tested.

2. ABOUT DIMENSION STONE AND CRUSHED STONE AGGREGATE

According to the basic definition, dimension stone is a solid non-metallic mineral raw material used in construction for decorating internal and external, horizontal or vertical surfaces, depending on the properties and requirements. Throughout history, natural stone has long been used as the main load-bearing element in the construction of numerous structures (religious buildings, residential buildings, infrastructure facilities - bridges, amphitheaters, retaining walls, etc.). In recent times, the main role of stone, or dimension stone, is to cover horizontal and vertical surfaces, or to be used for protection and decoration of load-bearing structures built from other structural materials.

In terms of the petrographic structure, properties and durability, it is distinguished:
- carbonate stone (limestone, dolomite, marble) which is unstable in acidic media, corrodes quickly in an industrial atmosphere containing SO_2, slowly dissolves in natural water containing free CO_2, and decomposes at high temperatures releasing CO_2;
- silicate stone (granite, gneiss, gabbro), which has high corrosion resistance in the atmosphere and in water, and with the content of free and bound SiO_2, its resistance to acidic environments also increases (the exception is HF solutions that dissolve SiO_2).

Commercially, on the local and foreign markets, the general division is:
- granites include all silicate rocks regardless of their genesis, primarily igneous and metamorphic rocks. Apart from rare exceptions, they can meet the strictest technical criteria for interiors and exteriors, regardless of the size of the load. This group integrates all markedly hard silicate rocks, which are processed using granite processing technology. Their common property is durability, unchanging appearance, even of colored varieties that contain stable natural pigments. For the most part, they are smoothed and polished to a high shine, but their face surfaces can also be processed in other ways, for example thermally. Due to their physical and mechanical properties, they are widely used for covering horizontal and vertical exterior and interior surfaces, for memorials and cemetery architecture;
- marbles include all carbonate rocks regardless of genesis, both sedimentary (limestones and dolomites) and marbles in the petrological sense, meaning metamorphic rocks. Due to markedly different physical and mechanical properties compared to silicate stone, carbonate stone requires a good knowledge of the differences between individual varieties, which causes different behavior in buildings. Thus, for example, the same variety of stone (commercially "marble") is worn and damaged differently in different installation positions. Therefore,

carbonate stone is characterized by high anisotropy, which is reflected in (micro) layering, stylolitization and schistosity, and the content of ingredients of different sizes and shapes. The biggest differences are in water absorption and wear resistance, which, in addition to the mineral composition, has a decisive effect on its application. This group combines the categories of hard and medium hard carbonate, calcite and dolomite rocks of sedimentary and metamorphic origin. These are rocks that are very well and relatively easily processed by marble processing technology. Depending on their physical and mechanical properties, they have a more specific or wider application. They are unstable to the effects of atmospheric agents, especially in the urban environment, when polished surfaces lose their shine, and the stability of color depends on the stability of the natural pigment. The stone of this group is primarily an interior stone, regardless of the fact that many types are also abundantly used for exterior cladding.

According to another classification, which is considerably expanded and more practical for application (by N. Bilbija), we distinguish seven groups of rocks: granites, marbles, soft rocks, travertines, onyxes, schists and sandstones.

The purpose of these and other divisions is to get to know and properly select the type of stone in order to better preserve its load-bearing capacity, durability and decorativeness, and to avoid mistakes in the choice and method of use.

Crushed stone aggregate (CSA) is a stone that is blasted, mechanically crushed and pulverized, and is used as: crushed stone for road maintenance, crushed stone for construction of road bed (base courses), stone chips for making bituminous material on roads, stone aggregate for the production of concrete, crushed stone for the production of railway ballast, crushed stone for masonry, for making training works and culverts, and as a raw material for the production of other various materials, such as binders and thermal insulation materials. In addition to construction, it is used in metallurgy, production of abrasives, such as fillers in the production of paints, varnishes, polymers and paper, for mineral fertilizers, ceramics, medicines, etc. For each case of use, this stone is crushed, ground, pulverized or broken into irregular pieces of larger dimensions. It must have certain physical and mechanical properties, grain size distribution and purity.

3. THE MAIN HOLDERS OF DS AND CSA EXPLOITATION IN THE HERZEGOVINA REGION

In territorial terms, the most widely distributed stone in the territory of Herzegovina (almost 80%) and beyond, that is also most used in construction, is limestone. Several companies engaged in the extraction and processing of DS operate in the territory of Herzegovina.

Municipality / City	**Quarries**
The Municipality of Posušje	Paljevine Vlake, Vinjani, Dočić-Ričina, Bukovac B, Bosiljna, Radovanj, Rakitno
The City of Ljubuški	Crveni Grm, Bokoćuša - Crveni Grm, Cerno
The City of Široki Brijeg	San - the locality of Muša, Ivankovića Dolac, Kusačko Brdo, Vidikovac -Polugrno
The Municipality of Jablanica	Ploče, Car, Suljo Čilić
The City of Mostar	Ortiješ
The Municipality of Ravno	Ivanica - Štitar
The Municipality of Berkovići	The locality of Rudine (Kremnice)

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The most important dimension stone locations and quarrying facilities in Herzegovina and beyond, presented by companies holding concessions, are:

Company	Quarry and geodetic position X; Y
Ukraskamen d.d. Posušje	Ćesića Draga (old exploitation fields without current exploitation, X=4 809 420; Y=6 449 950)
Ukraskamen d.d. Posušje	Gradac (old exploitation fields without current exploitation, X=4 809 420; Y=6 449 950)
Sediment d.o.o. Posušje	Strana-Ćesića Draga (investigated area in the phase of obtaining permits, area 0.7 ha, X=4 809 755; Y=6 448 650)
Plava vječnost d.o.o.	Vignjiština (investigated area in the phase of obtaining permits, area 2.4 ha, X=4 808 848; Y=6 449 974)
Lager d.o.o.	Osoje (investigated area in the phase of obtaining permits, area 3.9 ha, X=4 812 28; Y=6 443 461)
INKA d.o.o. Ljubuški	Crveni Grm P (exploitation field area 1.0 ha, X=4 718 000; Y=6 459 950)
DINARAKAMEN d.o.o. Široki Brijeg	Tvrda Ljut-Kusačko Brdo (exploitation field area 7.2 ha, X=4 807 945; Y=6 461 335)
DINARAKAMEN d.o.o. Široki Brijeg	San (exploitation field area 4.3 ha, X=4 811 945; Y=6 455 956)
T.A.J.M. d.o.o. Široki Brijeg	Osoje (exploitation field area 2.1 ha, X=4 807 500; Y=6 453 100)
Kamenica d.o.o. Široki Brijeg	Kamenice (investigated area in the phase of obtaining permits, area 2.4 ha, X=4 807 890; Y=6 462 299)
Granit d.d. in bankruptcy Jablanica	Majdan, Ploča, Bukov Pod
Granit Industry d.o.o. Jablanica	Ploča, Staro Haldovište
Štitar d.o.o. Ravno	Začula - Ivanica
Kremnice d.o.o.	Rudine

CSA is investigated and exploited in a large number of deposits throughout Herzegovina. There are practically unlimited reserves of limestone, although there are detailed requirements that must be met before systematic exploitation. However, the value of the aggregate, as a final product, cannot withstand long transport distances, and its consumption is of a regional character. Approved exploitation deposits of crushed stone aggregate by municipalities are:

Municipality / City	Quarries
The Municipality of Posušje	Paljevine Vlake, Vinjani, Dočić-Ričina, Bukovac B, Bosiljna, Radovanj, Rakitno
The Municipality of Grude	Platica Otok, Cerov Dolac
The City of Ljubuški	Crveni Grm, Bokoćuša - Crveni Grm, Cerno
The City of Široki Brijeg	San - the locality of Muša, Ivankovića Dolac, Kusačko Brdo, Vidikovac - Polugrno
The Municipality of Čitluk	Dubrave - the locality of Blizanci, Vlake - the locality of Cerno
The Municipality of Tomislavgrad	Cebara
The Municipality of Livno	Lazine, Podgradina

The Municipality of Kupres	Grguljača, Lisičić
The Municipality of Prozor-Rama	Podbor
The City of Mostar	Mokri Do - Miljkovići, Krivodol, Bijela, Grabovica, Sirge - Raška Gora, Zukulja (Kuti Livač)
The Municipality of Ravno	Orahov Do, Začula
The Municipality of Ljubinje	Vođeni and Strujići
The Municipality of Bileća	Drakuljica
The City of Trebinje	Lučin Do
The Municipality of Nevesinje	Majdan Bojište
The Municipality of Berkovići	The locality of Rudine (Kremnice)

The most important CSA locations and quarrying facilities in Herzegovina and beyond, presented by companies holding concessions, are:

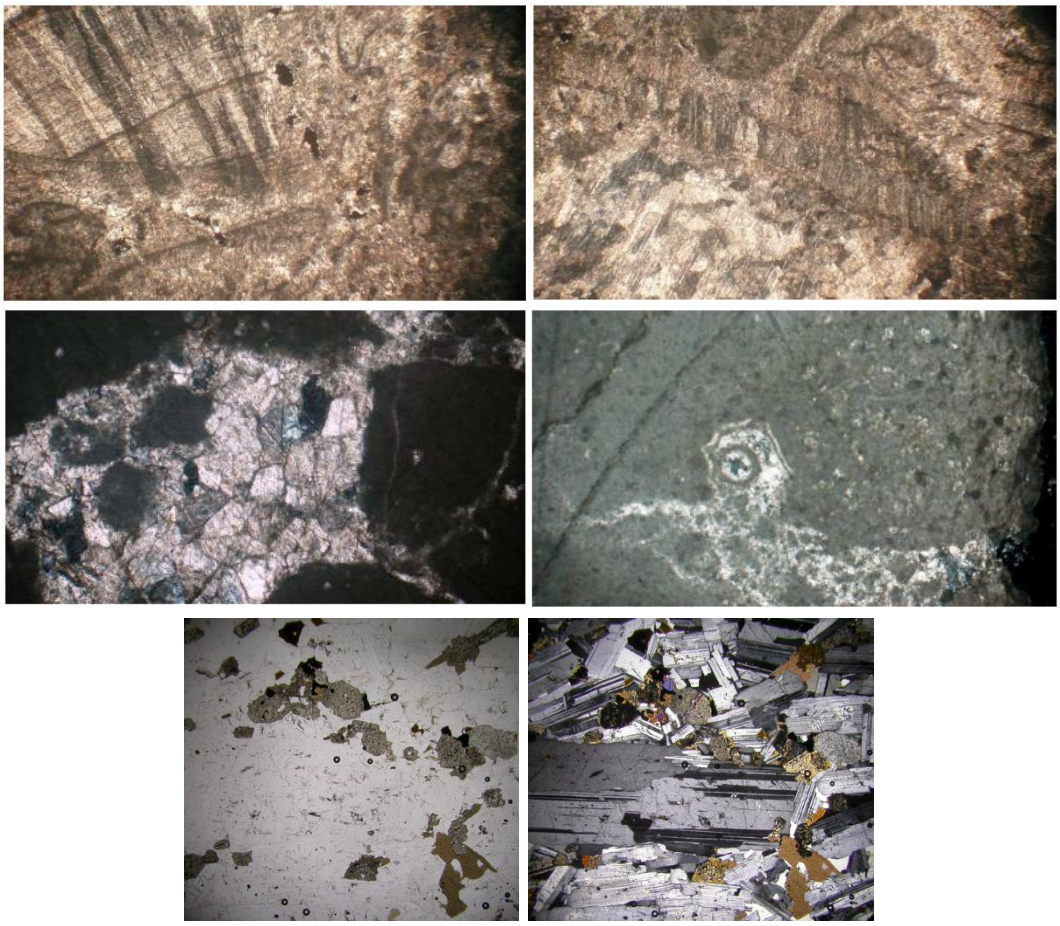
Company	**Quarry and geodetic position X; Y**
Mrvelji d.o.o. Posušje	Paljevine–Vlake 7-14 (exploitation field area 8.9 ha, X=4 817 725; Y=6 441 800)
Point d.o.o. Posušje	Paljevine–Vlake 1-7 (exploitation field area 5.6 ha, X=4 818 027; Y=6 441 800)
KTM-Brina d.o.o.	Vinjani (exploitation field area 2.4 ha, X=4 818 380; Y=6 441 210)
Lager d.o.o. Posušje	Bosiljna (exploitation field area 4.9 ha, X=4 822 565; Y=6 458 884)
Putovi d.o.o. Grude	Cerov Dolac (exploitation field area 5.4 ha, X=4 797 857; Y=6 454 765)
Platica Žurkovača d.o.o. Grude	Platica-Otok (exploitation field area 6.8 ha, X=4 801 752; Y=6 442 988)
INKA d.o.o. Ljubuški	Crveni Grm (exploitation field area 7.5 ha, X=4 780 300; Y=6 460 000)
Graming d.o.o. Široki Brijeg	Polugrno (investigated area in the phase of obtaining permits, X=4 797 857; Y=6 454 765)
HP Investing d.o.o. Mostar	Bijela
Vran Dukić d.o.o. Tomislavgrad	Cebara
Livnoputovi d.o.o. Livno	Lazine
Promark d.o.o. Mostar	Mokri Do - Miljkovići (exploitation field area 8.16 ha, X=4 818 380; Y=6 481 201)
Beton Kop d.o.o. Mostar	Krivodol
GS Građenje d.o.o. Prozor - Rama	Podbor
Granit d.d. in bankruptcy Jablanica	Field 1: Suljo Čilić, Car, Ploče (exploitation field area 65.24 ha, X=4 837 194; Y=6 478 450) Field 2: Padešnica, Velja Stijena (exploitation field area 69.8 ha, X=4 837 356; Y=6 479 000)
Granit Industry d.o.o. Jablanica	Ploča, Staro Haldovište (exploitation field area 4.96 ha, X=4 836 963; Y=6 478 798)
Herc gradnja d.o.o. Bileća	Drakuljica

Dolomit d.o.o. Kupres	Grguljača
Građevinar d.o.o. Ljubinje	Vođeni and Strujići
Štitar d.o.o. Ravno	Začula

4. MINERALOGICAL AND PETROGRAPHIC ANALYSIS

The test is carried out according to the standard *BAS EN 12407:2020 Natural stone test methods - Petrographic examination*. The petrographic description was made using the classifications of samples according to tables or classifications according to Folk (1962), Flugel (1982), Dunham (1962), that is, Embry and Klovan classification (1972) and their modification Wright (1981).

The mineralogical and petrographic composition was not examined for each sample. From the analyses we received, it can be concluded that most often these are various types of limestone, organogenic limestone or biomicrite, biopelmicritic limestone, then laminated to massive limestone, fine-grained limestone and oolitic limestone. The next type is dolomites of dolosparitic structure ("rujan"), and gabbro as a representative of eruptive rocks.



Figures 1-6. Microphotographs of preparations

Table 1. Mineralogical and petrographic descriptions of the examined stone samples of dimension stone

Quarry	Mineralogical petrographic description
Ladina	Rock: Sedimentary, cohesive, carbonate: limestone, organogenic, cavernous. Structure: Crystalline; Texture: Homogeneous, to a lesser extent cavernous (Figures 1 and 2)
Crveni Grm	Rock: Sedimentary, carbonate: limestone - biomicrite; Structure: Micritic to microcrystalline. Texture: Massive (Figures 3 and 4)
Gabro	Macroscopically, the stone is dark gray in color and has a homogeneous texture. The sawn surface shows a granular structure made of dark black gray-green irregular crystals with a section up to 1 x 2 mm in size and light gray platy to irregular crystals with a section up to 3 x 5 mm in size. The stone has an irregular fracture, its fracture surface is coarsely rough, and it does not react with cold, diluted HCl (5%). It has a relative hardness of about 6 on the Mohs scale, and has no taste or smell. In the microscopic preparation, there is a granular crystalline structure made of plagioclase and clinopyroxene crystals. Sections of plagioclase are platy and prismatic, hypidiomorphic to idiomorphic, and between 0.5x1.0 mm and 2.5x4.5 mm in size. The sections of clinopyroxene are irregular, allotriomorphic, and their sizes range from 0.25x0.35 mm to 1.0x1.5 mm. The clinopyroxene crystals are mainly unaltered, only chloritized grains are visible in some places. Plagioclase crystals are completely fresh, unaltered. Biotite and opaque minerals appear as accessory minerals in the preparation. The stone was determined as gabbro (Figures 5 and 6).

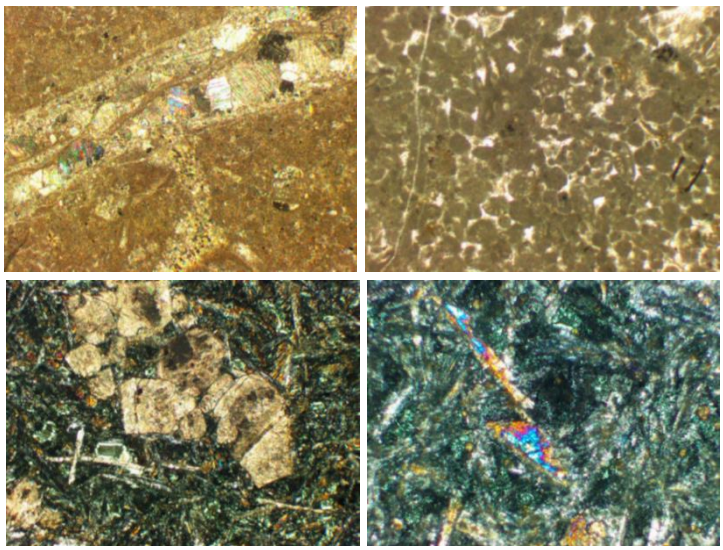


Figure 7-10. Microphotographs of preparations

Table 2. Mineralogical and petrographic descriptions of the examined stone samples of CSA

Quarry	Mineralogical petrographic description
Miljkovići	Rock: Sedimentary, cohesive, carbonate: limestone, microcrystalline to micritic
Crveni Grm	Rock: Sedimentary, carbonate: limestone - biomicrite; Structure: Micritic to microcrystalline; Texture: Massive.
Kota - Spilite	Rock: Igneous, mafic, extrusive: spilite; Structure: Hypocrystalline porphyritic; Texture: Amygdaloidal (Fig. 7 and 8)
Kota - Limestone	Rock Sedimentary, micritic limestone with signs of recrystallization; Structure: Crystalline; Texture; Massive
Lazine	Rock: Sedimentary, carbonate rock: limestone, micritic, fossiliferous - Biomicrite; Structure: Microcrystalline to crystalline; Texture: Massive (Fig. 9 and 10)

5. CHEMICAL ANALYSIS

The chemical analysis determines the content of the main oxides like SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, K_2O, MnO, TiO_2, P_2O_5, Cr_2O_3, ... using various chemical methods, such as powder X-ray diffraction and emission and mass spectrometry methods, as well as chemical techniques such as potentiometry, volumetry, gravimetry. As the most common sample is limestone, so the most prevalent oxide according to test results is calcium oxide (CaO). In addition to the main oxides, this analysis examines the loss on ignition (LOI) at 1000 °C. Also, chemical analysis can determine the content of sulfates, sulfides, and chlorides.

Table 3. Chemical composition of the sample from the locality of Miljkovići near Mostar

Main oxides	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	Sulfates	Sulfides	Chlorides	LOI
Result (%)	0.24	0.00	0.04	55.33	0.18	0.19	0.001	0.0005	0.0001	43.92

Furthermore, by stoichiometry, the content of $CaCO_3$ (%) is obtained by multiplying the amount of CaO by the coefficient 1.78462 and the content of $MgCO_3$ (%) by multiplying the content of MgO by the coefficient 2.01968.
For the sample shown in the table above, the content of $CaCO_3$ is 98.74% and the content of $MgCO_3$ is 0.36%.

Figure 11-12. Equipment for chemical analysis (left); Calcimeter (right)

6. COMPRESSIVE STRENGTH

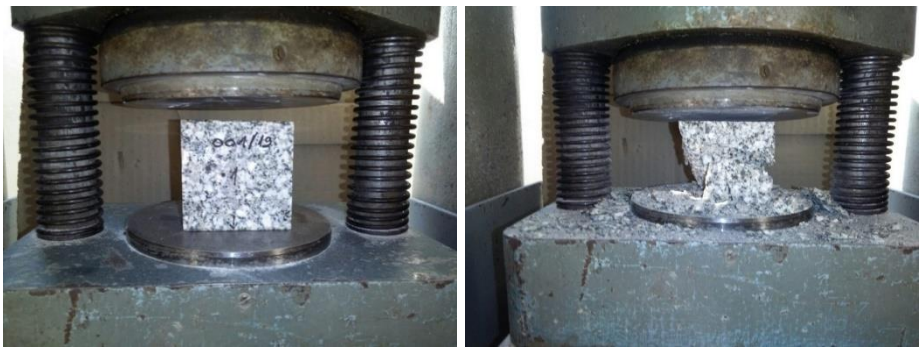
The test is carried out according to *BAS EN 1926:2009 Natural stone test methods - Determination of uniaxial compressive strength*. Samples in the form of a cube or a regular cylinder are tested. According to the literature, the compressive strength of limestone ranges from 30 to 250 MPa, of dolomite between 80 and 250 MPa, and of gabbro between 180 and 300 MPa. The test is carried out in dry (D) and water-saturated (WS) state, and in a state after a certain number of freeze/thaw cycles (F). This method describes the dry and water-saturated state, and the compressive strength tests after freezing / thawing are carried out after the

procedure according to the method *BAS EN 12371:2011 Natural stone test methods - Determination of frost resistance*.

When testing natural stone in different states, the selection and preparation of test samples has the most important role.

Due to its heterogeneity, method of exploitation, adaptation to dimensions, etc., stone does not always behave in a predictable way.

The best results should be obtained for samples in a dry state, followed by samples in a water-saturated state (decrease in compressive strength of up to 20% compared to the dry state), and the lowest values of compressive strength in samples after exposure to a certain number of freezing cycles (decrease in compressive strength of up to 20% compared to the water-saturated state).



Figures 13-14. The sample before the test (left) and after the test (right) of the DS sample

Table 4. Some values of compressive strength of DS

Quarry	Type of DS	Compressive strength (MPa)			Coefficient of softening	
		D	WS	F	Soaking (4/3)	Freezing (5/3)
1	2	3	4	5	6	7
Crveni Grm	Limestone	216.0	211.0	203.0	0.98	0.94
Bokoćuša - Crveni Grm	Limestone	172.0	170.0	169.0	0.99	0.98
Ćesića Draga	Limestone	161.0	154.0	147.0	0.96	0.91
Ladina	Limestone	186.0	173.0	-	0.93	-
Štitar, Ivanica	Limestone	199.0	178.0	162.0	0.89	0.81
Osoje	Limestone	170.0	160.0	140.0	0.94	0.82
Staro Haldovište	Gabbro	243.0	197.0	184.0	0.81	0.76
Ploče, Jablanica	Gabbro	241.0	202.0	192.0	0.84	0.80
Car, Jablanica	Gabbro	242.0	231.0	217.0	0.95	0.90
Suljo Čilić, Jablanica	Gabbro	267.0	251.0	221.0	0.94	0.82

Figures 15-16. The sample before the test (left) and after the test (right) of the CSA sample

Table 5. Some compressive strength values of CSA

Quarry	Type of CSA	Compressive strength (MPa)			Coefficient of softening	
		D	WS	F	Soaking (4/3)	Freezing (5/3)
1	2	3	4	5	6	7
Crveni Grm	Limestone	216.0	211.0	203.0	0.98	0.94
Kota	Spilite	210.0	185.0	164.0	0.88	0.78
Kota	Limestone	138.0 - 170.0	113.0 - 155.0	-	0.82 - 0.91	-
Ulog	Limestone	155.0	134.0	119.0	0.86	0.77
Lapišnica	Limestone	148.0	145.0	130.0	0.98	0.88
Lazine	Limestone	192.0	173.0	167.0	0.90	0.87
Lisičić, Kupres	Dolomite	218.0	191.0	179.0	0.88	0.82
Štitar, Ivanica	Limestone	199.0	178.0	162.0	0.89	0.81
Vlake, Cerno	Limestone	185.0 - 195.0	155.0 - 185.0	-	0.84 - 0.95	-
Zukulja, Mostar	Dolomite	186.0	146.0	-	0.78	-
Zukulja, Mostar	Limestone	175.0	156.0	-	0.89	-
Ploče, Jablanica	Gabbro	241.0	202.0	192.0	0.84	0.80

Based on the obtained compressive strength test results, it can be concluded that it is dimension stone and crushed stone aggregate of medium and high compressive strength. The obtained coefficients of softening are within the expected limits.

7. DETERMINATION OF WATER ABSORPTION

Water absorption at atmospheric pressure is determined according to the method *BAS EN 13755:2009 Natural stone test methods - Determination of water absorption at atmospheric pressure*. The method determines how to measure masses in dry and water-saturated state, and to calculate the percentage of mass increase, or water absorption.

Water absorption is classified into descriptive groups such as: very low (below 0.5%), low, moderate, noticeably high, very high, exceptionally high (above 30.0%). A large number of samples belong to the group with very low and low absorption (Ab < 0.5 %). Some of the water absorption test results of natural stone (DS and CSA) are shown in the tables below.

Table 6. Results of the water absorption tests of DS

Quarry	Type of DS	Water absorption (%)
Crveni Grm	Limestone	0.10
Bokoćuša - Crveni Grm	Limestone	0.10
Ćesića Draga	Limestone	0.14
Ladina	Limestone	0.13
Štitar, Ivanica	Limestone	0.10
Osoje	Limestone	0.10
Ploče, Jablanica	Gabbro	0.10
Car, Jablanica	Gabbro	0.10
Suljo Čilić, Jablanica	Gabbro	0.15
Staro Haldovište	Gabbro	0.20

Table 7. Results of the water absorption tests of CSA

Quarry	Type of CSA	Water absorption (%)
Crveni Grm	Limestone	0.10
Kota	Spilite	0.34
Kota	Limestone	0.10 - 0.50
Ulog	Limestone	0.10
Lapišnica	Limestone	0.10
Ladina	Limestone	0.13
Lazine	Limestone	0.30
Lisičić, Kupres	Dolomite	0.20
Štitar, Ivanica	Limestone	0.10
Vlake, Cerno	Limestone	0.20 - 0.40
Zukulja, Mostar	Dolomite	1.0
Zukulja, Mostar	Limestone	0.20
Osoje	Limestone	0.10
Ploče, Jablanica	Gabbro	0.05

Based on the obtained results of water absorption at atmospheric pressure, we conclude that it is a natural stone with low and very low water absorption.

8. DETERMINATION OF DENSITY AND BULK DENSITY, TOTAL AND OPEN POROSITY

The physical properties of stone such as density, bulk density, total and open porosity are determined according to the method *BAS EN 1936:2009 Natural stone test methods - Determination of real density and apparent density, and of total and open porosity*.

In terms of this property, natural stone belongs to one of the following categories: very heavy (above 3000 kg/m^3), heavy, medium heavy, light and very light (below 1000 kg/m^3).

Total porosity is the ratio (in percentage) of the volume of open and closed pores of the sample to the apparent volume of the sample. In terms of this property, natural stone is ranked according to the value of the porosity result, so the stone can be: compact (below 1.0%), slightly porous, moderately porous, quite porous, highly porous and extremely porous (above 20%). The results of the tested samples largely fall into the group of compact and slightly porous stone.

Open porosity is the ratio (in percentage) of the volume of open pores of the sample to the apparent volume of the sample.

Table 8. Test results of properties of dimension stone

Quarry	Type of DS	Density (kg/m^3)	Bulk density (kg/m^3)	Total porosity (%)	Open porosity (%)
Crveni Grm	Limestone	2704	2690	0.14	-
Bokoćuša - Crveni Grm	Limestone	2704	2703	0.00	-
Ćesića Draga	Limestone	2705	2700	0.40	-
Ladina	Limestone	2709	2695	0.22	-
Štitar, Ivanica	Limestone	2720	2690	0.90	0.40
Osoje	Limestone	3000	2998	0.03	-
Staro Haldovište	Gabbro	2930	2910	0.70	-
Ploče, Jablanica	Gabbro	3000	2999	0.00	-
Car, Jablanica	Gabbro	2922	2910	0,44	-
Suljo Čilić, Jablanica	Gabbro	2955	2941	0.43	-

Table 9. Test results of properties of crushed stone aggregate

Quarry	Type of CSA	Density (kg/m^3)	Bulk density (kg/m^3)	Total porosity (%)	Open porosity (%)
Crveni Grm	Limestone	2704	2690	0.14	-
Kota	Spilite	2810	2770	1.40	-
Kota	Limestone	2720	2700	1.48	-
Ulog	Limestone	2705	2698	0.26	-
Lapišnica	Limestone	2697	2694	0.11	-
Lazine	Limestone	2700	2670	1.10	0.8
Lisičić, Kupres	Dolomite	2870	2810	2.1	0.6
Štitar, Ivanica	Limestone	2720	2690	0.90	0.4
Vlake, Cerno	Limestone	2700	2680	0.5 - 1.5	0.5 - 1.0
Zukulja, Mostar	Dolomite	2760	2700	2.80	2.6
Zukulja, Mostar	Limestone	2700	2690	0.40	0.4
Osoje	Limestone	2708	2702	0.25	0.2
Ploče, Jablanica	Gabbro	3000	2998	0.03	-

Depending on the type of natural stone (limestone, dolomite, gabbro) and considering the obtained test results of bulk density, it can be concluded that it is a medium heavy to heavy stone. Also, it can be concluded that these are stone samples that are compact, except for samples of dolomite, limestone from the Kota quarry and spilite, which are slightly to moderately porous.

9. FROST RESISTANCE

The resistance of dimension stone to frost is determined according to the method *BAS EN 12371:2011 Natural stone test methods - Determination of frost resistance*. According to this method, the stone is exposed to freezing and thawing cycles.

The number of cycles is not strictly defined, and a minimum of 14 cycles (identification test) are conducted for frost resistance of DS. Samples in the shape of a cube (a = 50 mm) and/or a rectangular cuboid (50x50x300 mm) are tested, and the compressive strength and bending strength after the freeze/thaw cycles can be tested on them. A visual inspection is performed, changes and damage are registered, and the volume of the test sample is measured before and after the test (by measuring the mass in air and under water).

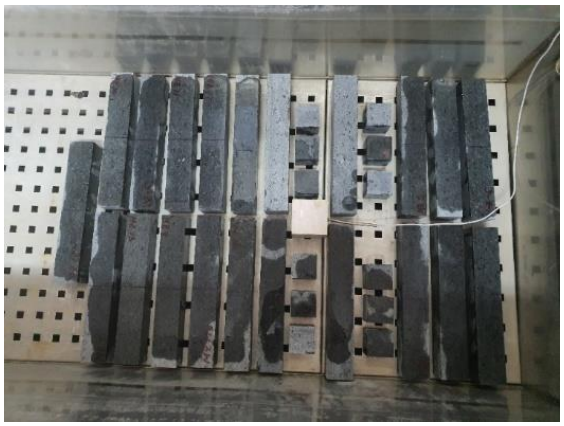


Figure 17. Frost resistance test samples

The test result is expressed descriptively and using volume loss ΔV (%). Most of the tested samples are resistant to frost (due to relatively low water absorption).

10. RESISTANCE TO SALT CRYSTALLIZATION

The test method used to test the resistance of natural stone to salt crystallization is *BAS EN 12370:2021 Natural stone test methods - Determination of resistance to salt crystallization*. This method is suitable for testing porous stone, especially for dimension stone with open porosity greater than 5%. During the test, occurrences of damage, breakage or disintegration of the samples are recorded, and the final test result is expressed as a loss of mass.

11. DETERMINATION OF RESISTANCE TO ABRASION (WEAR)

Determination of resistance to abrasion is carried out according to *BAS EN 14157:2009 Natural stone test methods - Determination of the abrasion resistance*. In recent literature, the term abrasion is used in our language instead of wear. Abrasion resistance was determined by method B, Böhme's method.

The mass is measured before and after the test and the loss of volume (mm^3) is calculated. The old measure for this test was the loss of volume in cm^3 per 50 cm^2 of test area.

According to this property, in terms of abrasion resistance natural stone is classified as: exceptionally hard (below 5.0 cm^3 / 50 cm^2), very hard, hard, moderately hard, soft, exceptionally soft (above 40.0 cm^3 / 50 cm^2). This property of dimension stone is very important when choosing the type of stone for paving walkways, squares, streets and other surfaces intended primarily for pedestrian traffic. The dimensioning measure is the daily number of passes. Some of the test results of the specified properties are shown in the tables below.


Figures 18-19. Böhme device (left); Test samples (right)

Table 10. Test results of resistance to abrasion (wear) of DS

Quarry	Type of DS	Loss of volume	
		mm^3	$cm^3/50\ cm^2$
Crveni Grm	Limestone	-	12.6
Bokoćuša - Crveni Grm	Limestone	-	12.5
Ćesića Draga	Limestone	-	13.2
Ladina	Limestone	-	15.1
Štitar, Ivanica	Limestone	13239	-
Osoje	Limestone	-	14.8
Ploče, Jablanica	Gabbro	-	8.8
Car, Jablanica	Gabbro	-	8.2
Suljo Čilić, Jablanica	Gabbro	-	7.9
Staro Haldovište	Gabbro	6792	-

Table 11. Test results of resistance to abrasion (wear) of CSA

Quarry	Type of CSA	Loss of volume	
		mm^3	$cm^3/50\ cm^2$
Crveni Grm	Limestone	-	12.6
Kota	Spilite	9910	-
Kota	Limestone	13250	-
Ulog	Limestone	-	15.8
Lapišnica	Limestone	-	16.5
Lazine	Limestone	11117	-
Lisičić, Kupres	Dolomite	16721	-
Štitar, Ivanica	Limestone	13239	-
Vlake, Cerno	Limestone	13660	-
Zukulja, Mostar	Dolomite	21378	-
Zukulja, Mostar	Limestone	11036	-
Osoje	Limestone	-	14.8
Ploče, Jablanica	Gabbro	-	8.8

Based on the obtained results of the wear resistance test, we conclude that it is a very hard stone (gabbro) and a moderately hard stone (limestone and dolomite).

12. FLEXURAL STRENGTH

Determination of flexural strength (strength to bending) is carried out according to *BAS EN 12372:2009 Natural stone test methods - Determination of flexural strength under concentrated load*.

Tests can be performed in three different states, dry (D), water-saturated (WS) and state after freeze/thaw treatment (F). The obtained results range from 7% to 20% in relation to the compressive strength. The most frequent values are in the range from 0.5 to 25 MPa.

This property is very important in the application of dimension stone when the stone element is subjected to bending loads (cantilever elements, staircase, various facade elements, channel covers, etc.).

Table 12. Test results of flexural strength of DS

Quarry	Type of DS	Compressive strength (MPa)			Coefficient of softening	
		D	WS	F	Soaking (4/3)	Freezing (5/3)
1	2	3	4	5	6	7
Crveni Grm	Limestone	12.6	-	-	-	-
Bokoćuša - Crveni Grm	Limestone	12.5	-	-	-	-
Ćesića Draga	Limestone	12.7	-	-	-	-
Štitar, Ivanica	Limestone	8.6	7.2	6.4	0.84	0.74
Osoje	Limestone	9,3	-	-	-	-
Ploče, Jablanica	Gabbro	20.2	18.7	-	0.93	-
Car, Jablanica	Gabbro	21.2	19.3	-	0.91	-
Suljo Čilić, Jablanica	Gabbro	19.0	15.0		0.80	-
Staro Haldovište	Gabbro	19.2	14.8	-	0.77	-

The test results of flexural strength are on average about 7% in relation to those of compressive strength. In limestones, flexural to compressive strength ratios range from 4.3% to 7.9%, while flexural to compressive strength ratios are more uniform in gabbro and range from 7.1% to 8.8%.

13. CONCLUSION

This paper presents the results of testing natural stone, mainly from the area of Herzegovina. Natural stone for architectural and construction purposes (DS) and stone for engineering purposes (CSA) were tested.

The evaluation of CSA, or the conditions for evaluating its suitability, are presented in the technical specifications for a particular type of natural stone product. Thus, for example, the technical specification BAS EN 13450 is used for the production of crushed stone for railway ballast, the technical specification BAS EN 1260 is used for the production of stone aggregate fractions for the production of concrete, etc. The conditions for evaluating DS are given by the design solution through the design documentation, depending on the type of load, exposure of the stone to various influences from the atmosphere and water, purpose, type of designed processing, etc.

During testing, it is very important to pay sufficient attention to the selection and production of test samples. It is necessary to provide a sufficient number of samples in order to meet the

minimum conditions from a particular method and in order to be able to carry out high-quality statistical processing of test results, which is very important for test samples with pronounced anisotropy, inhomogeneous structure, pronounced layering, etc.

Furthermore, the importance of conducting tests and monitoring test results at individual quarries should be emphasized. High-quality and timely monitoring with the commitment of all participants in exploitation work ensure high-quality raw materials, which eventually provides a high-quality and financially profitable final product.

In general, it can be concluded that natural stone that meets very high criteria in terms of physical and mechanical properties, both for civil engineering purposes and for architectural and construction purposes, is quarried in the territory of Herzegovina.

As the next goal, the authors plan to process the results of the DS and CSA tests from the period 1997-2013. and test results from the period 2013-2023, perform analysis and evaluation, and present conclusions.

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