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Experimental determination of mechanical characteristics of four types of stones and their influence on the construction machinery parts wear

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Abstract. In this paper were experimentally determined properties of four different types of stones and stone aggregates and they were compared to each other with respect to their influence on wear of working parts of machines for preparation and deposition of stones on roads. Rocks, the building stones are obtained from, consist of various types of minerals, namely of physically and chemically homogeneous rocks created within the Earths crust. Here are considered four, most important types of building stones: limestone, dolomite marble, calcite-dolomite marble and andesite. They are being exploited from four sites in Serbia, and they are convenient for deposition of certain layers of the carriageway on roads, streets, airports and foundations on railways, as well as for making different kinds of concrete and asphalt. In the paper are presented results of mineralogical-petrographic, physical-mechanical and special investigations. Wear resistance was also checked on certain samples.

Introduction

Construction machinery for manufacturing and building-in materials, during the construction of various civil engineering objects, are subjected to different types of high loads, especially their working elements that come into direct contact with stone materials [1-3]. In papers by some authors it was emphasized that the stone materials should possess the best possible shear strength [4, 5], as well as the tensile strength [6], in order to be exploited in the best possible way. That is the reason why knowing the physical-mechanical properties of stone is of a special importance, as emphasized by several authors [7-9], not only for their exploitation, but also for their processing and building-in. Since, during that, very complex tribo-mechanical processing are taking place, where participate working part of construction machinery, stones and third solids, it is especially important to properly select the material for manufacturing those working parts, as well as technology of reparation of the damaged or worn parts of the construction machinery [10, 11]. The objective of those investigations is to reveal the characteristics of the tested materials and their influence on the life span of machines that are used in their excavation and building-in, for the purpose of increasing the durability of the working parts.

Based on conducted investigations of the building stones from four sites, which were at authors' disposal, the useful data were obtained for both design and reparation of the working parts of machinery for minerals excavation and for their processing and building-in into the rods.

Experimental determination of mechanical properties of rocks

Rocks mainly consist of seven groups of minerals: silicates, carbonates, oxides, sulphates, sulphides, chlorides and hydro-oxides. To give the proper picture about the number of minerals that constitute rocks, it should be pointed out that only the silicates group includes about 800 kinds of minerals, which belong to different subgroups. Mineral masses in the Earth's crust could be found in bound-stone form or the unbound-dispersed form, thus the rocks are being categorized as weak, hard and exceptionally hard rocks, since minerals could be in crystalline, crystallite or amorphous form. Properties of rocks are significantly changed by action of water, frost and fire, thus it is very important to know all the laws of those changes [1-3, 8-9].

As it was already mentioned, in this paper are analyzed four types of materials from four sites: limestone – site "Vučjak", dolomite marble – site "Samar", calcite-dolomite marble – site "Gradac" and andesite – site "Šavnik".

Of all the mechanical properties of rocks, most frequently tested ones are the compressive strength, hardness, elasticity, toughness and wear resistance, while other properties are seldom tested. The way of investigation of mechanical properties of rocks is similar to the way of testing the metal materials, but there are also some specific features in rocks' testing. The rocks' mechanical properties are tested according to standards [12 - SRPS B.B8.012:1987 to SRPS B.B8.018].

Hardness measurements and microstructure. Rocks' hardness is an important property, since it affects other mechanical properties. It represents resistance to another solid penetrating into the rock's mass. For practical purposes, it suffices to determine the relative hardness of rocks, mainly by the Mohs scale. Hardness of a rock is actually average hardness of minerals that constitute that rock.

The basic Mohs scale is created in such a way that each mineral further up the scale cuts (scratches) all the previous ones; hardness is expressed by the hardness grade, which ranges from 1 to 10, where the smallest is hardness of talc, while the highest is that of diamond.

Considering that one rock consists of several minerals and bindings that connect the mineral grains, whose hardnesses are different, the determination of hardness by some other method would not be reliable (e.g. by the Shore method).

The crypto-crystallite fine-grained rocks possess the highest hardness. They are made of minerals of high hardness, whose grains are directly bound; those are the magmatic rocks, quartzite, quartz sandstone, etc. The low hardness characterizes rocks formed by the minerals of low hardness, whose grains are indirectly bound by natural bindings like cement. In Table 1 is presented hardness of different rock minerals contained in rocks.

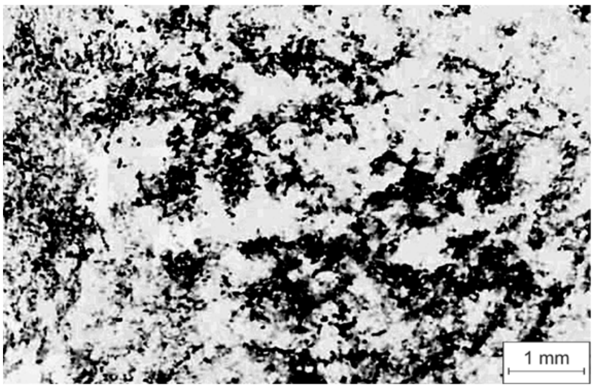
Table 1. Hardness of various rock minerals

Mineral type	Mohs hardness	Mineral type	Mohs hardness	Mineral type	Mohs hardness
Silicates		Oxide		Hydroxides	
Feldspar	6.0-6.5	Quartz	7.0	Limonite	5.0
Mica	2.0-3.0	Magnetite	5.5-6.5	Bauxite	2.5-6.5
Amphibole	5.0-6.0	Hematite	5.5-6.5	Opal	5.5-6.5
Pyroxen	3.1-6.0	Corundum	9.0	Sulphates	
China clay	2.0-2.5	Carbonates		Anmiorite	3.0-4.0
Garnet	7.0-7.5			Gypsum	2.0
Talc	1.0	Calcite	2.5-3.0	Sulphides	
Serpentine	2.5-4.0	Magnetite	2.5-3.5	Pyrite	6.0-6.5
Olivine	6.5-7.0	Dolomite	3.5-4.5	Chlorides	
Epidote	5.0-6.0	Aragonite	3.5-4.5	Halite	2.0

Based on percentage content of tested types of rocks, hardness of minerals that constitute them and the Mohs scale, it is possible to determine the relative hardness of the tested rocks. The main mineral that constitutes all types of limestones is calcite, so their hardness is usually about 650 HB. Hardness of the calcite-dolomite mineral depends on the percentage share of calcite and dolomite, so it usually ranges within 650-850 HB, while the dolomite marble usually has hardness within range 850-1150 HB. Besides calcite and dolomite, grains of quartz, mica, chlorite, graphite and others, mainly metamorphic silicates, could be found in the marble structure. The most frequently found are the calcite marbles, while the dolomite marbles are rare. Hardness of different types of andesite varies within wide limits, depending on their content. Thus, for instance, biotitic andesite has hardness approximately the same as limestone 500-700 HB, enstitic andesite has hardness of 750 HB, amphibolic andesite hardness ranges between 1000 and 1500 HB, while the quartz (SiO_2) content of 55-65% can increase andesite's hardness up to 1800 HB.

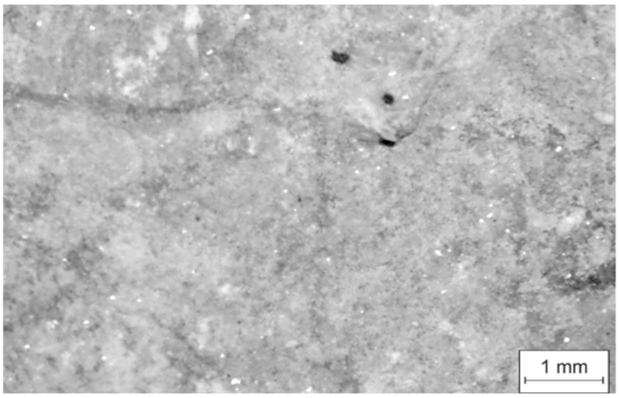
Rocks' hardness has strong influence on possibility of their machining and application, as well as on degree of wear of the construction machinery elements during the processing and building-in of the rock materials. This is why during the machining and building-in of the rock materials stones and stone aggregates) one must apply metals, which possess high hardness, with carbides in the metal matrix, or relatively mild steels in which, due to pressure or impact, a martensitic transformation of austenite may occur. This was first noticed by Robert Hadfield, who in 1882. Was the first to apply the manganese steel for casting the streetcars' wheels [11].

Besides the hardness measurements, the recording of microstructures was done, as well. The obtained recordings are presented in Fig. 1.

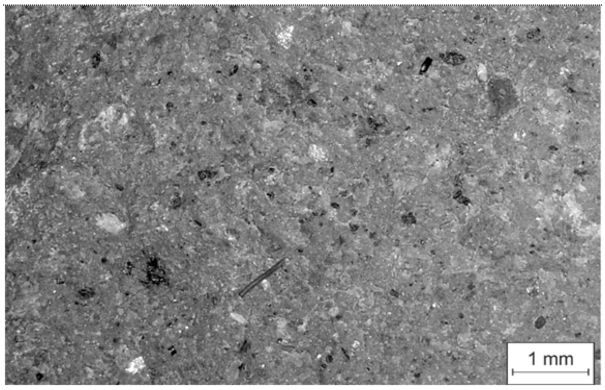


Limestone rock - crystallite to micro-crystallite

Dolomite marble - granoblastic structure



Calcite-dolomite marble rock - granoblastic structure



Andesite rock - porphyritic structure

Figure 1. Appearance of microstructure of four different rock structures; magnification 10×

Determination of the impact toughness of rocks. This property primarily depends on the content of the rock, namely the structure of the rock and only as the second on the type of minerals that constitute it. The aphitic rocks have the highest toughness, then crypto-crystallite (granular) and porphyritic structures. Rocks' resistance to impact is inversely proportional to compressive strength, since rocks that possess relatively high compressive strength can also possess low impact toughness. Impact toughness test is defined by the appropriate standards and it is done in the similar manner as for the metallic materials.

In Table 2 is given the impact toughness of the tested rock materials. Testing was done in three mutually perpendicular directions (direction I-I is parallel to the rocks stratification direction; direction II-II is perpendicular to the previous one and it lies in the stratification plane; direction III-III is perpendicular to direction of stratification propagation). Thus defined directions are related to all the testing of rocks' mechanical properties. This is important to emphasize, since some of the rocks are markedly anisotropic due to stratification and schistosity-inhomogeneity.

Table 2. Impact toughness of rocks

Impact toughness [J/cm^2]	Limestone "Vučjak"	Dolomite-marble "Samar"	Calcite-dolomite marble "Gradac"	Andesite "Šavnik"
Direction I-I	22.40	17.00	27.20	13.40
Direction II-II	24.20	20.60	26.10	17.20
Direction III-III	28.80	24.60	28.30	22.40
Average value	25.13	20.73	27.20	17.67

Based on those results, one can conclude that all the tested rocks have very low impact toughness, what could also have been concluded based on the fracture surface appearance, since the fractured surfaces have coarse roughness and sharp edges.

Determination of elasticity of rocks. Elasticity of rocks is a property, which characterizes rocks that can sustain some elastic deformation due to action of external forces. This property is related to strongly bounded rocks (stony) and it depends on type and hardness of the rock minerals, structure and texture, roundness of grains and freshness of minerals, humidity, intensity and direction of applied load, etc. Fine-grained rocks, with well-rounded grains, have higher values of the elasticity modulus than the coarse-grained rocks of the same composition. In stratified and inhomogeneous rocks, elasticity modulus is higher in the direction, which is perpendicular to stratification and schistosity, than in the direction, which is parallel to it.

By testing the samples of the limestone rock material, the following average values of the rock's properties were obtained: the Poisson's ratio $\upsilon = 0.36$, the elasticity modulus $E = 50247$ MPa, the shear modulus $G = 18608$ MPa and the bulk modulus $K = 59714$ MPa.

Determination of the rocks' strength. Experimental determination of the rocks' strength is done with at least three samples, more frequently with five samples, cut out from the rock in the three mutually perpendicular directions. Samples of the prismatic form are the most frequently used for this type of tests; the complete testing process (samples preparation, testing procedure and presentation of the obtained results) is defined in corresponding standards [13 - SRPS EN 14158:2007].

Humidity has big influence on strength of rocks and is being expressed by the so-called *softening degree*, which represents the ratio of strength of water-saturated sample and strength of the dry sample. This coefficient is less than unity; the most favorable for application are rocks whose values of this coefficient are within range 0.6 to 0.9, while rocks with the softening degree values less than 0.6 are not recommended for applications, at all.

Usually, strength of rocks is tested in all the three conditions (dry, water-saturated and post-freezing); all the rocks in general, have higher values of the compressive than of the tensile, bending, torsional or shear strength. For conducting the experimental investigations of the rocks' properties were used: universal hydraulic press with applied force range 60000-100000 daN and results recording device with accuracy of 1 %, rock cutting machine, grinding machine, drying chamber with capacity for achieving and maintaining the temperature of 110 ± 5°C, digital scales with accuracy ± 0.01 % and auxiliary equipment (bath for samples submerging in water, freezing baths, etc.).

Compressive strength. Determination of the compressive strength was done on dry and on water-saturated samples of the cubic form, edge length 40 ± 1 mm, whose surfaces were ground and planparallel. The average value of the compressive strength of samples made of limestone from the Vučjak site (fifteen samples, five per each direction) amounts to R_{cm} = 131 MPa.

In the same way, experimental investigations were conducted on samples from other sites (dolomite marble, calcite-dolomite marble and andesite). For obtaining the compressive strength results after 25 cycles of freezing, three samples were used, that had the cubic form, edge length 100±1 mm (Table 3).

Table 3. Compressive strength of rocks

Type and origin of rocks	Compressive strength R_{cm}, [MPa]			Softening coefficient, K_{soft}
	Dry samples	Water-saturated samples	Samples after 25 freezing cycles	
Limestone "Vučjak"	131	123	117	0.94
Dolomite-marble "Samar"	150	136	130	0.91
Calcite-dolomite marble "Gradac"	161	140	138	0.87
Andesite "Šavnik"	195	186	184	0.95

Tensile strength. Though the tensile strength testing is done rarely, it most certainly is the significant property. The testing was done on samples of the same form and sizes and under the same conditions as the compressive tests; the sole difference was that only the dry samples were tested. The average value of the tensile strength of the tested limestone samples was R_m= 6.00 MPa. Based on results from literature of numerous limestones' testing, the tensile strength amounts to 1.5 MPa for the porous limestones, while for the vigorous ones this value reaches about 6.4 MPa. For the other types of rocks, tests were done in the same manner with results presented in Table 4.

Table 4. Tensile strength of rocks

Type and origin of rocks	Tensile strength R_m, [MPa]			Average values
	Direction I-I	Direction II-II	Direction III-III	
Limestone "Vučjak"	5.97	6.14	5.89	6.00
Dolomite-marble "Samar"	5.26	5.42	3.72	4.80
Calcite-dolomite marble "Gradac"	5.64	5.36	4.03	5.00
Andesite "Šavnik"	9.48	9.82	8.90	9.40

Shear strength. Determination of the shear strength was done only on samples from the limestone site "Vučjak", by the direct shearing method. This method is the most frequently applied by the Casagrande device. This device provides possibilities for testing rocks' samples for shear strength at different angles in order to determine the shear strength parameters (cohesive strength – C and the internal friction angle – φ); the test is usually done at angles of 45° and 60°.

Determination of the shear and normal stresses was done in such a way that for the different shear angles (45° and 60°) the samples were loaded by the vertical compressive force and the components of the in-plane displacements were red-off and then the stresses were calculated; results are presented in Figure 2.

Bending strength. The bending strength testing was done on a single sample per each type of the tested rocks, on dry samples and for the direction which is perpendicular to stratification and schistosity direction, for the purpose of obtaining the best results (the highest values) (Table 5).

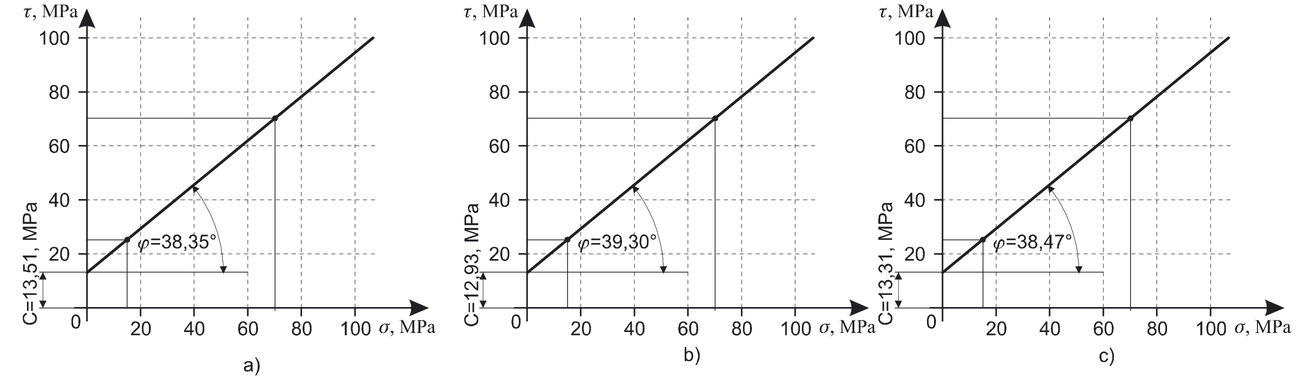


Figure 2. Graphical presentation of results of the limestone rock's shear parameters determination (C, φ): a) Shear direction I-I; b) Shear direction II-II; c) Shear direction III-III.

Table 5. Bending strength of rocks

Type of rocks		Limestone "Vučjak"	Dolomite-marble "Samar"	Calcite-dolomite marble "Gradac"	Andesite "Šavnik"
Bending strength	$\sigma_s = \frac{3 \cdot F \cdot L}{2 \cdot b \cdot h^2}$, MPa	13.20	5.46	6.25	9.82

Determination of wear resistance of rocks. The wear resistance of the rock materials is their stability related to various wear processes, what is manifested by the lesser or bigger loss of the material's mass. Their resistance to wear does not depend only on hardness, but also on structure, mineral freshness, cleavability and type of the natural binding (if they are naturally bounded). When considering the bounded rocks (stones), smaller wear resistance possess rocks made of minerals of low hardness (mica, talc, coarse-grained calcite, etc.). It can be said that the smaller wear resistance possess chloride, sulphide and carbonate rocks, while the higher wear resistance characterizes silicon and silicate rocks, made of fresh minerals.

Experimental investigation of the wear resistance of rocks is defined by the corresponding methods: The *Los Angeles* method [12 - SRPS B.B8.045] (Table 6), the *Bohme* method [12 - SRPS B.B8.015] (Table 6), and the *Deval* procedure [12 - SRPS B.B8.043]. The Bohme method is used for testing the wear resistance of rock samples of the cubic form, while the other two methods are mainly used for the stone aggregates. Results of wear resistance investigations of rock materials and their aggregates are given in Table 6. Tests were done on three dry samples for each material in the Laboratory for construction materials in Belgrade, Serbia.

Table 6. Results of rock wear testing according to the Los Angeles / Bohme method

Type and origin of rocks	Wear quantity [mm^3/50 mm^2] ($\times 10^3$)			Average value [%]
	Sample 1	Sample 2	Sample 3	
Limestone "Vučjak"	22.80 / 23.20	23.10 / 22.90	23.40 / 21.80	23.10 / 22.63
Dolomite-marble "Samar"	27.70 / 19.50	27.30 / 18.30	28.10 / 20.60	27.70 / 19.47
Calcite-dolomite marble "Gradac"	29.30 / 23.40	28.80 / 24.3	28.60 / 23.60	28.70 / 23.77
Andesite "Šavnik"	11.80 / 10.20	12.20 / 9.10	12.40 / 9.90	12.10 / 9.73

Based on results of tests by the Los Angeles method (Table 6) can be concluded that the aggregates of the tested rock materials possess good wear resistance as well. In addition, according to results obtained by the Bohme method, one can conclude that the limestone samples possess average or good wear resistance, the dolomite marble samples possess good wear resistance; samples of calcite-dolomite marble possess average or good wear resistance, while andesite samples possess exceptionally good wear resistance. This means that the parts of the construction machinery, which would be in contact with this andesite would be exposed to abrasive wear of high intensity.

Summary

In this paper are presented results of investigations of the physical-mechanical properties of the four types of the rock materials that are most frequently processed and built-in during the road constructions. Estimates of the most important physical properties of those materials led to conclusion that one here deals with vigorous and homogeneous materials of the medium to high hardness. Through the numerous experimental investigations of mechanical properties, it was established that values of compressive strength are, on the average, 10 to 40 times higher than the shear, bending and tensile strength, while the wear resistance is good in majority of the rock materials, while it is exceptionally high for andesite.

Obtained results enable estimates of quality of certain rock materials on one hand, while on the other they point to the complexity of the problem of selecting the material for the working parts of construction mechanization, since that is done according to properties of the corresponding rock materials. Experimental results of the certain characteristic properties of the rock materials, as well as the complex working conditions of the tribological system – machine parts-rock materials, must be taken into account in selecting the proper base materials for the parts and the basic parameters and reparation technology of the damaged or worn parts of the construction machinery.

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