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INFLUENCE OF PETROGRAPHIC CHARACTERISTICS OF SILICATE ROCKS ON THE QUALITY OF AGGREGATES

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Key words: Rock aggregates; Crushing resistance; Los Angeles abrasion test

Sažetak

The mechanical properties of crushed rock aggregates are greatly influenced by the petrographic characteristics of parent rock. The main objective of this study was to determine the relation between the petrographic characteristics of some volcanic and subvolcanic (silicate) rocks from Croatia, and the crushing resistance of aggregates produced by their comminution. The aggregate resistance to crushing was tested by means of the Los Angeles abrasion test. During this testing, an aggregate is subjected to dynamic load by impact and abrasion. The petrographic characteristics were examined with the petrographic and scanning electron microscope and by X-ray powder diffraction with CuKα (1,54 Å) radiation. In order to obtain the most correct evaluation of aggregates crushing resistance, four different values had been used – the recrushing index (Ir), the reduction ratio (RR), the Los Angeles abrasion value (LA) and the Los Angeles abrasion value residue (LAr). On the basis of the obtained results, the following petrographic factors have been revealed as the most important ones for rock aggregates resistance to crushing: a – the size of crystals, b – the form, arrangement and dimensions ratio of crystals, and, especially, c – the presence of microfractures in parent rock.

Ključne riječi: Kameni agregati, Otpornost prema drobljenju, Metoda "Los Angeles"

Abstract

Petrografska obilježja ishodišne stijene bitno utječu na mehanička svojstva drobljenih kamenih agregata. Glavni cilj ovog rada bio je utvrditi odnose između petrografskih obilježja nekih vulkanskih i subvulkanskih (silikatnih) stijena i otpornosti prema drobljenju agregata dobivenih njihovim usitnjavanjem. Otpornost prema drobljenju ispitivana je metodom "Los Angeles". Tijekom ispitivanja agregat je izložen dinamičkim opterećenjima na udar i habanje. Mineralni sastav i druga petrografska obilježja određeni su petrografskim i elektronskim mikroskopom, te metodom rendgenske difrakcije na prahu vertikalnim rendgenskim goniometrom s CuKα (1,54 Å) zračenjem. Kako bi se što točnije ocijenila otpornost prema drobljenju ispitivanih agregata korištena su četiri različita pokazatelja: koeficijent Los Angeles (LA), koeficijent Los Angeles ostatka (LAr), indeks pregranulacije (Ir) i stupanj usitnjavanja (RR). Na temelju dobivenih rezultata kao najvažnija petrografska obilježja kamenih agregata u pogledu otpornosti prema drobljenju izdvojeni su: a – veličina kristala; b – oblik, prostorni raspored i međusobni odnos veličina kristala; i, posebice, c – prisustvo mikropukotina u ishodišnoj stijeni.

Introduction

Rock aggregates are used in numerous and various constructions. The durability of any construction in which they are used largely depends upon the properties of the aggregate. Therefore, the quality testing of aggregates is important in determining their suitability for any engineering application.

It is well known that mechanical properties of crushed rock aggregates are greatly influenced by the petrographic characteristics of parent rock. During quarrying, a geologist is required to evaluate the properties and quality of stone. For that reason, it is necessary to define the main petrographic characteristics that have an influence on mechanical properties of rock aggregates.

The influence of microstructure and other petrographic characteristics on the properties of aggregates has been elaborated by Ramsay et al. (1974), Hartley (1974) and Lees and Kennedy (1975). In the recent period, the same subject was elaborated by AL-Edeenan et al (1994) and Tomašić et al. (1992, 1997).

The main objective of this study was to determine the relation between the petrographic characteristics of some silicate rocks from Croatia, and the crushing resistance of aggregates produced by their comminution. The crushing resistance was selected because it is one of the most important mechanical properties, especially in the chemically and mechanically stabilised constructions and in the bituminous bound constructions.

The silicate, volcanic and subvolcanic rocks, which are favourable for production of high quality road aggregates, cover very small areas in Croatia and there are great variations in their petrographic characteristics. Six different aggregates were laboratory tested. The four of them were from diabase quarries (Brensberg, Žervanjska 1, Žervanjska 2, Hruškovec), one was from basalt quarry (Kraljev Vrh), and one was from andesite quarry (Fužinski Benkovac).

Sampling and test procedures

The samples for petrographic analyses, as well as for certain physical and mechanical tests of stone, were collected at the quarry faces from blasted rock. For rock aggregates, the testing samples were collected from stockpiles of sized material.

In order to determine the mineral composition and other petrographic characteristics, the samples were examined with the petrographic and scanning electron microscope. Some samples were also analyzed by X-ray powder diffraction with CuKα (1,54 Å) radiation.

The physical and mechanical properties of rock samples were measured according to the Croatian

Standards as listed below, which correspondent with EN, DIN or ASTM standards in parentheses:

- real density, apparent density and total porosity
  HRN EN 1936 (EN 1936:1999)
- water absorption
  HRN B.B8.010 (ASTM C 97-90)
- compressive strength
  HRN EN 1926 (EN 1926:1999)
- abrasion resistance
  HRN B.B8.015

The aggregate resistance to crushing was tested by means of the Los Angeles abrasion test since it is the main method used for that purpose in Croatia. The standard for Los Angeles abrasion test in Croatia (HRN B.B8.045) corresponds with ASTM C 131-89 and ASTM C 535-89 standards. Although the aggregate in the Los Angeles testing machine suffers a combination of attrition and impact, the method was assessed as being correct for testing the aggregates crushing resistance because the impact is probably more significant (Smith and Collis, 1993) and because the Los Angeles abrasion value shows very good correlation with the Aggregate crushing value (ACV).

In this study, the grades B, C and D (according to ASTM C 131-89) of each aggregate were tested; however, some changes were done in the testing procedure. All samples (grades B, C, D) were charged with eight steel balls in order to maintain constant crushing energy. In that way, the comparison of results for different grades was enabled. It is necessary to emphasize that the Los Angeles abrasion value (LA) obtained in that manner differs from the standard Los Angeles abrasion value.

Ramsay et al. (1974) wrote that the measurement of fines passing sieve smaller than the original lowest grain size gives an imperfect assessment of crushing resistance. That is particularly present in the Los Angeles abrasion test because the results for samples of different grading are obtained by sieving through a sieve of the same aperture (circular openings of 2,0 mm). In order to avoid this imperfection, three additional values for evaluation of aggregates crushing resistance were used: Los Angeles abrasion value residue (LAr), recrushing index (Ir) and reduction ratio (RR).

The Los Angeles abrasion value residue (LAr) is the proportion (mass%) of material remaining within the original size range after the crushing (for grade D the content of particles larger than 3,15 mm, for grade C the content of particles larger than 6,3 mm and for grade B the content of particles larger than 12,5 mm). The definition of this value was based on the same principle as the definition of aggregate impact value residue (Ramsay, 1965) and aggregate crushing value residue (Dhir et al., 1971).

The recrushing index (Ir) was calculated as a ratio of surface below grading curve of tested sample after the crushing to area below grading curve before the crushing (Tomašić et al., 1992). The areas below grading curves were determined with numerical – graphical integration.

The reduction ratio (RR) was defined as a ratio of grains surface area before the crushing to grains surface area after the crushing. The total surface area of grains was calculated from the following equation:

$$PZ = \sum_{i=1}^{k} \frac{6}{\gamma d_i} * \frac{m}{100}$$

in which:

PZ – grains surface area (m^2/kg)
γ – apparent density of aggregate grains (g/cm^3)
d_i – mean grain diameter of each class (cm)
m – mass portion of each class (%)

The mean grain diameter of each class was determined as harmonic mean value of the class size range.

Results

Results of analyses and testings are divided in two groups. In the first group, the results of petrographic analyses of tested samples are presented. They consist of the results of petrographic microscope analyses and X – ray analyses. For the rock structure determination, the results of analyses by scanning electron microscope were also obtained but they are presented in the fourth chapter.

In the second group the results of mechanical properties testing are displayed, separately for stone samples and for rock aggregates samples.

Petrographic characteristics of samples

The results of mineralogical and petrographic analyses are presented in Tables 1 and 2. For the samples from the Fužinski Benkovac and Hruškovec quarries, the results of X-ray diffraction have been published in papers of Vragović and Golub (1969) and of Slovenec and Babić (1976).

Table 1
Mineralogical and petrographic characteristics of samples determined with the petrographic microscope (Legend: Cpx – clinopyroxene, Pl – plagioclase, Ab – albite, Am – amphiboles, Hbl – hornblende, Act – actinolite, Qtz – quartz, Ser – sericite, Cal – calcite, Ep/Zo – minerals of the epidote/zoisite group, Chl – chlorite, Prh – prehnite, Fe – iron oxides and hydroxides, Ttn – titanite, Ap – apatite)

Tablica 1
Mineraloško-petrografska obilježja uzoraka određena petrografskim mikroskopom (Legenda: Cpx – klinopirokseni, Pl – plagioklasi, Ab – albit, Am – amfiboli, Hbl – hornblenda, Act – aktinolit, Qtz – kvarc, Ser – sericit, Cal – kalcit, Ep/Zo – minerali iz skupine epidota i coisita, Chl –klorit, Prh – prehnit, Fe – oksidi i hidroksidi željeza, Ttn – titanit, Ap – apatit)

Quarry	Microstructure	Primary mineral composition	Minerals formed by secondary processes	Size of crystal sections (mm)	Microdefects
BRENSBERG	Intergranular – – intersertal	- clinopyroxene - plagioclase	Relics of Cpx completely filled with Am, Cal, Chl. Pl filled with aggregate of Ser, Cal, Chl, Ep/Zo. In the spaces between Cpx and Pl, grains of Qtz and flaky Chl are present.	Cpx: 0,3 – 0,7 x 0,4 – 2,3 Pl: 0,3 – 0,8 x 2,0 – 4,0	Veins filled with Cal, Qtz and sporadically also with Act, Chl. Pl and Cpx fractured, in fractures sporadically Chl and Fe occur.
ŽERVANJSKA 1	Ophitic	- clinopyroxene - plagioclase	Some Cpx altered to Am. Pl filled with aggregate of Ser and Ep/Zo.	Cpx: 0,6 – 1,2 x 0,9 – 2,8 Pl: 0,8 – 1,3 x 4,0 – 6,0	Sparse microfractures in Cpx and Pl.
ŽERVANJSKA 2	Ophitic	- clinopyroxene - plagioclase	Sparse Cpx altered to Am. Pl filled with aggregate of Ser and Ep/Zo.	Cpx: 1,0 – 2,0 x 1,5 – 3,0 Pl: 0,2 – 0,4 x 0,6 – 1,5	Sparse veins filled with Qtz and Cal. Sparse microfractures in Cpx and Pl.
KRALJEV VRH	Porphyritic and glomeroporphyritic with intergranular and arborescent microstructure of matrix	- clinopyroxene - plagioclase - volcanic glass	In some samples, only small part of Cpx altered to Cal and Chl, but in most samples most of Cpx is completely altered to Cal and Chl. Pl filled with cryptocrystalline products of alteration in which minerals could not have been identified.	Phenocrysts: Pl: 0,2 – 0,4 x 0,7 – 0,8 Cpx: 0,3 – 0,4 x 0,6 – 0,8 Matrix crystals: Pl: 0,05 – 0,3 x 0,1 – 0,7 Cpx: 0,1 – 0,2 x 0,2 – 0,4	Veins filled with Qtz and Cal. Some samples tectonically fractured. Fractures filled with black-brown substance which could not have been identified.
HRUŠKOVEC	Ophitic, intergranular, intersertal and hyaloophitic	- clinopyroxene - plagioclase - volcanic glass (some samples)	Cpx completely altered to Cal, Chl, Ttn, Am, Fe, Ep/Zo. Pl filled with Cal, Ser, Chl, Ep/Zo. Chl is present in spaces between Cpx and Pl. Some samples contain cryptocrystalline and arborescent products of devitrification.	Cpx: 0,05 – 0,2 x 0,1 – 0,6 Pl: 0,02 – 0,20 x 0,1 – 1,1	The most of mineral components intersected with irregular fractures. Veins filled with Cal in some samples are up to 4 mm thick.
FUŽINSKI BENKOVAC	Porphyritic	Phenocrysts: - hornblende - plagioclase Matrix crystals: Pl, Qtz, Chl, Ap	Ho completely altered to Chl, Cal, Ttn, Ep/Zo. Pl filled with Chl, Ser, Ep/Zo, Cal, Ab.	Phenocrysts Hbl: 0,4 – 1,0 x 0,7 – 2,0 Pl: 0,1 – 1,5 x 0,3 – 2,5 Matrix crystals: up to 0,05 in diameter	Veins filled with Cal. Pl fractured with different intensity from sample to sample. Bent margins and irregular extinction of Pl parts separated by fracture occurred in highly fractured samples.

Table 2.

Mineral composition of the samples determined by X – ray powder diffraction (Legend: Cpx – clinopyroxene, Pl – plagioclase, Am – amphiboles, Hbl – hornblende, Qtz – quartz, Ser – sericite, Cal – calcite, Ep/Zo – minerals of the epidote/zoisite group, Chl – chlorite, Prh – prehnite, Ap – apatite, Chl/Vrm – interstratified chlorite and vermiculite)

Tablica 2.

Mineralni sastav uzoraka određen kvalitativnom metodom rendgenske difrakcije praha (Legenda: Cpx – klinopirokseni, Pl – plagioklasi, Am – amfiboli, Hbl – hornblenda, Qtz – kvarc, Ser – sericit, Cal – kalcit, Ep/Zo – minerali iz skupine epidota i coisita, Chl – klorit, Prh – prehnit, Ap – apatit, Chl/Vrm – miješanoslojni klorit–vermikulit)

MINERALS	QUARRIES					
	BRENSBERG	ŽERVANJSKA 1	ŽERVANJSKA 2	KRALJEV VRH	HRUŠKOVEC	FUŽINSKI BENKOVAC
Pl				+		+
Cpx	+	+	+	+	+	+
Am	+	+	+		+	+
Hbl	+	+	+			+
Chl				+		+
Ser	+	+	+		+	
Cal	+	+	+	+	+	+
Qtz	+				+	+
Ep/Zo	+	+	+			
Chl/Vrm	+	+	+			
Prh				+	+	
Ap						+

Physical and mechanical properties of samples

The results obtained by standard laboratory tests of physical and mechanical properties of stone are displayed in Table 3. Discussion about them is presented in chapter four. The crushing resistance of tested rock aggregates, presented through four different values is displayed in diagrams in Figure 1.

Table 3.

Physical and mechanical properties of the stone samples (Legend: BR – Brensberg, Z1 – Žervanjska 1, Z2 – Žervanjska 2, KV – Kraljev Vrh, HR – Hruškovec, FB – Fužinski Benkovac)

Tablica 3.

Fizikalna i mehanička svojstva uzoraka kamena (Legenda: BR – Brensberg, Z1 – Žervanjska 1, Z2 – Žervanjska 2, KV – Kraljev Vrh, HR – Hruškovec, FB – Fužinski Benkovac)

TESTED PROPERTIES	QUARRIES					
	BR	Z 1	Z 2	HR	KV	FB
Real density (g/cm^3)	2,960	2,970	2,968	2,907	2,942	2,746
Apparent density (g/cm^3)	2,939	2,933	2,951	2,849	2,923	2,713
Total porosity (%)	0,71	1,3	0,6	2,02	0,65	1,2
Water absorption (%)	0,22	0,07	0,14	0,43	0,32	0,27
Compressive strength (MN/m^2)	219,1	249,2	179,1	180,3	195,4	191,8
Abrasion resistance ($cm^2/50cm^3$)	9,22	6,31	8,38	9,10	11,40	9,00

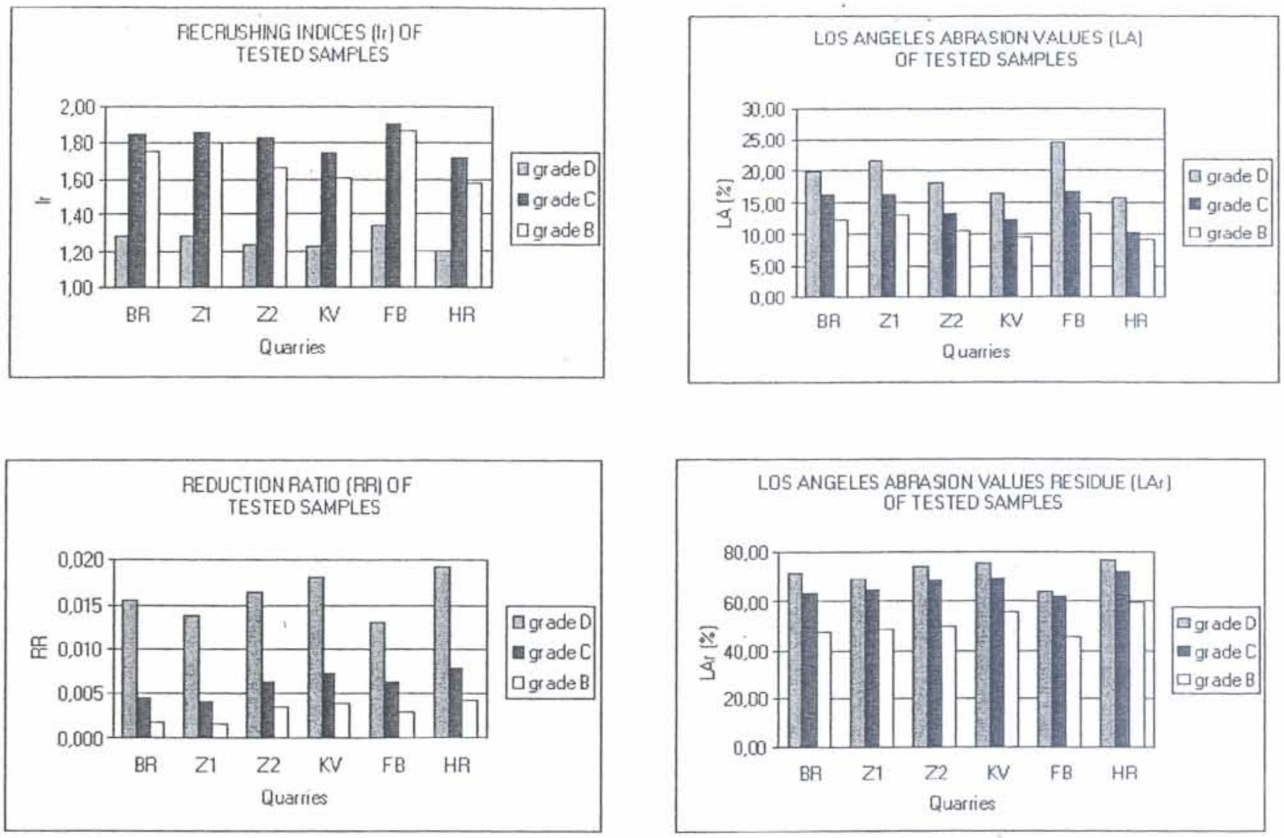


Fig. 1. Crushing resistance of rock aggregates presented by: a – recrushing index (Ir), b – reduction ratio (RR), c – Los Angeles abrasion value (LA) and d –Los Angeles abrasion value residue (Lar). (Legend: BR – Brensberg, Z1 – Žervanjska 1, Z2 – Žervanjska 2, KV – Kraljev Vrh, HR – Hruškovec, FB – Fužinski Benkovac)

Sl. 1. Otpornost kamenih agregata prema drobljenju prikazana pomoću: a – indeksa pregranulacije (Ir), b – stupnja usitnjavanja (RR), c – koeficijenta Los Angeles (LA) i d – koeficijenta Los Angeles ostatka (Lar). (Legenda: BR – Brensberg, Z1 – Žervanjska 1, Z2 – Žervanjska 2, KV – Kraljev Vrh, HR – Hruškovec, FB – Fužinski Benkovac)

From presented diagrams, it is clear that the applied values differently evaluate crushing resistance for various grades of the same rock material. According to the recrushing index (Ir), the lowest crushing resistance for each material has grade C and the highest crushing resistance has grade D (Figure 1a). According to the reduction ratio (RR) and Los Angeles abrasion value residue (LAr), the lowest crushing resistance regularly has grade B, and the highest crushing resistance has grade D (Figures 1b and 1d). On the other hand, according to the Los Angeles abrasion value (LA) the lowest crushing resistance for each material has grade D, and the highest crushing resistance has grade B.

The relation between Ir for different grades of the same rock material, as well as the relation between RR for different grades of the same rock material, is caused by their mathematical definitions. Namely, the lowest area under the grading curve before testing has grade C, so the ratio of the area under the grading curve of a sample after the testing to the area under the grading curve of a sample before the testing (Ir) is always the highest for grade C. The areas under the grading curves were calculated from the diagram with a linear scale on the abscissa. In the calculation of RR, the highest surface area of grains before testing has grade D, so the ratio of the surface area of grains before the testing to the surface area of grains after the testing is always the highest for grade D. The different evaluation of various grades for the same rock aggregate, which shows LA and LAr, comes from different ways of measurement of crushed material amount, which had been discussed in the previous chapter.

From these observations ensues that in the aggregates crushing resistance evaluation, apart from the crushing test, the way of measurement of crushed material amount and form of result presentation also influence the final assessment. This is especially emphasized if the samples of different grading have been tested.

The influence of the applied form of test result on the evaluation is not so strong if the crushing resistance for the same grade of different rock materials has been analyzed. Namely, the sequences of tested aggregates by their crushing resistance, in order from the best to the worst one, established by Ir, RR, LA and LAr for each grade separately, are identical in eight cases (table 4, first column). In other four cases, these sequences show very little difference (Table 4, second and third column).

Table 4.
Sequences of tested aggregates (from the best to the worst one) by their crushing resistance, established by Ir, RR, LA and LAr for each grade
Tablica 4.
Redoslijedi ispitivanih agregata od boljeg prema lošijem uspostavljeni na temelju Ir, RR, LA i LAr za svaku gradaciju

Ir (grade D,C,B), RR (grade D) LA (grade D,C,B), LAr (grade D)	RR (grade C and B)	LAr (grade C and B)
Hruškoveci	Hruškoveci	Hruškoveci
Kraljev Vrh	Kraljev Vrh	Kraljev Vrh
Žervanjska 2	Žervanjska 2	Žervanjska 2
Brensberg	Fužinski Benkovac	Žervanjska 1
Žervanjska 1	Brensberg	Brensberg
Fužinski Benkovac	Žervanjska 1	Fužinski Benkovac

Therefore, the sequence in the first column of Table 4 has been accepted as being relevant for the aggregates sequence by their crushing resistance (hereafter: **the crushing resistance sequence).**

Discussion

On the basis of results in table 3, sequences of samples by their compressive strength and abrasion resistance (from the best to the worst one) are established. These sequences are compared with the crushing resistance sequence and, with addition of the sequence by content of unsound minerals (from the sample with the lowest to the one with the highest content); they are all together displayed in table 5. From the comparison of the mentioned sequences (Table 5) it ensues that the quality of rock aggregates cannot be evaluated on the basis of mechanical properties tested on stone samples only. Namely, the samples Žervanjska 1 and Brensberg have the highest values of compressive strength, and the samples Žervanjska 1 and Žervanjska 2 have the best abrasion resistance (Table 3). On the other hand, the aggregates Hruškovec and Kraljev Vrh (Table 4) have the best resistance to crushing. That kind of relation between mentioned results again confirms that the correlation between the performance of rock in the intact state and in the aggregate form is not consistent (Dhir et al., 1971).

It is clear that each property is controlled by somewhat different factors. Therefore, the following petrographic factors were analyzed in this study as being of importance for rock aggregates resistance to crushing: a – the size of crystals; b – the form, arrangement and dimensions ratio of crystals; c – the content of unsound minerals; and d – the presence of microfractures.

Table 5.
Sequences of samples by their mechanical properties (from the best to the worst one) and by content of unsound minerals (from sample with the lowest to one with the highest content)
Tablica 5.
Redoslijedi ispitivanih kamenih materijala prema njihovim mehaničkim svojstvima i prema udjelu slabih minerala

CONTENT OF UNSOUND MINERALS	RESISTANCE TO CRUSHING	ABRASION RESISTANCE	COMPRESSIVE STRENGTH
Žervanjska 1	Hruškoveci	Žervanjska 1	Žervanjska 1
Žervanjska 2	Kraljev Vrh	Žervanjska 2	Brensberg
Fužinski Benkovac	Žervanjska 2	Fužinski Benkovac	Kraljev Vrh
Hruškoveci	Brensberg	Hruškoveci	Fužinski Benkovac
Kraljev Vrh	Žervanjska 1	Brensberg	Hruškoveci
Brensberg	Fužinski Benkovac	Kraljev Vrh	Žervanjska 2

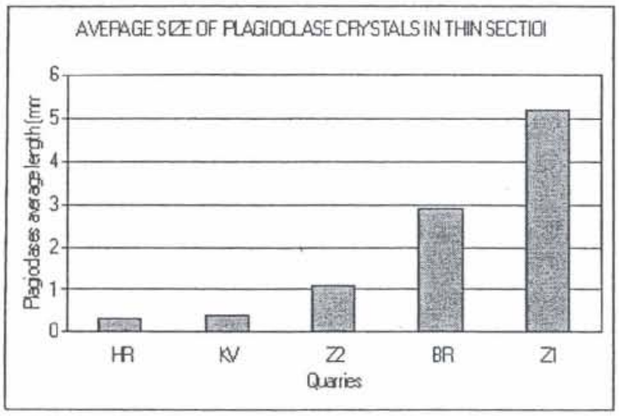
The size of crystals

In order to determine the influence of crystal size on crushing resistance of rock aggregates, numerous crystal dimensions in thin sections were measured. From the obtained data, an average crystal size of the main mineral constituent for each sample was calculated.

In crystal size analyses, only the aggregate from the andesite Fužinski Benkovac quarry was excluded due to its distinct porphyritic microstructure with numerous phenocrysts and the great difference between their size and the size of groundmass crystals. In the samples from Kraljev Vrh, only the dimensions of groundmass crystals were measured because the phenocrysts in those samples are sparse and the difference between their dimensions and the dimensions of groundmass crystals is small.

For that reason, it can be justifiably considered that the petrographic characteristics of the groundmass have the main influence on mechanical properties of the Kraljev Vrh aggregate.

The diagram in Figure 2a shows that the crushing resistance sequence (Table 4, first column) is completely coincidental with the order by average size of plagioclase crystals. Due to their elongated, bladed shape, the size of plagioclases is represented by the average length of their crystals in thin sections.



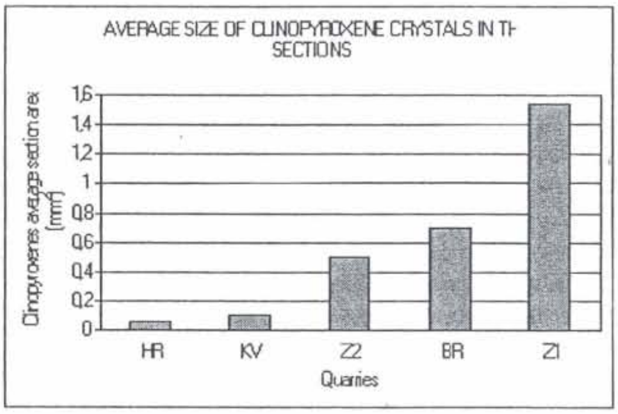


Fig. 2. Average size of main mineral constituents of tested aggregates, measured in thin sections: a – average length of plagioclase crystals, b – average section area of clinopyroxene crystals. (Legend: BR – Brensberg, Z1 – Žervanjska 1, Z2 – Žervanjska 2, KV – Kraljev Vrh, HR – Hruškovec)

Sl. 2. Histogrami srednjih veličina presjeka glavnih kristala ispitivanih kamenih agregata:
a – prosječne dužine kristala plagioklasa, b – prosječne površine kristala klinopiroksena. (Legenda: BR – Brensberg, Z1 – Žervanjska 1, Z2 – Žervanjska 2, KV – Kraljev Vrh, HR – Hruškovec)

The size of the clinopyroxenes (Figure 2b) is represented by the average section area of their crystals because only one dimension is not dominant in their shape. The average section area was calculated from the longest average and the shortest average dimension of clinopyroxene crystals in thin sections. In the case of Žervanjska 2 diabase with distinct ophitic microstructure in which clinopyroxenes are intersected by plagioclases, the dimensions of created clinopyroxene fragments were included in the calculation instead of the dimensions of the whole grains. The crushing resistance sequence and the order by clinopyroxenes average section area are also coincidental, as illustrated in Figure 2b.

It is necessary to point out that the average size of crystals in samples Kraljev Vrh and Hruškovec would have been smaller if their measurement in samples with arborescent microstructure had been made possible.

The form, arrangement and dimensions ratio of crystals

The rocks with intergranular and ophitic microstructures are known to have good crushing resistance, which is once more confirmed in this study. Namely, the bladed plagioclase crystals are crossed, the clinopyroxene crystals are interlocked between them, and somewhere plagioclases penetrate in clinopyroxenes. Therefore, the bonds between crystals are very strong and the rock has solid structure with mainly isotropic mechanical properties.

The andesite aggregate from Fužinski Benkovac has the lowest results in crushing resistance testing. Besides microfractures, the probable reason for that may be its porphyritic microstructure with the ratio of the average size of phenocrysts to the average size of groundmass crystals above 30. However, in the samples where the phenocrysts are scarce and where the difference between dimensions of phenocrysts and groundmass crystals are not high, the porphyritic microstructure has no significant influence on rocks crushing resistance. For example, in the basalt samples from the Kraljev Vrh quarry, the phenocrysts are scarce and the above-mentioned ratio is around 2,0, so the aggregate has very good resistance to crushing. In the cases like that, the dominant influence on material properties has the microstructure of groundmass and if it is favorable, the aggregate may have a high value of crushing resistance.

The rock aggregates which have, besides the intergranular and/or ophitic microstructure, the devitrificational microstructures (samples Hruškovec and Kraljev Vrh) have especially high resistance to crushing. This is probably due to very small dimensions and disoriented intertwining of crystals produced by devitrification, which results in a very tough structure of the rock material.

Content of unsound minerals

It is well known that the presence of unsound minerals has a negative influence on the mechanical properties of stone. That is why the influence of unsound minerals on crushing resistance of rock aggregates has been analyzed in this study. With respect to technical properties of rock materials, unsound minerals are neither necessarily the secondary minerals, neither the products of alterations only, or chemical weathering only. Some of alteration processes like epidotization – zoisitization, silicification, devitrification etc., can even improve the technical properties of stone. There are also some alteration processes, like uralitization and albitization, which have no practical influence on technical properties of stone. Therefore, the expression **unsound minerals** which has been used in this paper, means every mineral with Mohs hardness under 3, no matter of its origin.

It ensues from X–ray analyses of mineral content (Table 2) that unsound minerals in tested samples are mainly sericite and chlorite. By comparison of petrographic microscope analyses (Table 1), their relative content in tested rocks was determined and the sequence of samples by their content of unsound minerals, in low to higher order, has been established (Table 5).

The presented sequence of samples by their content of unsound minerals completely differs from their crushing resistance sequence (Table 5). There may be two explanations. Firstly, the portions of unsound minerals in each rock aggregate may be too small to significantly influence their crushing resistance. Therefore, certain other factors have the dominant influence on crushing resistance of tested aggregates. The second explanation may be that during the comminution, the parts of rock with higher content of unsound minerals are crushed in very fine particles (classes 0 – 2 mm), which crushing resistance was not tested in this study.

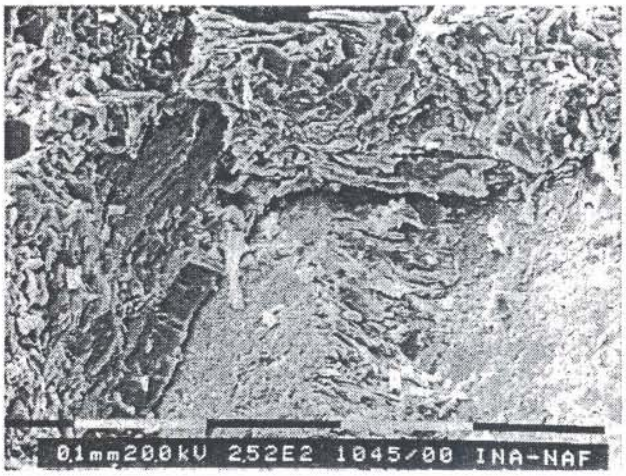
However, it is interesting that the established sequence of samples by their content of unsound minerals is almost completely coincidental with the sequence of samples by their abrasion resistance in the best to worst order (Table 5). This is in accordance with certain observations that were made by Tomašić et al. (1997) who concluded that intensively microfractured and altered rock material has high abrasion resistance if it does not have an increased content of unsound minerals. The mentioned phenomenon is understandable because the abrasion resistance mainly depends upon the content of soft minerals in a sample.

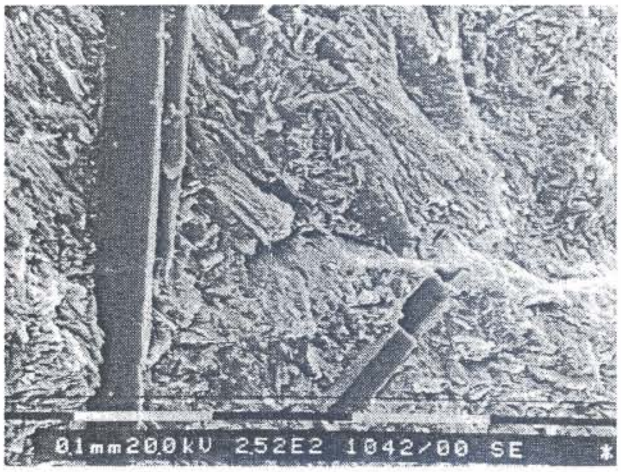
In this study, the application of micropetrographic indices (Mendes et al., 1966; Irfan and Dearman, 1978; Tugrul and Gurpinar, 1997) has been attempted in order to estimate the technical properties of rock aggregates. However, appropriate results were not obtained because almost all primary minerals are altered and filled with cryptocrystalline aggregate of secondary minerals. In that kind of samples, it was impossible to clearly differ sound from unsound minerals and perform modal analyses with the petrographic microscope. In the samples which underwent devitrification processes, an extremely small dimension of matrix minerals also disabled individual mineral determination and calculation of micropetrographic indices.

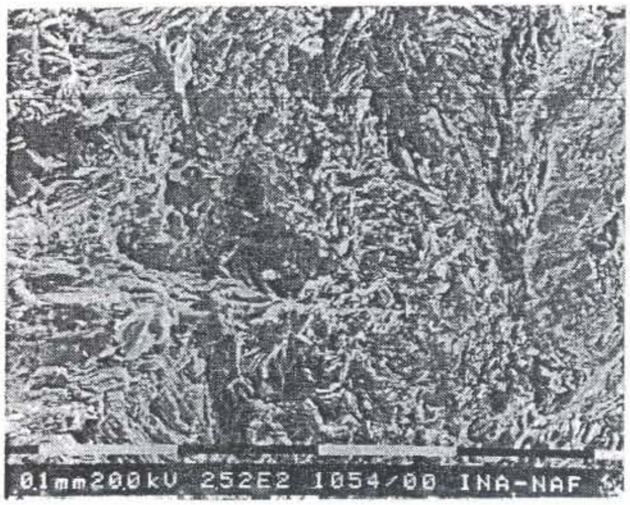
The presence of microfractures

There are fractures in each tested rock. If the sample size is small, as the rock aggregate particles are, it is less likely to include the macroscopic fractures. Besides that, during the comminution, the rock is cracking along the fractures. Therefore, multiple crushing reduces the number of fractures in the produced aggregate grains in regard to parent rock (Tomašić et al., 1990). So, the importance and negative influence on the mechanical properties of rock aggregates, especially on their resistance to crushing, can only have microscopic and especially submicroscopic fractures. The presence of submicroscopic fractures is especially dangerous because they cannot be detected with the petrographic microscope. In this paper, all fractures thinner than 0,1 mm are called microfractures.

The photographs taken by SEM (Figures 3. a – e) show that the andesite samples (Figures 3e) have the most clearly defined and mutually intertwined microfractures. This type of microfracturing led to the formation of microblocks – relatively integral and at the same time still well connected crystal aggregates (Tomašić et al., 1997.), marked with microfractures. The presence of microblocks weakens the structure of material and reduces its mechanical properties, especially the crushing resistance. Besides the disadvantageous microstructure, this is one of the main reasons for the low crushing resistance of rock aggregate from Fužinski Benkovac.







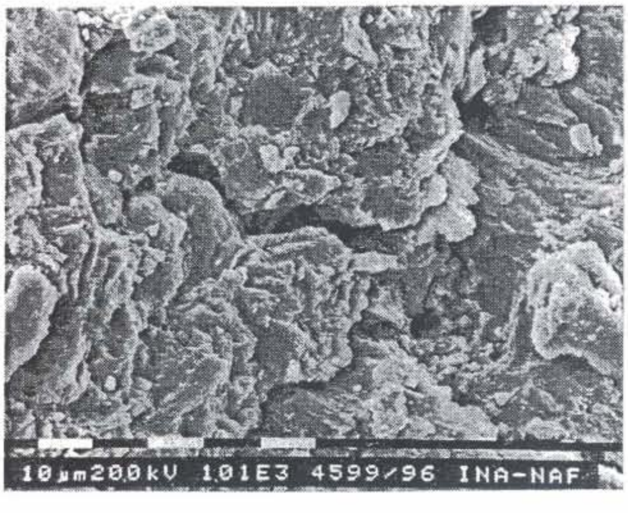


Fig. 3. Scanning electron micrographs of tested samples: a – microfractures in diabase sample Brensberg are sparse and microblocks are formed only sporadically, b – microfractures in diabase sample Žervanjska 1 are very sparse and isolated, so microblocks are not formed, c – microfractures in diabase sample Žervanjska 2 are sparse and isolated, so microblocks are not formed, d – microfractures in diabase sample Hruškovec are sparse and microblocks are formed only sporadically (Tomašić et al.,1997), e – microfractures in andesite sample Fužinski Benkovac are abundant, clearly visible and intertwined, so numerous microblocks are formed (Tomašić et al.,1997).

Sl. 3. Mikrofotografije ispitivanih uzoraka snimljene elektronskim mikroskopom: a – Mikropukotine u uzorku dijabaza Brensberg. Malobrojne su i samo mjestimično formiraju mikroblokove. b – Mikropukotine u uzorku dijabaza Žervanjska 1. Vrlo su rijetke i izolirane pa ne formiraju mikroblokove. c – Mikropukotine u uzorku Žervanjska 2. Malobrojne su i izolirane tako da mikroblokovi nisu formirani. d – Mikropukotine u uzorku dijabaza Hruškovec. Malobrojne su i vrlo rijetko formiraju mikroblokove (Tomašić et al.,1997). e – Mikropukotine u uzorku andezita Fužinski Benkovac. Jasno su izražene i isprepletene, te formiraju brojne mikroblokove (Tomašić et al.,1997).

The described phenomenon, observed by SEM, is in accordance with petrographic observations because only in andesite samples significant crystal defects were found. This points out that the rock material from the Fužinski Benkovac quarry was under intense tectonic activity in the geological past.

The samples Hruškovec (Figure 3d) and Brensberg (Figure 3a) have a lower number of microfractures, with very rare microblocks, while the samples Žervanjska 1 (Figure 3b) and Žervanjska 2 (Figure 3c) have very few isolated microfractures with no microblocks. It is evident that the microfractures are not the factor that has a significant influence on crushing resistance of those rock aggregates.

Conclusion

The present study was performed as an attempt to improve the understanding of microstructure and other petrographic factors that influence the crushing resistance of rock aggregates. The results of Los Angeles test were analyzed in relation to the results of mineralogical and petrographic analyses.

In order to obtain the most correct evaluation of aggregates crushing resistance, after the crushing in the Los Angeles testing machine, four different values had been used – the recrushing index (Ir), the reduction ratio (RR), the Los Angeles abrasion value (LA) and the Los Angeles abrasion value residue (LAr). After having analyzed these values, the conclusion was made that the way of measurement of crushed material amount and the form of result presentation, besides the crushing test, also have an influence on the final assessment, especially if the samples of different grading have been tested.

On the basis of the obtained results, the following petrographic factors have been revealed as the most important ones for rock aggregates resistance to crushing: the size of crystals, the form, arrangement and dimensions ratio of crystals and the presence of microfractures in parent rock. The content of unsound minerals in parent rock may also have influence on rock aggregates resistance to crushing but this has not been proven in this study.

With respect to crystal size, it was noticed that the rock aggregate with very large crystals (Žervanjska 1) has low crushing resistance, although their other petrographic characteristics are very advantageous (ophitic microstructure, very sparse microfractures, the lowest content of unsound minerals). Further studies should be performed to determine the crystal dimension limit after which the aggregate has unsatisfactory low crushing resistance for specified application.

Regarding regards the form, arrangement and the dimension ratio of crystals, intergranular and ophitic microstructures once more proved to be favorable for aggregates crushing resistance. The porphyritic microstructures with numerous phenocrysts and the great difference between their dimension and the dimension of groundmass crystals are disadvantageous for aggregates crushing resistance (andesite from Fužinski Benkovac). However, if the ratio of the average size of phenocrysts and groundmass crystals is small (about 2 for basalt from Kraljev Vrh), the porphyritic microstructure has no practical influence on rock aggregates resistance to crushing. Besides that, if the microstructure of groundmass is favorable, the rock aggregate may have very high values of crushing resistance. The materials which, among others, have devitrificational microstructures (Hruškovec, Kraljev Vrh) showed especially good crushing resistance.

The presence of microfractures (fractures less than 0,1 mm wide) in parent rock is dangerous because these fractures may be present in aggregate grains, even in the finest classes. If the microfractures are very numerous and mutually intertwined, as those in the sample from Fužinski Benkovac, the microblocks are formed. The presence of microblocks weakens the structure of material and reduces its compactness and crushing resistance, although its abrasion resistance is still high, even higher than the abrasion resistance of aggregates with better crushing resistance (Kraljev Vrh, Hruškovec).

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