



EVALUATION OF MICROTTEXTURE CHANGES OF COARSE AGGREGATE DURING SIMULATED POLISHING

W. GARDZIEJCZYK¹, M. WASILEWSKA²

This paper presents application of optical microscope for evaluation of microtexture changes of coarse aggregate during simulated polishing in laboratory. Observations of the apparent changes on surfaces of seven different aggregates are presented. Simulation polishing of aggregate was performed in accordance with PN-EN 1097-8:2009. Images of the aggregate surface were taken with the optical microscope in the reflection mode in particular stages of polishing. Digital images were analyzed. Standard deviation was determined on the basis of the histogram of intensities from digital images of the surfaces of aggregate grains which was assumed as the measure of changes in microtexture during simulated polishing (namely the σ_h parameter). Statistical analysis has shown that the changes of the σ_h parameter between the particular stages of polishing confirm certain trends related to the petrographic characteristic of the rocks. Aggregates which included minerals of similar hardness (granodiorite, dolomite, basalt) were more prone to polishing than gabbro and postglacial. Regeneration of the microtexture, the recovery to its original asperity, occurred in the case of quartz sandstone and steelmaking slag.

Keywords: coarse aggregate, microtexture, image analysis, histogram of intensities, PSV

1. INTRODUCTION

Skid resistance plays an important role in reducing road accidents in wet conditions. Especially macrotexture and microtexture influence skid resistance [6]. Macrotexture depends on asphalt mixture properties (size and gradation of aggregate) or the texturing method used on concrete pavement surfaces. Macrotexture has an effect on skid resistance especially at high vehicle speed. Microtexture depends on polishing resistance of coarse aggregate in wearing course. In actual traffic conditions the phenomenon of polishing which affects the protruding aggregate grains is caused by tires, pollution and water. This process as a result leads to pavement slipperiness.

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During the process of polishing the surface of aggregate undergoes changes depending on the petrographic content, hardness of minerals, texture, structure, porosity and the extent of rock weathering.

In Poland, the resistance to polishing of coarse aggregates used for the wearing course is quantified by the *PSV* (Polished Stone Value) according to the standard PN-EN 1097-8:2009. The resistance to polishing of seven different aggregates were conducted. Specimens of aggregates and specimens of control stone were clamped round the periphery of the road wheel of polishing machine and were brought to the speed of 315 rev/min. The outer surface of the specimen form a continuous strip, upon which rubber tire rode freely and moved without bumping or slipping. Test lasted 6 hours and consisted of two three-hour stages. In the 1st stage water and corn emery were fed continuously on to the road wheel and in the 2nd stage water and emery flour were fed. *S* friction coefficient measured with portable Skid Resistance Tester (namely the British Pendulum Tester) was made before polishing (0 h), after the 1st stage (after 3 h) and after the 2nd stage of polishing (after 6 h). *S* friction coefficient is calculated from the measurement of kinetic energy loss when the rubber slider is dragged on the wet specimen surface.

The *PSV* was calculated after 2nd stage of polishing with consideration for both mean values *S* obtained for four aggregates specimens and mean values *S* obtained for control stone specimens. Therefore for the presentation of the results during the polishing process *S* values were used. The *PSV* and *S* values with their standard deviation (*STD*) in particular stages are presented in Table 1. Aggregates ranking for resistance to polishing based on *S* values is shown in Fig. 1 before polishing and after 2nd stage.

Before polishing *S* was high (above 70). A significant decrease of *S* was registered at the end of the process. The lowest values of *S* were obtained for dolomite, granodiorite and basalt. Quartz sandstone was characterized by the highest *S* value. Steelmaking slag, gabbro and postglacial performed well during the polishing resistance test too. Based on the results (Table 1 and Fig. 1) it was discovered that the type of rocks had a different degree of sensitivity to polishing during particular stages of this process. It should be noted that under actual conditions on roads both polishing and abrasion take place. Therefore the use of test procedure according the standard PN-EN 1097-8:2009 allows evaluating changes of aggregates surface under the influence of two different abrasives. In the 1st stage of the test by applying the coarse emery and water the phenomenon of abrasion were simulated and in the 2nd stage the emery flour and water were used for polishing.

Table 1. Results of the *PSV* and *S* values and standard deviation

Aggregates		Dolomite (D)	Granodiorite (Gd)	Gabbro (G)	Postglacial (Po)	Quartz sandstone (P)	Steelmaking slag (Z)	Basalt (B)
		<i>S</i> - Before polishing	Mean	81.8	71.9	76.4	77.5	82.6
	STD	2.25	2.31	3.08	2.11	1.89	3.77	2.79
<i>S</i> - After the 1st stage	Mean	59.9	61.3	66.7	67.5	71.5	66.9	65.3
	STD	2.15	1.52	1.47	1.34	1.67	6.15	1.26
<i>S</i> - After the 2nd stage	Mean	44.6	49.7	54.4	53.8	57.4	54.7	51.1
	STD	1.76	1.10	0.84	1.28	1.82	1.87	0.71
<i>PSV</i>		43	49	55	52	58	57	52

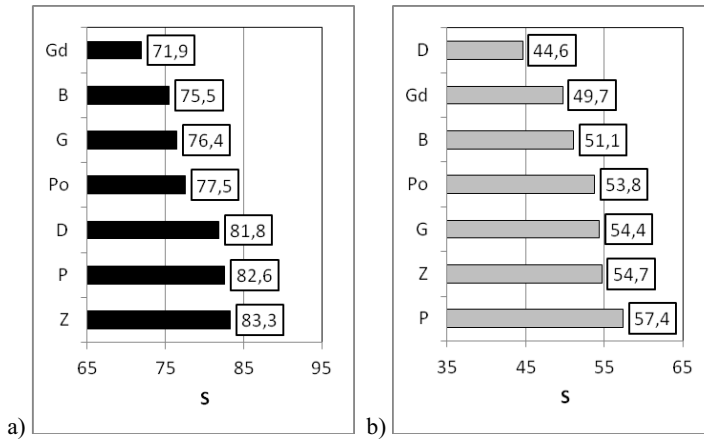


Fig. 1. Aggregates ranking for resistance to polishing based on *S* values a) before polishing
b) after the 2nd stage

In Poland, according to the requirements for the wearing course subjected to heavy traffic coarse aggregates with their $PSV \geq 50$ (asphalt pavements), $PSV \geq 53$ (concrete pavements) can be applied. It should be noted there are not many aggregate deposits which satisfy both *PSV* and another physical properties. Aggregates with high *PSV* are recommended for locations especially exposed to slippery conditions such as intersections, crossroads, roundabouts, junctions etc. That is why such aggregates should be rationally used in road construction.

However, it is hard to explain phenomena which occurs on the grain surface based only on *S* or *PSV* results. This requires insight into the phenomena which occurs on the surface of the particular grains. It means the thorough knowledge of the polishing process related to the aggregates made from rocks with different origin and petrographic characteristics is indispensable.

One of the theories of polishing (the wear-deformation theory) mentions wearing of microscopic protrusions on the surface of grains as a result of abrasion caused by car tires combined with spatial deformation of crystalline structure of minerals [8]. Dahir and Mulle explained the phenomenon of polishing of stone materials on the basis of the content of minerals in the rock and their hardness. Tourenq and Fourmaintraux proved that the presence of minerals of varied hardness in the rock results in varied microtexture of grain surface and greater resistance to polishing [1, 12]. In France a model was developed which describes skid resistance to get a better understanding of the influence of the polishing process on the evolution of surface texture. The model was based on the description of geometry of microtexture on the grain surface [2, 3]. In other studies the analyses of microtexture were conducted on the basis of microscope images of aggregate [5, 10, 14]. Dunford et al. showed that the use of three-dimensional surface measurement of aggregate profile ensures accurate analysis of changes in microtexture of aggregates in the polishing process [4].

The advances in opto-electronic and computer technology were accompanied by the advances of surface analysis based on the computer processing of digital images. Many methods are applied in fields such as metallography, crystallography, tribology, geology, medicine [7,13,15]. In the last decades the image analysis method has been often used to characterize the morphology of coarse aggregates [4, 5, 16].

In this paper the possibility of using digital images for understanding reasons of changes occurring on grain surface of aggregates in polishing process is presented.

2. PROGRAM RESEARCH

Images of the aggregate surface were taken with the optical microscope in the reflection mode before polishing (0 h), after the 1st stage (after 3 h) and after the 2nd stage of polishing (after 6 h). Dolomite, granodiorite, gabbro, postglacial, quartz sandstone, steelmaking slag and basalt were taken for investigation. The results of S values and PSV were previously presented (Table 1). Four specimens of each aggregate were prepared. Polishing process was simulated according to the standard PN-EN 1097-8:2009 [17]. The 30 images (3.2 x magnifications) from randomly selected locations were taken for each of the specimen. Specimen surfaces were registered using a CCD camera under controlled lighting conditions.

The images of aggregates from the optical microscope are raster images having a finite set of digital values, called pixels. Each image contains a fixed number of rows and columns of pixels. Such image may be subject to digital image processing. Primary goal of this processing is to improve its

visual quality and obtain quantitative information (image analysis). Image analysis involves the determination of numerical descriptors calculated on the basis of various statistical characteristics for a set of pixels that make up digital images. Modern technology includes many tools for image processing and analysis. Most descriptions are used by a statistical method. Each of the pixels in an image holds quantized values which represent the brightness of a given grey level at any specific point. A statistical distribution of brightness of pixels is described as a histogram of intensities. This histogram is a graph showing the number of pixels in an image at each different intensity value found in that image. In our case the image was saved in an 8-bit grayscale image. They were characterized by 256 different possible intensities, and so the histogram graphically displayed 256 numbers showing the distribution of pixels amongst those grayscale values. Grayscale variations represent local surface-relief variations. The value of the σ_h parameter from the histogram of intensities was assumed as a measure of microtexture (Fig. 2).

3. RESULTS AND ANALYSIS

Median, the lower and the upper quartile, minimum and maximum calculated by the given data set of the σ_h parameter of particular aggregates were presented in Fig 3.

Non-parametric Friedman test was used to check if on the accepted significance level $\alpha = 0,05$ significant differences between mean of the σ_h parameter registered for the given aggregate in the polishing stages have occurred. The results are presented in Table 2.

In the case of dolomite, granodiorite, gabbro, postglacial, steelmaking slag, basalt $p = 0.00$ is lower than the chosen significance level $\alpha = 0.05$. It means that there is a statistically significant difference between the σ_h parameter on the particular stages of polishing. There are no basis to reject the H_0 hypothesis only for quartz sandstone ($p = 0.08$).

The highest the σ_h parameter before polishing had holocrystalline aggregates (gabbro and granodiorite), the lowest – steelmaking slag and hypocrytalline (basalt). Images analyzed showed that irregularities on the surface which resulted from natural fracture, which is typical for the given rock type (Fig. 4, Fig. 5). Percentage change of the σ_h parameter between the particular stages of polishing show certain trends related to the petrographic characteristics of the material (Table 3).

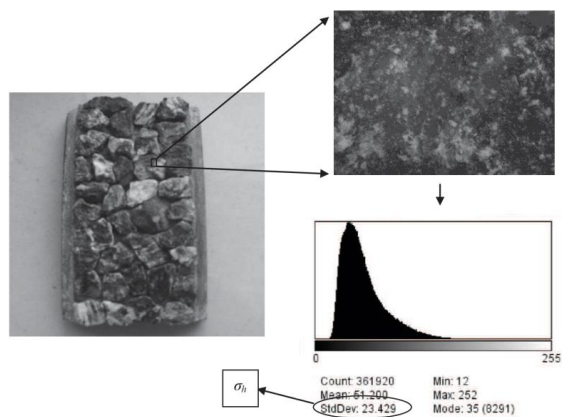


Fig. 2. Exemplary specimen of the aggregate (gabbro), its surface digital image and its grey level histogram

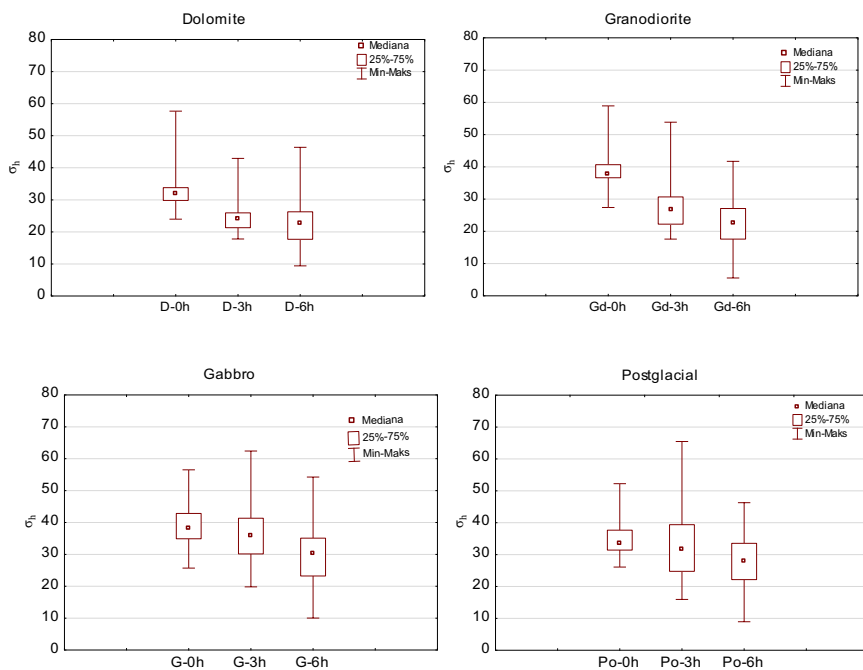


Fig. 3. Summary statistics in particular stages of polishing

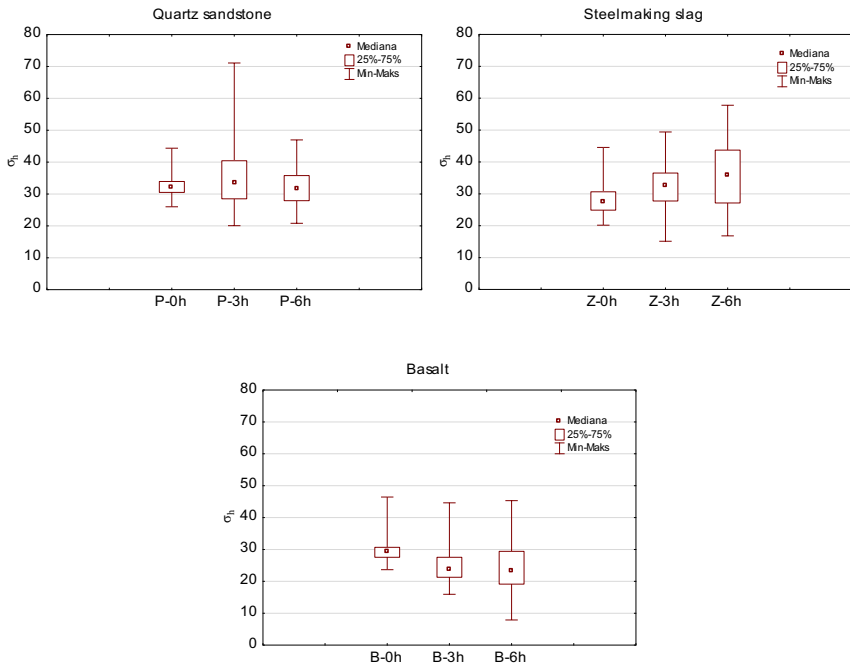


Fig. 3. Summary statistics in particular stages of polishing - continued

Table 2. Friedman test results

Stage:	Mean rank	Rank sums	Mean the σ_h parameter	STD	χ^2 ANOVA (2; 120)	p
Dolomite						
Before polishing	2.91	349.00	32.09	3.99	149.72	0.00
After the 1st stage	1.62	194.00	24.29	4.10		
After the 2nd stage	1.48	177.00	22.55	6.71		
Granodiorite						
Before polishing	2.85	342.00	38.24	3.78	137.40	0.00
After the 1st stage	1.75	210.00	27.89	7.87		
After the 2nd stage	1.40	168.00	23.09	7.39		
Gabbro						
Before polishing	2.42	290.00	38.95	5.85	54.07	0.00
After the 1st stage	2.10	252.00	37.01	9.39		
After the 2nd stage	1.48	178.00	29.82	8.57		
Postglacial						
Before polishing	2.29	275.00	34.53	4.55	26.15	0.00
After the 1st stage	2.07	248.00	32.74	9.78		
After the 2nd stage	1.64	197.00	28.31	7.45		

Table 2. Friedman test results - continued

Stage:	Mean rank	Rank sums	Mean the σ_h parameter	STD	χ^2 ANOVA (2; 120)	p
Quartz sandstone						
Before polishing	1.98	238.00	32.48	2.88	4.87	0.08
After the 1st stage	2.15	258.00	35.14	10.25		
After the 2nd stage	1.87	224.00	31.56	5.23		
Steelmaking slag						
Before polishing	1.64	197.00	28.36	4.67	27.12	0.00
After the 1st stage	2.05	246.00	31.85	6.81		
After the 2nd stage	2.31	277.00	35.51	10.26		
Basalt						
Before polishing	2.49	299.00	29.54	3.27	43.52	0.00
After the 1st stage	1.75	210.00	25.27	5.78		
After the 2nd stage	1.76	211.00	24.24	7.22		

Table 3. Percentage change of mean values of the σ_h parameter in particular stages of polishing

Aggregate	Between before polishing and 1 st stage	Between the 1 st and 2 nd stage	Between before polishing and 2 nd stage
Dolomite	24.3	8.2	29.7
Granodiorite	27.1	17.2	39.6
Gabbro	50	19.4	23.4
Postglacial	5.2	13.5	18.0
Quartz sandstone	-8.2	10.2	2.8
Steelmaking slag	-12.3	-11.5	-25.2
Basalt	14.5	4.1	17.9

The highest decrease of the σ_h parameter after 1st stage was registered for dolomite, granodiorite and basalt. It testifies that they are more prone to polishing in the 1st stage which favors abrasion of the surface more than in the 2st stage conditions. This behavior is typical particularly for monomineral rock (dolomite and basalt) and aggregate built from minerals with similar hardness (granodiorite). On the basis of observations of images from these aggregates it was noticed that the grain surfaces were polished and edges of some minerals changed their original appearance (Fig. 6). In the case of gabbro and postglacial the slight decrease of the σ_h parameter after the 1st stage indicates that a process of abrasion of microscopic protrusions and slight changes in the crystalline structure of the surface occur. Typical matte (without gloss) appearance was observed on their surface (Fig. 7). Postglacial aggregate is composed of 60% igneous and metamorphic rocks (granite, gneiss, granodiorite) and of 40% sedimentary rocks (sandstones, limestones and dolomites) which results in different susceptibility to polishing factors.

Basalt and dolomite are aggregates which are easier to polish and probably their surface was polished as a result of big differences in crystalline structure – very gloss surface (Fig. 8), as early

as in the 1st stage of polishing. In the 2nd stage, when fine emery was used, not many changes occurred. In the 2nd stage the highest changes in the values of the σ_h parameter were noted for aggregates on the surface of which process of abrasion in the 1st stage (gabbro, postglacial) underwent. Surface of two holocrystalline rocks (gabbro and granodiorite) were compared. Granodiorite had glossy surface which means that material is very prone to polishing. But only some parts of gabbro surface were glossy (Fig. 9).

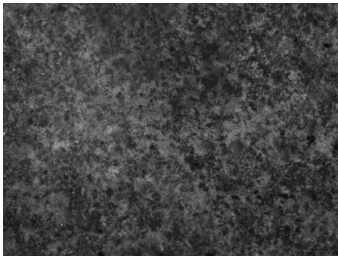


Fig. 4. Dolomite before polishing

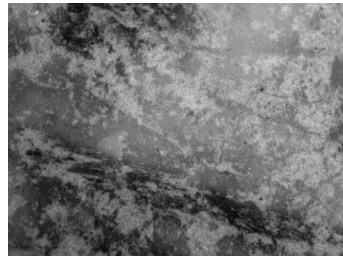


Fig. 5. Gabbro before polishing

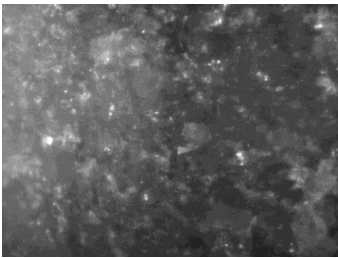


Fig. 6. Dolomite after 1st polishing

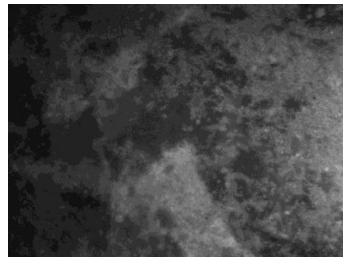


Fig. 7. Gabbro after 1st polishing

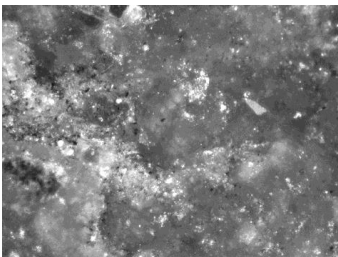


Fig. 8. Dolomite after 2nd Polishing

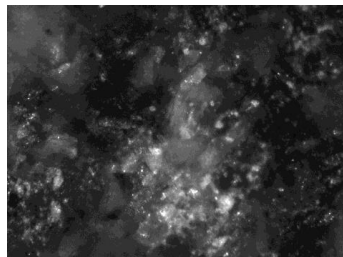


Fig. 9. Gabbro after 2nd polishing

When dolomite, gronodiorite, gabbro, postglacial, basalt were tested decrease of the σ_h parameter was registered steelmaking slag and quartz sandstone behaved otherwise.

The surface of quartz sandstone grains acted differently. In the case of this material the images indicate that polishing occurs only on the surface of quartz grains after the 2nd stage. The 1st stage extraction of quartz grains from soft mastic occurred. It was followed by regeneration in 2nd stage (Fig. 10). However, in the 2nd stage polishing affected only the surfaces of quartz grains (Fig. 11). This confirms that changes which result from wearing of microscopic protrusions occur on their surface.



Fig. 10. Quartz sandstone before polishing

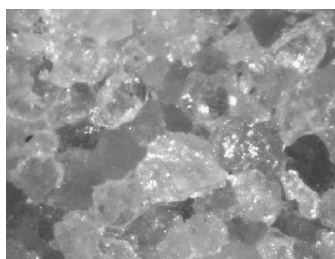


Fig. 11. Quartz sandstone after the 2st stage

In case of the aggregate grains from steelmaking slag there was no decrease of the σ_h parameter neither after the 1st nor after the 2nd stage of polishing. It means that the microtexture underwent regeneration after polishing. The surfaces of steelmaking slag grains after polishing displayed the features of polished surface, with its typical gloss and they also resembled surfaces before starting the process of polishing. Some aggregate grains displayed smooth surface during polishing, while after the following hours of polishing the same grains displayed significant roughness (Fig.12-15).

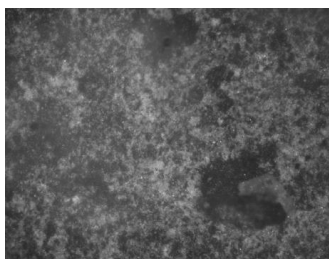


Fig. 12. Steelmaking slag before polishing

– smooth surface



Fig. 13. Steelmaking slag before polishing

– roughness surface

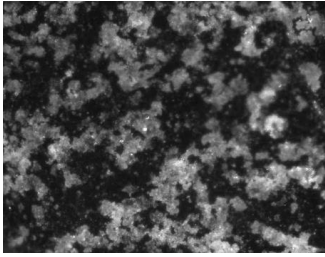


Fig. 14. Steelmaking slag after the 2st stage
– smooth surface with gloss

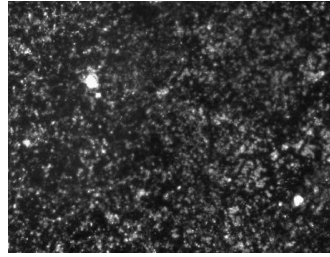


Fig. 15. Steelmaking slag after the 2st stage
– roughness surface

The results of the analysis are consistent with some theoretical types of polish resistance which were proposed by Hosking [8]. On this basis it may be stated that the low polishing resistance of dolomite, granodiorite, basalt is due to the mineral composition minerals with similar hardness. Gabbro and postglacial are composed of different minerals and they are more resistant to polishing. Hosking also describes aggregates with high polishing resistance, these porous materials like steelmaking slag or with sandstorm structure of rocks like sandstone. But only microscope images allow proving that these rocks have the additional ability to regeneration their microtexture.

4. CONCLUSIONS

The investigations of resistance to polishing were conducted on seven aggregates. On the basis of non-parameter Friedman significance test it was found that the σ_h parameter determined on the basis of the histogram of intensities from digital images can be used to describe the changes of microtexture in the process of polishing.

The analysis of the σ_h parameter shows a diverse course of the changes on microtexture of aggregate depending on its type. Aggregates which included minerals of similar hardness (granodiorite, dolomite, basalt) are prone to polishing. Gabbro, postglacial and quartz sandstone are the best aggregates for wearing course. It should be note that different character of changes occurring on the surface of grains from steelmaking slag in comparison with the surface of natural aggregates. Image analysis showed that the aggregates tend to regenerate the microtexture.

It is very important information considering shortage of high *PSV* aggregates. Such aggregates as steelmaking slag or quartz sandstone should be built in road sections particularly subjected to polishing.

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OCENA ZMIAN MIKROTEKSTURY KRUSZYWA GRUBEGO PODCZAS SYMULOWANEGO POLEROWANIA

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Słowa kluczowe: kruszywo grube, mikrotekstura, PSV, analiza obrazu, histogram wzmocnień

STRESZCZENIE:

W rzeczywistych warunkach ruchu, pod wpływem opon samochodowych, drobnych zanieczyszczeń oraz wody, zachodzi zjawisko polerowania wystających ziaren kruszywa, przyczyniając się do śliskości nawierzchni drogowych. W czasie polerowania ich powierzchnia ulega zmianom w zależności od składu petrograficznego, twardości minerałów, tekstury, struktury, porowatości i stopnia zwiertzenia skały. Miarą odporności na polerowanie kruszywa grubego stosowanego do warstwy ścieralnej nawierzchni drogowych jest wskaźnik polerowalności *PSV* (Polished Stone Value). Na jego podstawie trudno jest jednak oceniać zachowanie się kruszywa w procesie polerowania, gdyż wymaga to poznania zjawisk zachodzących na powierzchni poszczególnych ziaren.

W literaturze są prezentowane różne teorie dotyczące oceny zmian zachodzących na powierzchni ziaren pod działaniem kół pojazdów samochodowych. Opisują one ścieranie się mikroskopijnych protuzji na powierzchni ziarna w powiązaniu z deformacją przestrzenną sieci krystalicznej minerałów. Wraz z rozwojem technologii optoelektronicznej i komputerowej rozwinęły się metody analizy powierzchni bazujące na komputerowym przetwarzaniu obrazów cyfrowych.

Celem artykułu jest ocena zmian mikrotekstury powierzchni ziaren kruszywa grubego w procesie polerowania w oparciu o obrazy wykonane pod mikroskopem optycznym.

Do badań wytypowano kruszywo dolomitowe, granodiorytowe, gabrowe, polodowcowe, z piaskowca kwarcytowego, z żuźla stalowniczego i bazaltowe. Wykonano po cztery próbki analityczne, które polerowano zgodnie z normą PN-EN 1097-8:2009. Proces polerowania trwał 6 godzin z podziałem na I fazę ze ścierniwem korundowym frakcji 300/600 μm i wodą oraz II fazę z proszkiem korundowym frakcji mniejszej od 53 μm i wodą. Zarówno przed polerowaniem i po każdej fazie polerowania na każdej próbce w losowo wybranych miejscach wykonywano po 30 obrazów powierzchni ziaren kruszyw pod mikroskopem optycznym w powiększeniu $\times 3.2$. Za miarę mikrotekstury przyjęto wartość odchylenia standardowego σ_n , odczytaną z histogramu wzmocnień dla obrazu cyfrowego badanej powierzchni.

Analiza wyników w oparciu o nieparametryczny test Friedmana wykazała, że istnieją statystycznie istotne różnice pomiędzy średnimi wartościami parametru σ_n z histogramów wzmocnień, ustalonymi na tych samych kruszywach w poszczególnych etapach polerowania. Oznacza to, że w procesie polerowania następują istotne zmiany w mikroteksturze na powierzchni kruszywa grubego. Są one uzależnione od charakterystyki petrograficznej skały z której kruszywo zostało wyprodukowane. Ważną rolę odgrywa przy tym twardość minerałów. Wykazano, że kruszywa wyprodukowane ze skał, które są zbudowane z minerałów o zbliżonej twardości (dolomit, granodioryt) lub skał o strukturze skrytokrystalicznej (bazalt) bardzo łatwo poddają się czynnikiem polerującym. Na ich powierzchni dochodzi

do istotnej deformacji sieci krystalograficznej już w I fazie oznaczenia (przy użyciu grubego ścierniwa i wody). Natomiast powierzchnia kruszywa zbudowanego ze skały o zróżnicowanej twardości minerałów (gabro) pod wpływem grubego ścierniwa i wody ulega jedynie ścieraniu. Dopiero materiały polerujące takie, jak: mączka korundowa i woda, dozowane w II fazie, przyczyniają się do deformacji sieci krystalograficznej niektórych obszarów minerałów.

Na podstawie analizy obrazów udowodniono, że piaskowiec kwarcytowy i żużel stalowniczy mają zdolności do regeneracji mikrotekstury podczas symulacji procesu polerowania. Takie kruszywa są szczególnie pożądane do zastosowania do warstwy ścieralnej w obszarach takich, jak: skrzyżowania, łącznice drogowe, pasy włączeń i wyłączeń. Wyniki badań potwierdziły, że z punktu widzenia odporności na polerowanie bardzo dobrym materiałem są kruszywa z piaskowca kwarcytowego, żużła stalowniczego oraz gabra, a gorszym materiałem - kruszywa z dolomitu i granodiorytu.