GOSPODARKA SUROWCAMI MINERALNYMI

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The influence of joints and micro-fractures on the limestone aggregate shape and quality

Introduction

Rock divides naturally into blocks along parallel surfaces of discontinuity caused by different factors e.g.: sedimentation processes, thermal changes and tectonic stress. Zones of weakness manifest as visible fractures or remain as latent structures in the rock (Price 1959; Hencher, Knipe 2007). It was assumed that exertion of additional pressure on a stone causes forming of the fractures in macro- and microscale which have an orientation similar to the natural joint system. In practice this process can be initiated by a blasting in quarry, crushing during aggregate production, atmospheric agents and pressure impact on the aggregate grains used in road or railway tracks.

This thesis was indirectly proved by Bromowicz (2000, 2002). His investigation revealed that in some cases mechanical properties of a stone worsen significantly as a result of the process of the aggregate production. The comparison of parameters of original and crushed material in different fractions showed growth of the water absorption and reduction of the apparent density. Petrological characteristic and rock genesis are mentioned together with production conditions as the main factors affecting the aggregate shape by Smith & Collis (1993). Kieslinger (1960), Bromowicz & Karwacki (1976), Grześkowiak & Modrzejewski (2002) and Jern (2004) reported problem of influence of residual stresses in dimension stones on their properties. Given the rise in aggregate demand in recent years (Kozioł et al. 2008) one should take into account the appropriate quality of material.

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The aim of this paper was to estimate the influence of residual stress and fracture appearing on the properties of crushed aggregates. The relation between joint system observed in a quarry and aggregate shape was a subject of special concern.

1. Subject of the study

The phenomenon of appearance of originally invisible fractures has been analysed during the research on Jurassic limestone from the Nielepice deposit, also known as *Młynka,* located ca. 20 km west of Kraków (Fig. 1). The Nielepice deposit is located in the southern part of the Kraków–Wieluń Upland, in the southern slope of the Krzeszowice Graben. The Upper Jurassic limestone is represented there by three lithofacies: massive (dominating), bedded and platy limestone (Dżułyński 1951; Matyszkiewicz 1997).

The investigations were carried out within two sites of the bedded limestone (quarry level I and III) and in one site of the platy limestone recorded only in the lowest part of the quarry (level IV) (Fig. 2). The term "site" describes an outcrop of 6–10 m in height and 40–50 m in width within one level.

Beds of limestone are ca. 0.5–2 m in thick. In two lower sites (level III and IV) they are intercalated with thin (1–5 cm) marly layers. The limestone is generally pelitic and light, grey

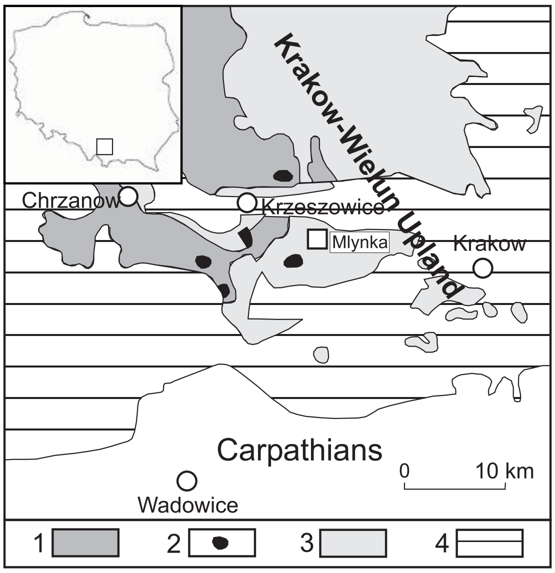

Fig. 1. Location of the Młynka (Nielepice) quarry (square) on a geological sketch map
1 – pre-Jurassic sedimentary rocks; 2 – Permo–Carbonian volcanic rocks; 3 – Jurassic; 4 – post-Jurassic (based on Gradziński 1993, simplified)

Rys. 1. Lokalizacja kamieniołomu Młynka (Nielepice) na szkicu geologicznym
1 – przedjurajskie skały osadowe, 2 – permo-karbońskie skały wulkaniczne, 3 – skały jurajskie, 4 – osady młodsze od jury; kwadrat – lokalizacja kamieniołomu (wg Gradziński 1993, uproszczona)

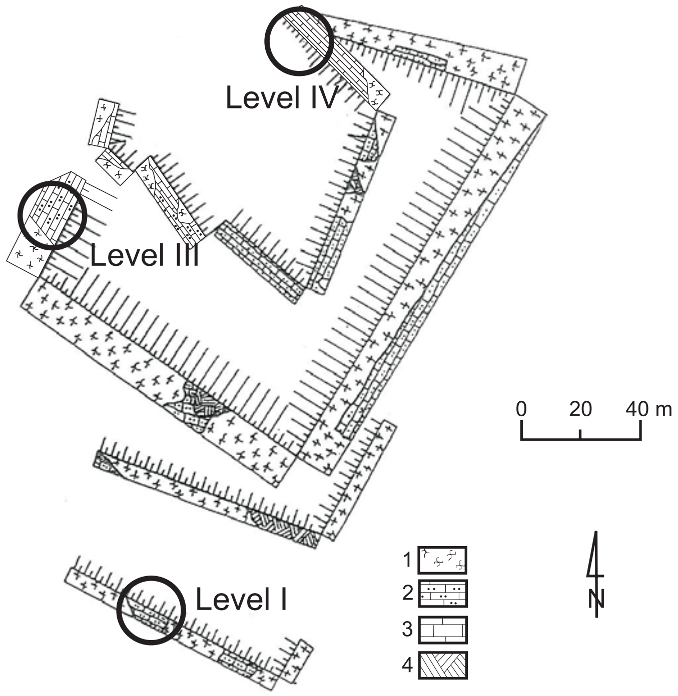

Fig. 2. Map of the Nielepice quarry with location of investigation sites (circles)
1 – massive limestone; 2 – bedded limestone; 3 – platy limestone; 4 – rock debris
(after Bromowicz 2001, modified)

Rys. 2. Zarys kamieniołomu Nielepice z lokalizacją punktów badań i pobrania prób (kółka)
1 – wapienie skaliste; 2 – wapienie uławicone; 3 – wapienie płytowe; 4 – rumosz skalny
(wg Bromowicz 2001, zmienione)

and beige in colour. Bioclasts of 2 mm to a few cm in size (the biggest are in level I) are visible on a rock surface. Peloids, bioclasts and intraclasts, sometimes grains of detritic quartz and concentrations of opal or pyrite are visible in limestone from all levels in the microscope.

Peloids with micrite matrix are the most numerous components of the specimens from level III and level IV (Fig. 3). Bioclasts (mainly sponges and brachiopods) and intraclasts are unevenly distributed among them. The amount of bioclast (generally not identifiable) is lower in platy limestone from the level IV. All listed components are bound together with micrite matrix and seldom calcite crystals. The rocks represent intra-bio-micrite limestone, locally pelmicrite (according to Folk 1959), generally a packstone (according to Wright 1992). Therefore, the platy limestones represent more homogeneous rocks than the bedded ones.

Limestone with dominating rounded intraclasts and large amount of ooids with visible signs of micritization, small oncoids and tuberoids has been observed in the level I. Unevenly distributed allochemical components (bigger than in level III and IV) are bound together by

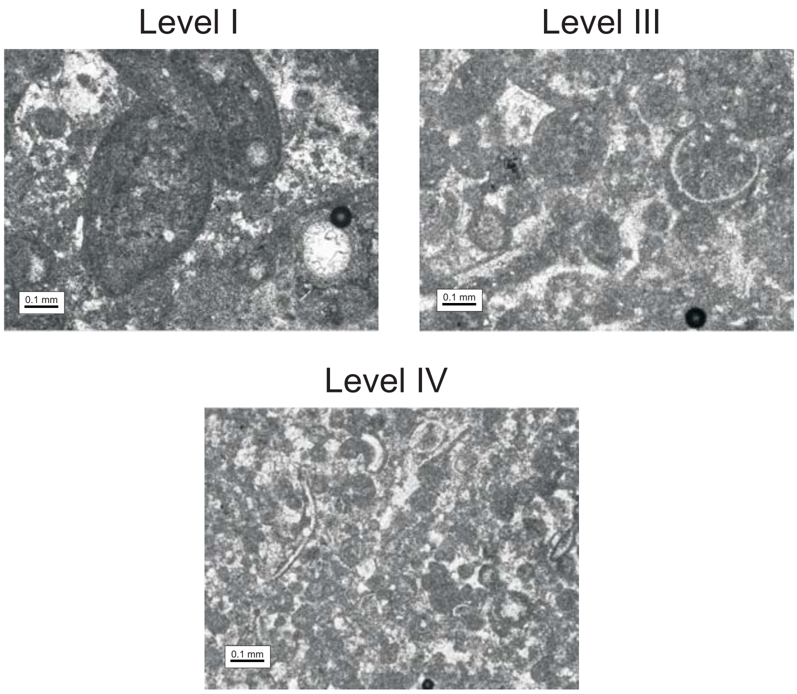

Fig. 3. Limestones from the Nielepice quarry (microphotographs)

Rys. 3. Wapienie z Nielepic (obrazy mikroskopowe)

micro-spar calcite cement with a predominance over micro-matrix. According to Folk classification these rocks represent mainly intra-bio-sparite limestones, and according to Wright classification – they are generally of wackstone type, locally packstone (Folk 1959; Wright 1992) (Fig. 3). They can be also named detrital limestones.

2. Methods

Measurement of joints orientation accompanied by sampling was the first stage of investigations. Cuboids (15 × 5 × 5 cm in size) were cut from the fresh samples. They were spatially oriented in order to retain spatial relationships between field and lab measurements. Cuboids were nextly subjected to changing pressure (not attaining average crushing critical value estimated for the deposit) and to 35 cycles of freezing and thawing. Some samples were subjected to a continuous stress (ca. 20 MPa) lasting 30 sec. They were pressed mainly in one direction, because of an anisotropic structure of material, especially expressed perpendicularly to the bedding. The exception was limestone from level III where fractures parallel to the joint set B emerged as the most visible in macroscopic observations. The process of rock fatigue by uniaxial stress was continued to the sample destruction. The proposed method of sample fatigue was aimed at provoking new fractures and rock disintegration in long term.

Freezing-thawing test of other part of rock gave the possibility to achieve multidirectional stress. Water soaked samples were freezed during 12 hours at a temperature of –21°C and thawed in water at 20°C during 8 hours. The procedure was repeated 35 times.

Thin sections cut perpendicularly to the directions of the main joint sets were used to describe the nature of fatigue in the rock. The technique of impregnation with blue resin was applied. The relations between joint orientation recorded in quarry and micro-fractures orientation stated in thin sections are presented in the paper. The fatigue degree has been taken into consideration.

Change of the rock quality was determined by measurements of apparent density and water absorption conducted on fresh samples. The latter was determined once again at the end of the tests.

Measurements of the velocity of longitudinal ultrasonic waves perpendicular to the main joint sets were performed for the oriented samples subjected to every 5 subsequent phases of uniaxial stressing or freeze-thaw cycles. The aim of these investigations was to estimate a speed of changes that develop in the rock as an effect of the forming of new fractures. Details of this method and examples of its application can be found in numerous papers (e.g. Pinińska & Płatek 2002; Domonik 2003). The authors published preliminary results of investigations of the changes of the velocity of ultrasonic waves for the Nielepice (Bromowicz & Figarska-Warchoł 2008).

Rock samples have been crushed in a laboratory jaw crusher. Shape of the grains of various fractions has been analysed separately. Three diameters of each grain (the longest – a, the shortest – c and intermediate – b) were measured by a caliper and elongation and flatness ratios: b/a and c/b were calculated. The results were presented on the Zingg diagram (Zingg 1935). The limits for elongation and flatness are 0.66 in this scheme. These limits divide up a plot of elongation vs flatness ratios into four fields intended for: equidimensional (cuboidal) grains in the right, top corner, elongated grains in the right, bottom corner, flat grains in the left, top corner and bladed (both flaky, and elongated) grains in the biggest square. Elongated grains with the elongation ratio below 0.33 can be named as "very elongated". Similarly flat grains with flatness ratio below 0.33 can be named as „very flaky".

The shape of grains of crushed limestone has been compared to the shape of a "elementary fracture cell" – the smallest possible elementary cell of the rock enclosed by joint surfaces (after Dadlez, Jaroszewski 1994). Dihedral angles of aggregate grains have been measured for material from site in level IV. Only flat grains of quadrilateral shapes of the biggest cross section have been selected for analysis from each fraction. Measurements have been done on digital images of the grains. Similarity of the distributions for individual fractions were tested with the Kolmogorov–Smirnov test (Draper & Smith 1973).

3. Results

3.1. Joint orientation

Joint system orientation was determined on the basis of 186 measurements made in three investigated sites in the quarry. Orthogonal joint system with average orientation of planes for all levels: A – 32/90, B – 307/90 and C – 180/4 (near-horizontal) and two more sets: almost vertical (256/87) and oblique (21/45) exist in the deposit. There are differences among the orientation of the joint systems within levels (Fig. 4).

The most regular joint system cuts the platy limestone in the level IV. It consists of two main sets: vertical A and B, with the most frequent azimuths of dip of, respectively, ca. 37°, ca. 311° almost perpendicular to each other, and set C with a dip of ca. 9° towards ESE (ca. 138°). These three joint sets form basic orthogonal joint system. Local maxima of the orientation distribution of the joints indicate that the joint system is complex and consists of more than three joint sets in fact. The joints are clearly visible along the whole wall as straight lines.

Joint system of bedded limestone in the level III is the most irregular (Fig. 4). Azimuths of dips of main sets of vertical joints A and B are, respectively, ca. 31° and ca. 319°. Set C (poorly visible) dips at ca. 9° towards WNW. Joint lines visible in the wall are not straight in most of cases.

The joint system in the level I is similar to the others, but slight less regular than in the platy limestone. Vertical sets A and B with average dip azimuths of, respectively, ca. 34° and ca. 310° are clearly marked in the wall. Almost horizontal set C, which is not clearly visible, reveals tendency to dipping towards SW.

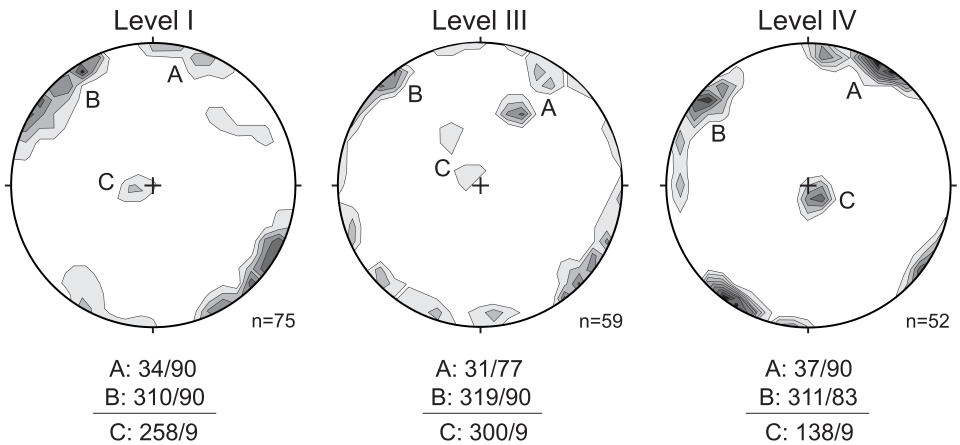

Fig. 4. Diagrams of the orientation of joint sets A, B and C with dip azimuth/dip in limestones from the Nielepice quarry (n – number of measurements)

Rys. 4. Diagramy orientacji zespołów płaszczyzn podzielności A, B i C w wapieniach z kamieniołomu Nielepice (orientacja podana jako azymut kierunku zapadania/upad, n – liczba pomiarów)

3.2. Laboratory tests

3.2.1. Micro-fractures

Microscopic observations of fresh rock from the level IV revealed only one fracture parallel to the horizontal joint set. No other signs of material weakness which could cause rock cracking were noticed. The micro-crack elongates almost straight, 0.03–1 mm wide, with smooth borders, fitted to the shape of grain components of rock. Locally, calcite crystals grow on the fracture sides. Freezing-thawing process provoked numerous fractures parallel to the horizontal joint set (C), visible in macro- and microscale (Fig. 5). Fractures observed in thin sections occur in bunches. Fine fractures (ca. 0.01–0.03 mm wide and 0.1–5.0 mm distant one from another) connect together creating wide crack (0.06 mm). The fractures adjust to the shape of micrite peloids and crystalline bioclasts or rarely cut them. The zone of fractures parallel to the joint set B was also observed (Fig. 6). The zone reaches a width of ca. 1.3 mm whereas single fractures reach ca. 0.04 mm. Their course is generally rectilinear. Frequently discussed fractures cut components of the rock. Locally, transversal fractures adjusted to the shape of peloids and bioclasts together with the main cracks form the fracture net.

Small fractures parallel to the bedding filled with dark, ferro-argillaceous substance are visible in fresh limestone from the level III. They reach a width of ca. 0.01–0.05 mm and length of ca. 7 mm. They are fitted to shapes of peloids and intraclasts. Only one empty, linear fracture has been found in the analysed thin sections.

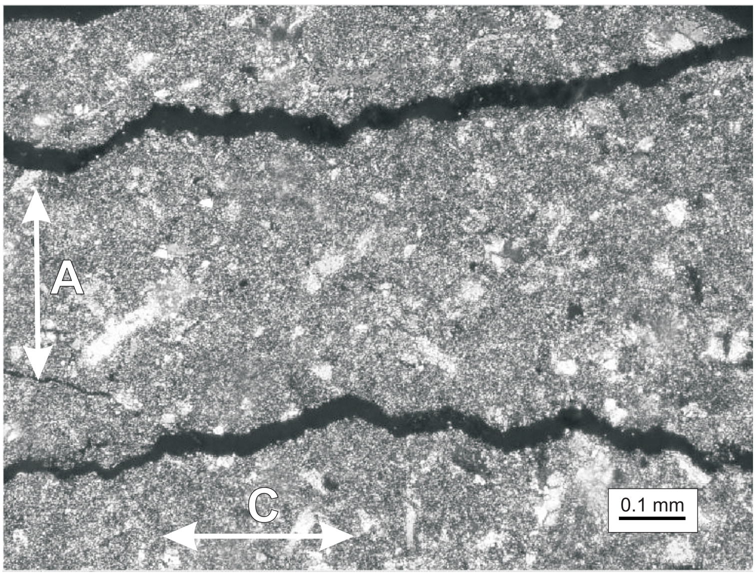

Fig. 5. Limestone from the Nielepice quarry (level IV). Microfractures. Arrows show directions of the joint sets A and C. Microphotograph

Rys. 5. Mikrospękania w wapieniu z Nielepic (poziom IV kamieniołomu) widoczne w zorientowanym przestrzennie szlifie mikroskopowym. Strzałki wskazują kierunki spękań zespołów A i C

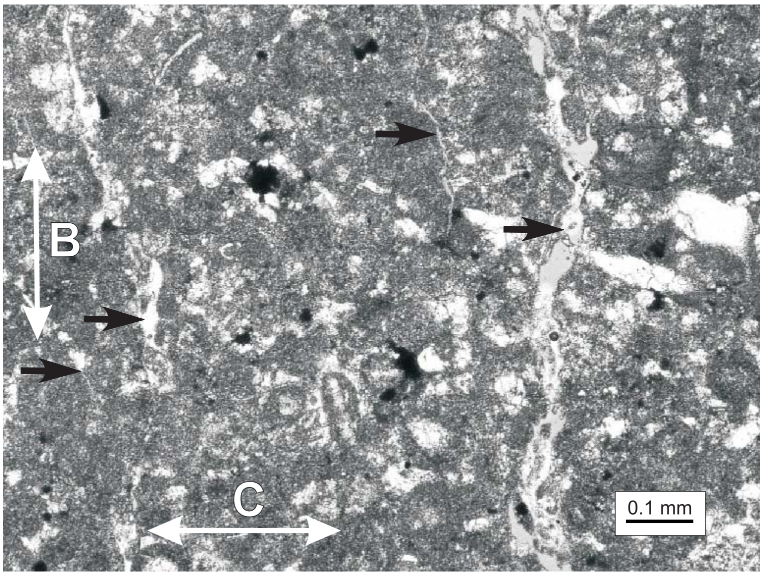

Fig. 6. Limestone from the Nielepice quarry (level IV). Microfractures (black arrows). White arrows show directions of the joint sets B and C. Microphotograph.

Rys. 6. Mikrospękania (czarne strzałki) w wapieniu z Nielepic (poziom IV kamieniołomu) widoczne w zorientowanym przestrzennie szlifie mikroskopowym. Białe strzałki wskazują kierunki spękań zespołów B i C

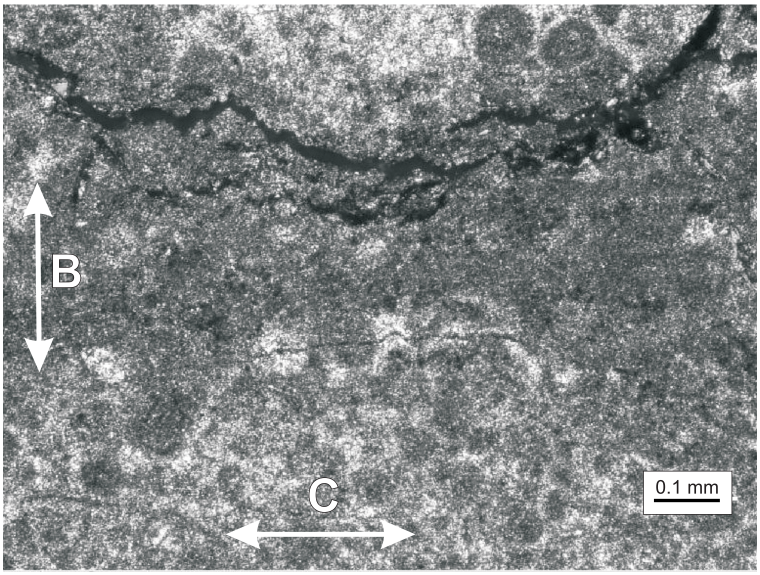

Fig. 7. Limestone from the Nielepice quarry (level I). Arrows show directions of the joint sets B and C. Microphotograph

Rys. 7. Mikrospękania w wapieniu z Nielepic (poziom I kamieniołomu) widoczne w zorientowanym przestrzennie szlifie mikroskopowym. Strzałki wskazują kierunki spękań zespołów B i C

In the fresh limestone from the highest (I) level fractures parallel mainly to the bedding can be observed. The fractures visible in macro- and microscale are mutually connected. The former are a few mm wide, while the latter, visible due to the blue resin application, are 0.03 mm wide. The observed fractures are similar to stylolites: they have jagged shape and filling of opaque minerals (iron oxide and hydroxides), clays and other dark components (e.g. organic matter) (Fig. 7). The micro-fractures course is definitely fitted to shapes of grains and micrite-sparite contacts. After 35 freeze-thaw cycles the number of fractures significantly increased. They form dense net, which surrounds individual limestone components, leading to the granular disintegration in some parts of the stone. This phenomenon is connected with the above-mentioned zones of fractures parallel to the joint set C. Course of the new cracks is not always adjusted to the contacts of the rock components.

3.2.2. Apparent density and water absorption

Apparent density of all the limestone samples of the quarry comprises in the range 2.48–2.60 Mg/m^3. Limestone from the level I reveals the highest values (average: 2.59 Mg/m^3). The others are lighter (average: ca. 2.51 Mg/m^3). The material fatigue caused significant growth of water absorption, especially in the platy limestone (level IV), which reveals the highest values (Fig. 8). The average for the fresh samples of this level is 3.9%

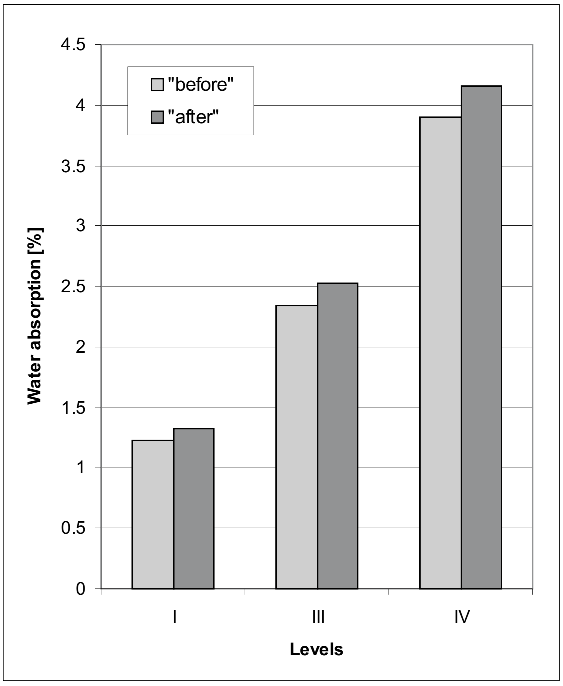

Fig. 8. Water absorption of limestone samples before and after fatigue process (Nielepice quarry)

Rys. 8. Nasiąkliwość wagowa próbek wapieni z Nielepic przed i po procesie męczenia whereas for the level III – 2.3%, and I – 1.2%. Provoking new fractures and widening of already existing brought to the water absorption growth by 0.1–0.25%.

3.2.3. Velocity of longitudinal ultrasonic waves

Shearing and destruction of some samples disabled a portion of tests of uniaxial stress. Apparently, the average value of subcritical stress estimated for the quarry was too high for single, fatigued samples. As a result, growing number of samples was eliminated after consecutive phases of the tests which were passed only by the samples of the most resistant rock. Therefore, ultrasonic waves velocity grew abnormally from the test phase to phase.

Graph (Fig. 9) shows the results of the testing of the limestone samples from the level III, pressured perpendicularly to the joint set B. The uniaxial stress initially caused growth of the waves velocity measured parallel to the stress direction. It is due to closing of existing fissures. In some cases clay filling squeezed from the cracks could be observed. The next phase of the rock compression led to opening new fractures parallel to the directions A and C, which are perpendicular to the stress direction and, therefore, more susceptible to cracking.

Results of freezing and thawing cycles of the limestone show more explicit picture of changes. The average velocity of ultrasonic waves for samples before fatigue from the level IV (platy limestone) was ca. 6–6.5 km/sec for directions perpendicular to the vertical joints (A and B) and ca. 5 km/sec, perpendicularly to the bedding (joint set C) (Fig. 10). After 35 cycles of freezing and thawing velocities decreased to 4 and 3 km/sec, respectively,

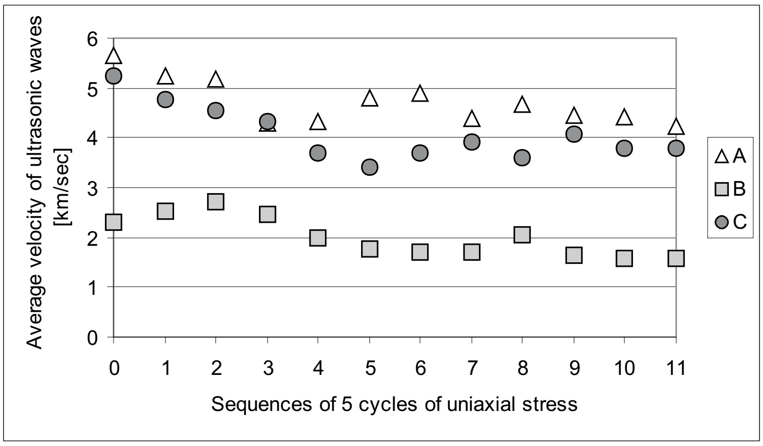

Fig. 9. Velocity of ultrasonic waves in samples subjected to uniaxial stress perpendicular to the joint set B. Limestone from the Nielepice quarry – level III

A, B, C – directions of propagation of ultrasonic waves perpendicular to the joint set A, B and C

Rys. 9. Prędkość podłużnych fal ultradźwiękowych w próbach wapieni z Nielepic (poziom III) poddanych jednoosiowemu ściskaniu prostopadle do spękań zespołu B

A, B, C – kierunki pomiaru prędkości fal mierzonych prostopadle do spękań zespołów A, B i C

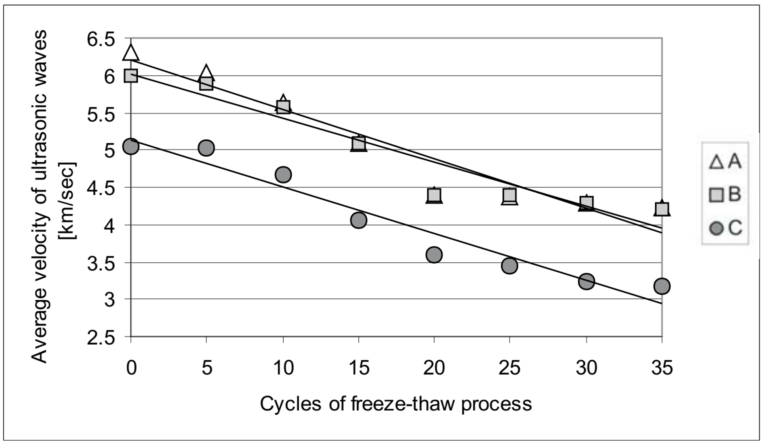

Fig. 10. Velocity of ultrasonic waves in samples subjected to repeated freeze-thaw cycles. Limestone from the level IV (For A, B and C – see explanation to fig. 9)

Rys. 10. Prędkość podłużnych fal ultradźwiękowych w próbach wapieni z Nielepic (poziom IV) poddanych wielokrotnym cyklom mrożenia i rozmrażania (A, B, C – jak na rys. 9)

as a result of the rock fatigue. Some samples crumbled during the test with the velocity ca. 2 km/sec. Gradients of the linear regression lines are similar to each other for velocities measured in different directions.

Changes of the velocity as well as the water absorption of the bedded limestone from the level III (Fig. 11) are smaller than these of the platy limestone. The average velocity of ultrasonic waves for the samples before fatigue was ca. 5.5 km/sec perpendicularly to

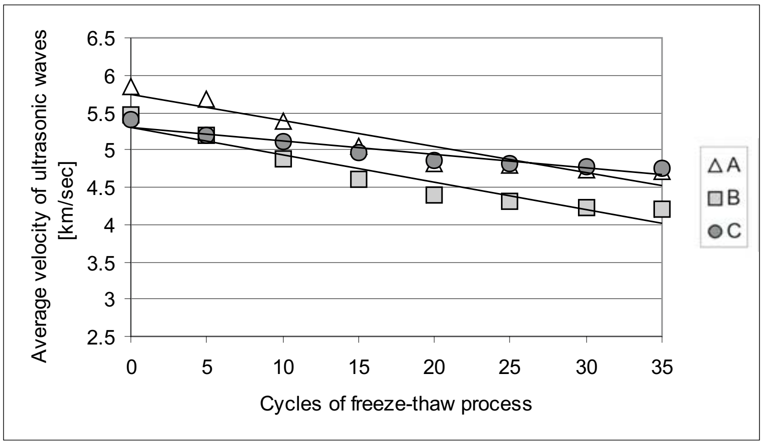

Fig. 11. Velocity of ultrasonic waves in samples subjected to repeated freeze-thaw cycles. Limestone from the level III. (For A, B and C – see explanation to fig. 9).

Rys. 11. Prędkość podłużnych fal ultradźwiękowych w próbach wapieni z Nielepic (poziom III) poddanych wielokrotnym cyklom mrożenia i rozmrażania. (A, B, C – jak na rys. 9)

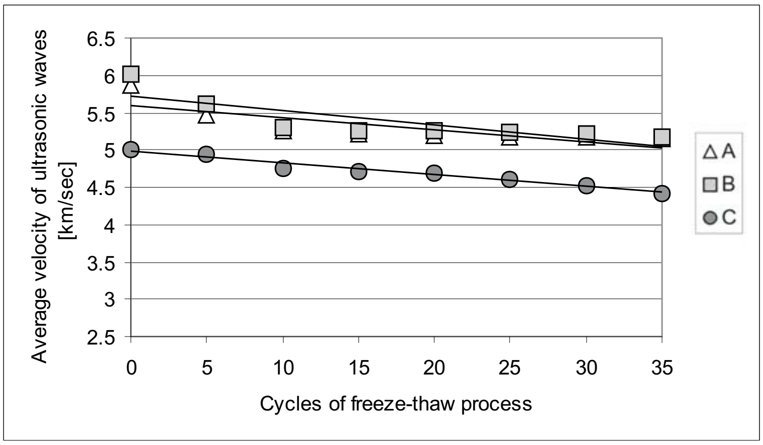

Fig. 12. Velocity of ultrasonic waves in samples subjected to repeated freeze-thaw cycles. Limestone from the level I (For A, B and C – see explanation to fig. 9)

Rys. 12. Prędkość podłużnych fal ultradźwiękowych w próbach wapieni z Nielepic (poziom I) poddanych wielokrotnym cyklom mrożenia i rozmrażania (A, B, C – jak na rys. 9)

the joint sets (B and C) and almost 6 km/sec perpendicularly to the joint set A. Fatigue process reduced the velocity to 4.7 km/sec for A and C directions and ca. 4.0 km/sec for B direction.

Velocity of the ultrasonic waves in the fresh limestone from the level I is ca. 5 km/sec for the direction perpendicular to the bedding and ca. 6 km/sec for direction perpendicular to vertical joint sets (Fig. 12). Freezing-thawing process weakens the samples and after 35 cycles velocities are 4.4 km/sec and 5.2 km/sec, respectively.

3.2.4. Shape of grains of crushed limestone: elongation and flatness ratios

Flat grains dominate in all fractions of the aggregate obtained from the limestone of the level I (Table 1). Their content (ca. 43%) is stable in all fractions. Frequently represented are bladed and isometric grains. However, the content of the latter drops significantly from 21.4% in the coarsest fraction (31.5–63 mm) to 6.9% in the finest (4–8 mm). Content of the elongated grains changes irregularly (10.7–20.7%). This aggregate gets, therefore, enriched in elongated grains towards finer fractions.

Similarly, the coarsest grains obtained from the limestone of level III are mostly flat (ca. 43%), while the finest – bladed (ca. 45%). Content of isometric grains changes irregularly in a range 6,7–18.1%. The number of elongated grains grows apparently towards finer fractions. There are more than 3% of very elongated grains (with elongation ratio < 0.3) in the finest fraction. It is the highest content of such grains in all analysed fractions and samples.

The flat grains prevail (up to 53.3% in fraction 31.5–63 mm) in the aggregate crushed from the limestone of the level IV in almost all fractions. Generally, content of the flat grains

TABLE 1

Content of grains of various shapes in fractions of aggregate made on the basis of Nielepice limestone

TABELA 1

Zawartość ziaren o różnych kształtach w poszczególnych frakcjach kruszywa łamanego z wapieni z Nielepic

		Shapes											
		elongated [%]			bladed [%]			flat [%]			isometric [%]		
		Level I	Level III	Level IV	Level I	Level III	Level IV	Level I	Level III	Level IV	Level I	Level III	Level IV
Fraction [mm]	63.0–31.5	10.7	10.8	15.6	25.0	37.8	15.6	42.9	43.2	53.3	21.4	8.1	15.6
	31.5–16.0	20.7	10.8	13.1	16.3	28.8	23.6	40.0	42.3	46.3	23.0	18.1	17.0
	16.0–8.0	20.7	20.2	13.4	20.0	33.4	30.2	43.4	37.9	45.6	15.9	8.5	10.7
	8.0–4.0	11.0	16.0	15.5	40.0	44.8	41.2	42.1	32.5	38.5	6.9	6.7	5.6

drops down towards finer fractions, except for the very flat grains. Content of the isometric grains falls down from 15.6% do 5.6%, contrary to the content of the bladed grains, which grows from 15.6% to 41,2%. Elongated grains are present in almost constant quantity (ca. 13–15%) in all fractions.

General tendency in changes of the grain shape is, therefore, similar to the tendency observed in the grains of level I and IV: from flat and isometric grains in coarse fraction to elongated grains in finer fractions.

Grains of the limestone from the level III have the most diversified shapes (the points are scattered on the diagram – Fig. 13) but, generally, are more elongated than other types of the limestone.

Generally, grains of the crushed aggregate from Nielepice are flat (especially from the level IV). The content of the flat grains decreases towards finer fraction in favor of bladed and (in the level III) elongated grains. Similarly, isometric grains are less frequent in finer fractions (several %) than in coarser ones (ca. 20%). Share of the very flat and very elongated grains grows in finer fractions.

3.2.5. Aggregate shape (dihedral angles of grains)

Measurements of dihedral angles of aggregate grains obtained from the limestone of the level IV have been made in the last phase of research. Limestone from this site was selected for its most regular joint system. The amount of flat grains of quadrilateral shapes of the biggest cross section decreased from ca. 90% in the coarsest fraction to ca. 50% in the finest. Such grains were a subject of further investigation.

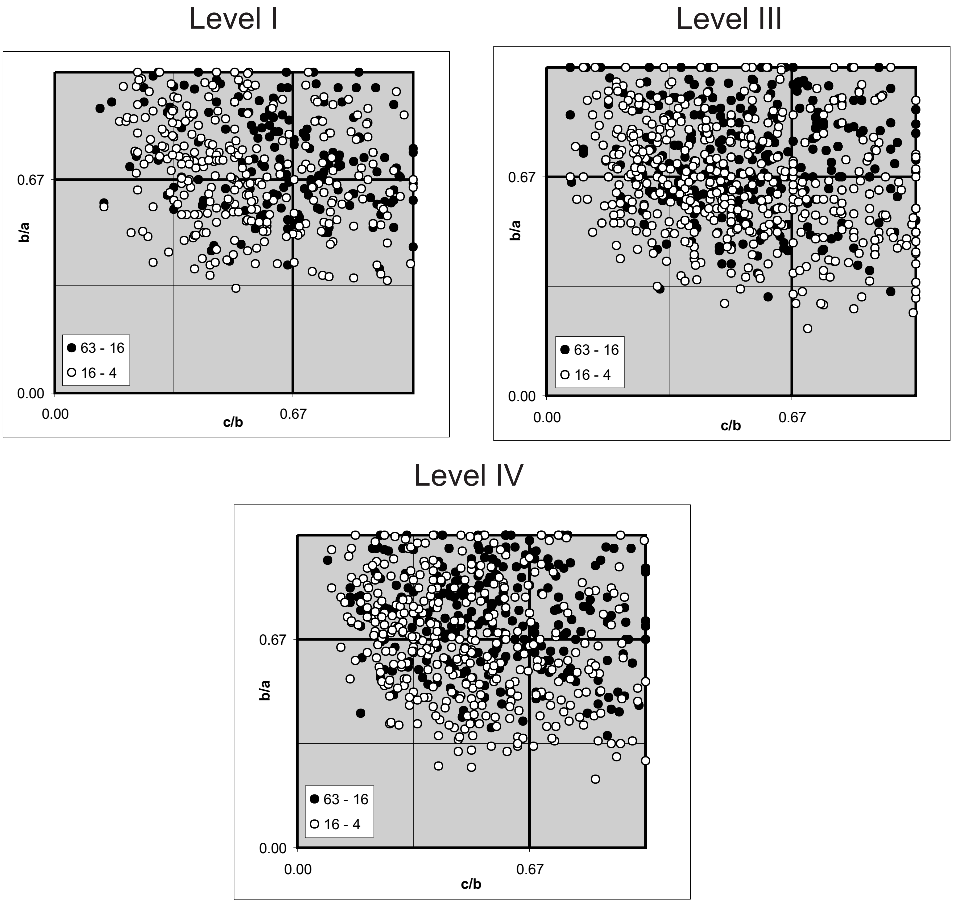

Fig. 13. Zingg diagrams of the grain shape (limestone aggregate from the Nielepice quarry) (fractions 4–16 mm and 16–63 mm)

Rys. 13. Diagramy Zingg'a – kształtu ziaren kruszywa łamanego z wapieni z Nielepic (frakcje 4–16 mm i 16–63 mm)

The results are presented on the histograms of relative frequency of the angle values (Fig. 14). As internal angles of quadrilaterals they can fall within a range of 0–180°. Measured values ranged from 13° to 157°. Their distribution is normal or nearly normal with an average ca. 90° and several local maxima: 44° and 135°, 51° and 128°, 60° and 119°, 64° and 116°, 75° and 105°, 79° and 101°, 82° and 98°, 84° and 96°, 86° and 94°, 87° and 93°, 88° and 92°, 89° and 91°. The above pairs of angle values sum to ca. 180°.

Approximated value of the Kolmogorov-Smirnov test for different fractions in all cases was greater than 0.05 pointed to the lack of statistically significant difference among the distributions at the confidence level of 95%. Neighbouring fractions revealed the biggest similarity of distributions. Local maxima of these fractions are also more similar than in extreme fractions.

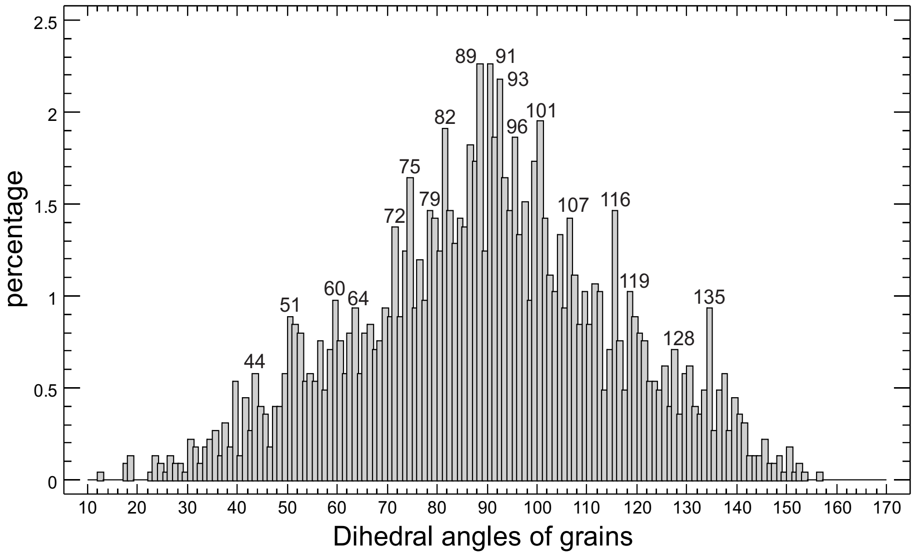

Fig. 14. Distribution of dihedral angles of aggregate grains for fraction 2–63 mm.
Platy limestone from the Nielepice quarry (level IV)

Rys. 14. Rozkład kątów dwuściennych ziaren kruszywa łamanego z wapieni płytowych z Nielepic (poziom IV) dla frakcji 2–63 mm

4. Discussion

The bedded limestone from the level I reveals higher values of the apparent density than other limestone types. This is probably due to a higher content of relatively rich spar cement in the former and rather pelitic nature of the latter. It is strongly connected with another rock parameter – water absorption. Its analysis reveals influence of gradual fatigue process on the appearance of new fractures. Its growth indicates distinctly that new spaces open in the rock. Such process affects especially platy limestone from the lowest (IV) level of the quarry.

Graphs of velocity of ultrasonic waves show differences which may suggest, that the directions parallel to the bedding in all three levels and to the joint set B in the limestone from the level III are the most sensitive and susceptible to fracturing. Freezing provokes the biggest changes in the platy limestone from the level IV, which can be connected with their highest water absorption. Similar gradients of the linear regression lines for velocities measured in different directions indicate that the degree of changes is the same regardless the direction. However, it may reflect not only the number of newly appearing fractures, but also opening already existing cracks.

Testing of the velocity of ultrasonic waves in the limestone from the level I shows that this limestone is the most resistant to cracking. Regression lines show that the intensity of the fractures expanding and appearing during the test is similar in all directions.

Observations in macro- and microscale revealed that the most intensive joint set is that one parallel to the bedding in levels I and IV. In the level IV surfaces of horizontal fractures are smooth and covered by rust. It facilitates disintegration of rock. In the level I the same set of joints is represented by jagged stylolites which do not open at small tension. Such differences reflect in grain shapes. The amount of flat grains is much higher in the platy limestone (level IV) than in bedded one. Progressing fatigue results in decreasing of the velocities of ultrasonic waves in all directions.

A thesis can be put that a rock is subjected to a fatigue process during crushing. The appearance of new fractures is a symptom of it. The more advanced fatigue process, the larger number of fractures. Therefore, it can be stated that finer grains represent more fatigued material than coarse grains. In the limestone from levels I and IV the fatigue process is reflected in changes of the shape of the aggregate grains from isometric to elongated and very flaky with the fractions fining.

Higher content of the flat grains in the initial stage of crushing (i.e. in coarser fractions) is probably caused by more frequent horizontal fractures than vertical ones, particularly in the platy limestone (level IV). Creation of elongated grains in the next stages of crushing (i.e. in finer fractions) requires additional fracture set perpendicular to the bedding. Its appearance is facilitated by lowered strength of flat grains formed in the initial stage.

The velocity of ultrasonic waves in various directions is more differentiated in the bedded limestones from the level III than in other levels. Different gradients of regression lines point to more complex relations between material fatigue degree and intensity of fractures. Vertical fractures filled with detrital material were observed in the quarry but could not be taken into consideration in microscopic investigation, because the samples easily disrupt along them. They are probably responsible for similarity of the velocity of ultrasonic waves perpendicular to the B direction and to the bedding. Fractures of both sets are probably a reason for greater amount of elongated and bladed grains. Diversity of the grain shapes and velocities of the ultrasonic waves are related to quite complex joint system recorded in this level.

It can be inferred from the above, that the velocity of ultrasonic waves measured in fatigued rocks does not linearly relate to the number of new created fractures. Usually the greatest changes occur in the early stages of the fatigue, when the most distinct fractures open. Then new cracks appear in predisposed directions. They are visible in fresh rock only under the microscope.

The shape of the grains depends also on the rock components (especially in the finest fractions). Big bioclasts form the whole grain and give it its own shape (e.g. flat ammonites, elongated belemnites), while their linear arrangement may cause rock cracking in directions parallel to it.

Probably in the flat grains the most of base and top walls reflect horizontal fractures of the joint set C. Therefore, we may assume that measured angles represent dihedral angles between fractures of joint sets A and B. If we do so, we can estimate the most probable angle. On the diagram (Fig. 4) one can distinguish 3 local joint subsets A and 4 local subsets B with different orientation (Table 2). The fractures of subsets A3 and B2 are the most frequent. Surfaces of joint set C cut the rock approximately at a 90° angle to the vertical joint sets. It enables estimating a shape of an elementary fracture cell. Maxima visible in the histograms of the distribution of dihedral angles of grains of various fractions point to directions predestined to cracking.

TABLE 2

Pairs of expected values of dihedral angles between fractures from joint subsets for Nielepice limestone (values of the most probable pairs are shown in bold)

TABELA 2

Pary spodziewanych wartości kątów dwuściennych w ziarnach kruszywa łamanego z wapieni z Nielepic obliczone na podstawie orientacji zespołów i podzespołów spękań w złożu (wartości najbardziej prawdopodobne zaznaczono pogrubioną czcionką)

Joint subsets:		A1	A2	**A3**	B1	**B2**	B3	B4
	Dip azimuth:	7	29	37	318	311	288	270
B4	270	83 + 97	61 + 119	53 + 127	48 + 132	41 + 139	18 + 162	
B3	288	**79 + 101**	**79 + 101**	**71 + 109**	**30 + 150**	23 + 157		
B2	311	56 + 124	**78 + 102**	**86 + 94**	7 + 173			
B1	318	49 + 131	**71 + 109**	**79 + 101**				
A3	37	**30 + 150**	8 + 172					
A2	29	22 + 158						
A1	7							

Results of calculation of expected angles are shown in the Table 2. Some pairs of angles repeat in various combinations of joint subsets. In such cases their appearance in aggregate grains is much more probable than other angles. One should expect also more frequent angles created by subsets A3 and B2. Taking into consideration median values of dip azimuths for subsets A and B (24° and 293°, respectively) expected angles are 89° and 91°.

Comparison of expected and measured angles has been made. All histograms indicate that angles close to 90° are the most frequent. They form local maxima in the range of 82°–98°. It results from the mutual orientation of joint sets A and B, which is nearly orthogonal. It is characteristic that in almost all fractions there are maxima for angles of 79° and 101°. Other frequent pairs of angles, which closely correspond to expected values, can be seen on the overall histogram. The relations described above allow to conclude that the joints observed in the quarry are reflected in the aggregate grains a few cm or a few mm in size.

Conclusions

1. The mechanical properties of the rock and the range of their changes provoked by the material fatigue are related to the lithological type of the limestone.
2. Changes of velocity of longitudinal ultrasonic waves triggered by this process correspond with the shapes of grains of various fractions. Pre-existing cracks and their later opening may cause developing of specific shape of the grains.
3. Directions of fractures observed in cuboidal samples and in thin sections coincide with the directions of main joint sets measured in the quarry. Distances between them range from micrometers to centimeters.
4. The analysis of dihedral angles of the aggregate grains points to distinct relationship between the shape of the aggregate grain and elementary fracture cell that reflects the joint system in the quarry. The same shape is reproduced in the finer fractions of the grains.
5. The shape of aggregate grains depends also on the structure and texture of rock (i.e. size and arrangement of its components, e.g. bioclasts).
6. The knowledge about the above-mentioned relationships is significant for the practice, because forming of new fractures can be initiated by blasting in quarry, crushing during aggregate production, atmospheric agents and pressure on the aggregate grains used in road or railway tracks generated by a traffic load.

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REFERENCES

B r o m o w i c z J., 2000 – Zmiany właściwości fizyczno-mechanicznych kamieni drogowych wywołane procesami kruszenia. Górnictwo Odkrywkowe 42, 2–3, 130–148.

B r o m o w i c z J., 2001 – Ocena możliwości wykorzystania skał z okolic Krakowa do rekonstrukcji kamiennych elementów architektonicznych. Gospodarka Surowcami Mineralnymi 17, 1, 5–74.

B r o m o w i c z J., 2002 – Zmiany właściwości fizyczno-mechanicznych skał wywołane kruszeniem i ich wpływ na kwalifikację surowcową złóż. Górnictwo Odkrywkowe 44, 2–3, 85–88.

B r o m o w i c z J., K a r w a c k i A., 1976 – Analiza spękań piaskowców kredowych z Radkowa w aspekcie oceny bloczności złoża. Górnictwo Odkrywkowe 4, 99–104.

B r o m o w i c z J., F i g a r s k a - W a r c h o ł B., 2008 – Próba oceny ilościowej zmęczenia skał na podstawie zmian właściwości wapieni jurajskich ze złoża Nielepice kolo Krakowa. Prace Naukowe Instytutu Górnictwa Politechniki Wrocławskiej. Konferencje. 121, 50, 19–36.

D a d l e z R., J a r o s z e w s k i W., 1994 – Tektonika.Warszawa. PWN.

D o m o n i k A., 2003 – Odwzorowanie powierzchni ciosowych piaskowców fliszu podhalańskiego w badaniach wytrzymałościowych z wybranych odsłonięć niecki podhalańskiej. Przegląd Geologiczny 51, 5, 430–435.

D r a p e r N.R., S m i t h H., 1973 – Analiza regresji stosowana. Warszawa. PWN.

Dżułyński S., 1951 – Powstanie wapieni skalistych jury krakowskiej. Rocznik Polskiego Towarzystwa Geologicznego 21, 2, 125–180.
Folk R.L., 1959 – Practical petrographic classification of limestones. Bulletin of the American Association of Petroleum Geologists 43, 1–38.
Gradziński R., 1993 – Geological map of Cracow Region without Quaternary and Terrestrial Tertiary Deposits. Scale 1:100 000. Muzeum Geologiczne Instytutu Nauk Geologicznych PAN, Kraków.
Grześkowiak A., Modrzejewski S., 2002 – Metoda ochrony blocznośći złóż przy wybuchowym urabianiu skał na potrzeby kruszyw łamanych. Górnictwo Odkrywkowe 44, 5–6, 25–29.
Hencher S., Knipe R., 2007 – Development of rock joints with time and consequences for engineering. In: Proceedings of the 11th Congress of the International Society for Rock Mechanics. Lisbon, 1, 223–226.
Jern M., 2004 – Determination of the in situ block size distribution in fractured rock, an approach for comparing in-situ rock with rock sieve analysis. Rock Mechanics and Rock Engineering 37, 5, 391–401.
Kieslinger A., 1960 – Residual stress and relaxation in rocks. International Geological Congress, XXI Session, Part XVIII, 270–276.
Kozioł W., Kawalec P., Kabziński A., 2008 – Production of aggregates in European Union. Gospodarka Surowcami Mineralnymi 24, 4/3, 61–73.
Matyszkiewicz J., 1997 – Stromatactis cavities and stromatactis-like cavities in the Upper Jurassic carbonate buildups at Młynka and Zabierzów (Oxfordian, southern Poland). Annales Societatis Geologorum Poloniae 67, 1, 45–55.
Pinińska J., Płatek J., 2002 – Badania ultradźwiękowe w ocenie wytrzymałościowej skał. Górnictwo Odkrywkowe 44, 2–3, 89–96.
Price N.J., 1959 – Mechanics of jointing in rocks. Geological Magazine 96, 2, 149–167.
Smith M.R., Collis L. (ed.), 1993 – Aggregates. Sand, gravel and crushed rock aggregates for construction purposes. 2nd edition. London. Geological Society Engineering Geology Special Publications 9.
Wright V.P., 1992 – A revised classification of limestone. Sedimentary Geology 76, 177–185.
Zingg T., 1935 – Beitrag zur Schotteranalyse. Schweiz. Min. Petr. Mitt. 15, 39–140

WPŁYW CIOSU I MIKRO-SPĘKAŃ NA KSZTAŁT ZIAREN I JAKOŚĆ KRUSZYWA WAPIENNEGO

Słowa kluczowe

Kruszywo łamane, kształt ziaren, spękania, właściwości mechaniczne, wapienie jurajskie, Wyżyna Krakowsko-Wieluńska

Streszczenie

Artykuł przedstawia wyniki badań nad wpływem ciosu i mikrospękań na właściwości kruszywa rozpatrywanego jako jego kształt. Badaniom poddano trzy odmiany teksturalne wapieni jurajskich eksploatowanych ze złoża Nielepice w pobliżu Krakowa (Polska). Prostopadłościenne próby wapieni płytowych i uławiconych wykształcone jako intra-bio-mikryt i intra-bio-sparyt poddawano wielokrotnym cyklom ściskania i mrożenia w celu wywołania spękań. Kierunki ich pojawiania się oraz częstotliwość określano na podstawie obserwacji mikroskopowych oraz badań prędkości fal ultradźwiękowych w różnych kierunkach.

Badania kształtu ziaren kruszywa wykonywano na podstawie materiału pokruszonego w laboratorium i podzielonego na frakcje. Dla każdego ziarna wykonano pomiar długości trzech prostopadłych do siebie osi. Obliczone na ich podstawie współczynniki wydłużenia i spłaszczenia przedstawiono na diagramach Zingga. Generalnie ziarna kruszywa łamanego z Nielepic wykazują spłaszczenie, szczególnie dla wapieni płytowych. Ilość ziaren izometrycznych zmniejsza się w drobniejszych frakcjach. W ziarnach najdrobniejszych na ich kształt wpływa w dużej mierze struktura i tekstura skały.

Kształt i dwuścienne kąty ziaren kruszywa porównano z kształtem spękaniowej komórki elementarnej, wynikającym z przecięcia powierzchni spękań ciosowych pomierzonych w wyrobisku. Kształt ten jest powielany wielokrotnie w coraz mniejszych frakcjach.

Szlify mikroskopowe zostały wycięte równolegle do kierunków głównych zespołów spękań. Ich badania wykazały obecność mikrospękań rozciągających się w tych kierunkach w odległościach od milimetrów do centymetrów.

Tendencja zmian prędkości fal ultradźwiękowych materiału poddawanego męczeniu znajduje swoje odbicie w tendencji zmian kształtu kruszywa określanego dla różnych frakcji. Istnienie założonych spękań i ich późniejsze otwieranie może doprowadzić do powstania ziaren o określonym kształcie.

Wpływ pojawiania się nowych spękań na jakość kruszywa został określony także poprzez istotny wzrost nasiąkliwości wagowej skał przed i po procesie ich męczenia. Różnica w gęstości pozornej była mniejsza.

THE INFLUENCE OF JOINTS AND MICRO-FRACTURES ON THE LIMESTONE AGGREGATE SHAPE AND QUALITY

Key words

Crushed aggregate, shape of grain, fractures, mechanical properties, Jurassic limestone, Kraków-Wieluń Upland

Abstract

The paper presents results of investigations on the influence of joint and micro-fractures on the shape of a crushed grain – one of the most important parameter of the quality of crushed aggregate. Three structural types of the Jurassic limestone exploited in the Nielepice deposit nearby Kraków (Poland) were analysed. Cuboidal samples of platy and bedded limestones formed as intra-bio-micrite and intra-bio-sparite were subjected to recurrent cycles of mechanical stress and freeze–thaw process with the aim of inducing fractures. Their directions and frequency were determined by the microscopic observation and by the measurements of longitudinal ultrasonic waves velocities.

Crushed and fractionated rock material was used in investigation of grain shape. Three diameter of each grain were measured. Calculated ratios of elongation and flatness have been presented on the Zingg diagrams. Generally, grains of the crushed aggregate from Nielepice are flat, the most in the platy limestones. Isometric grains are less frequent in finer fractions. The structure and texture of rock affect significantly the shape of the finest grains.

The shape and dihedral angles of aggregate grains have been compared to the elementary fracture cell, which resulted from the intersection of the joint surfaces observed in the quarry. The same shape is reproduced in the subsequent fractions of the grains.

Thin sections were cut parallel to the directions of the main joint sets. Their investigation revealed micro--fractures elongated in the same directions. Distances between them range from the micrometers to centimeters.

Changes of velocity of longitudinal ultrasonic waves triggered by rock fatigue process correspond with the shapes of grains of various fractions. Pre-existing cracks and their later opening may cause developing of specific shape of the grains.

The influence of new fractures on the aggregate quality has been also stated by significant growth of water absorption measured before and after process of rock fatigue. The apparent density difference was smaller.