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Models of rock deformation under uniaxial compression conditions

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Based on compression strength tests made on several hundreds of rock types of different lithology and originating from different locations of Poland, an attempt was made to associate the susceptibility of rock structure to brittle and ductile flow damage with intragranular and intergranular crack mechanisms. Based on thin-section tests, deformation curves and acoustic emission, four deformation models were compiled. These models relate the final rock structure failure either to the parting fracture of single grains characterising a rapid crushing of igneous, sedimentary and metamorphous rocks containing quartz or silicates, or, on the contrary, to the slow run of the shearing processes that characterise carbonate rocks and breccias with carbonate, ferruginous and silty cementation.

Key words: engineering geology, rock deformation, compression test, crack mechanisms, modelling, Poland

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INTRODUCTION

Discontinuous processes of rock deformation are initiated by local defects of inhomogeneous rock structure. Damaging micro-crack seed points often appear in the early pre-critical state and later develop into macro-cracks but the final loss of rock strength is reached only in a very advanced post-critical state. In polymineral and inhomogeneous rocks, initial crack seed points can be released very early by structural components of a lower strength as inclusions, soft detritus fragments or pores, and also at direct contacts among strong grains where a stress concentration is present (Brace, Bombolakis, 1963; Olson, Peng, 1976; Hori, Nemat-Nasser, 1985; Cundal, Fairhurst, 1986; Pinińska, 1992, 1997; Xie, 1993; Pininska, 1997).

A review of various types of rocks collected in Poland (Pinińska, 1994–2004; Pinińska, Dziedzic, 2006, 2007) shows that in the majority of crystalline hard rocks, seed points are created at the contact among strong grains. Therefore, the basic destructive mechanism is local intragranular cracking. On the other hand, in soft sedimentary rocks, carbonate rocks in particular seed points are the structural defects creating intergranular cracking and shear fracture. Symptoms of both those mechanisms, observed in uniaxial compression tests and acoustic emission (AE), allowed to compile comprehensive deformation models of sedimentary, igneous and metamorphic rocks from Poland in relation to their origin, lithology and structure.

STRUCTURE MODELS

Rock structure models can be created in a close connection to their origin. The structure of hard sedimentary rocks with monosized grains as well as of the majority of crystalline igneous rocks may be described by a periodical model where the role of repeatable basic cells is performed by polygon-shaped grains (Fig. 1a). The features of the aperiodical structural model may be associated with weak sedimentary rocks containing grains of various sizes, in particular carbonate rocks with a random tessellation pattern of irregular organic remains (Fig. 1b). In hard metamorphic rocks, crystalline repeatable elements are also present despite their lamination (Fig. 1c). Those models of structure can be easily compared with the polygonal and triangular structural mosaics (Fig. 1d) which were applied by Napier and Peirce (1995) in the simulation of extensive fracture formation by the Displacement Discountinuity Method (DDM) in brittle materials.

Compression strength experiments on several hundred types of Polish rocks with various structure patterns (Geomechanical Data Base, Pinińska, Dziedzic, 2001) show that in hard rocks with a polygonal, periodical structure, the seed points of fractures are induced by stress concentration on the grain / grain contact, resulting in the intragranular parting fracture of strong grains. In the soft rocks representing aperiodical, triangular models of structure, seed points are generated around grain borders as a grain / cement fracture.

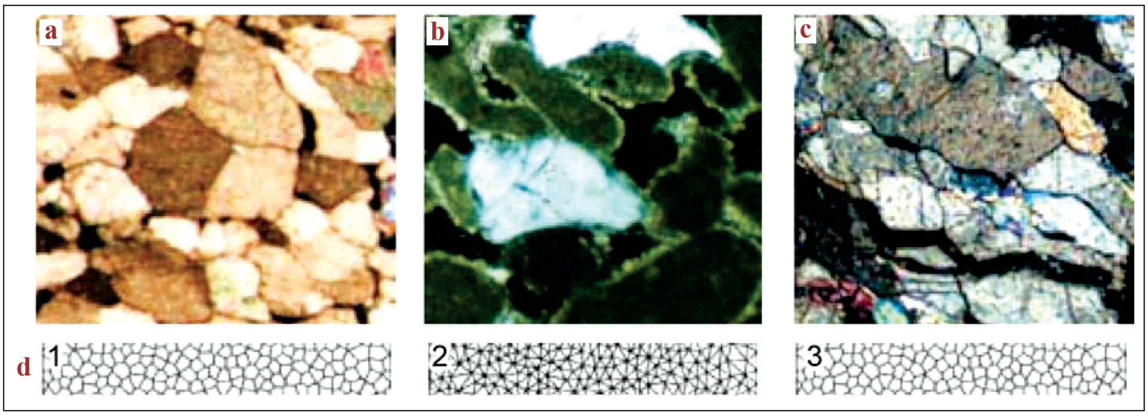

Fig. 1. Real structures: *a* – periodical, polygonal (quartzite sandstone from Wiśniówka – Świętokrzyskie Mts.), *b* – aperiodical with numerous pores and irregularly shaped grains (organodetritic limestone from Pińczów – Świętokrzyskie Mts.), *c* – poligonal quartz crystals in layer-wise structures (marble from Sławniowice – Sudety Mts.), *d* – structure models: *1, 3* – polygonal, *2* – triangular (Napier, Peirce, 1995)

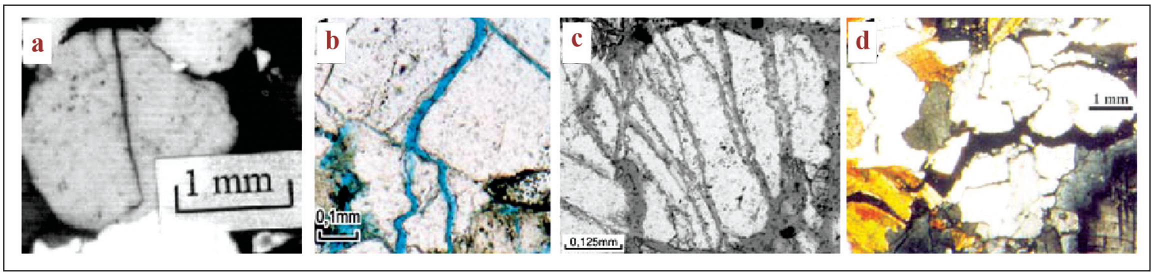

Fig. 2. Intragranural cracking centres: *a* – quartzite sandstone from Barcza (Świętokrzyskie Mts.) and flysch sandstones with silica cementation from Karpaty Mts.: *b* – rom Kobyle, *c* – from Tenczyn Górny, *d* – granite (Sudety Mts.)

Therefore, for a rock featuring a regular grained and compact structure bonded with strong cement, the main initiator of structure destabilisation is the brittle, intragranular parting fracture of single grains which contact one another directly. As a consequence, extensive microcracks inside of single grains appear, without any symptom of dilatancy that could be a presage of strength loss. These initial phenomena are well visible in thin section microscope analyses. As is shown in Fig. 2 a, b–c, microcracks occur commonly in quartz grains e. g., quartzite, sandstones with silica cementation or granite.

According to this mechanism of the initial destruction of rock structure, the final postcritical failure is burst-like in character, causing the fragmentation of the rock body into small pieces. This vary rapid process occurs when the critical number of intragranular microcracs has developed and the local destruction centres are transformed into transgranular macrocracks (Fig. 3 a, b).

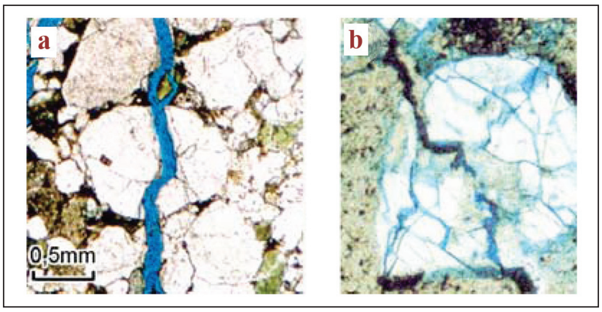

Fig. 3. Development of transgranular slot across a cracked quartz grain: *a* – flysch sandstone from Wisła (Karpaty Mts.), *b* – porphyry from Miękinia (Kraków-Częstochowa Jurassic Upland)

In rocks containing grains distributed randomly within a weak matrix, or in rocks containing a soft irregularly shaped grains, the process of seed point formation is related to the intergranular development of microcracks, initiated by structural defects. This process in the developed stage of destruction, particularly in the post-critical state of macrocracking, is dominated by shear fracture processes. This is a typical cracking mechanism for the majority of carbonate rocks, particularly of organogenic origin (Fig. 4 a–c) as well as of clastic rocks with carbonate cementation (Fig. 4d) and weak metamorphic rocks of carbonate composition. When their complex structure is built up with irregular fragments, corner shearing processes are induced. In such a case, the cracking is of a mixed nature: intergranular on the corner of grains and transgranular with displacement of crushed parts getting stuck in macrocracks (Fig. 4 e, f). Due to the surface roughness and general shear resistance, the final post-critical failure is slow and forecasted with a distinct dilatancy.

Both periodical and aperiodical types of the discontinuous process of rock destruction under load can be well observed on the deformation curves. The frequency pattern of stress relaxation and concentration phenomena monitored with a stiff-strength test machine as a hysteresis loops indicate the results of micro- and macrocracking. Simultaneously, the same phenomena recorded on the acoustic emission image indicate

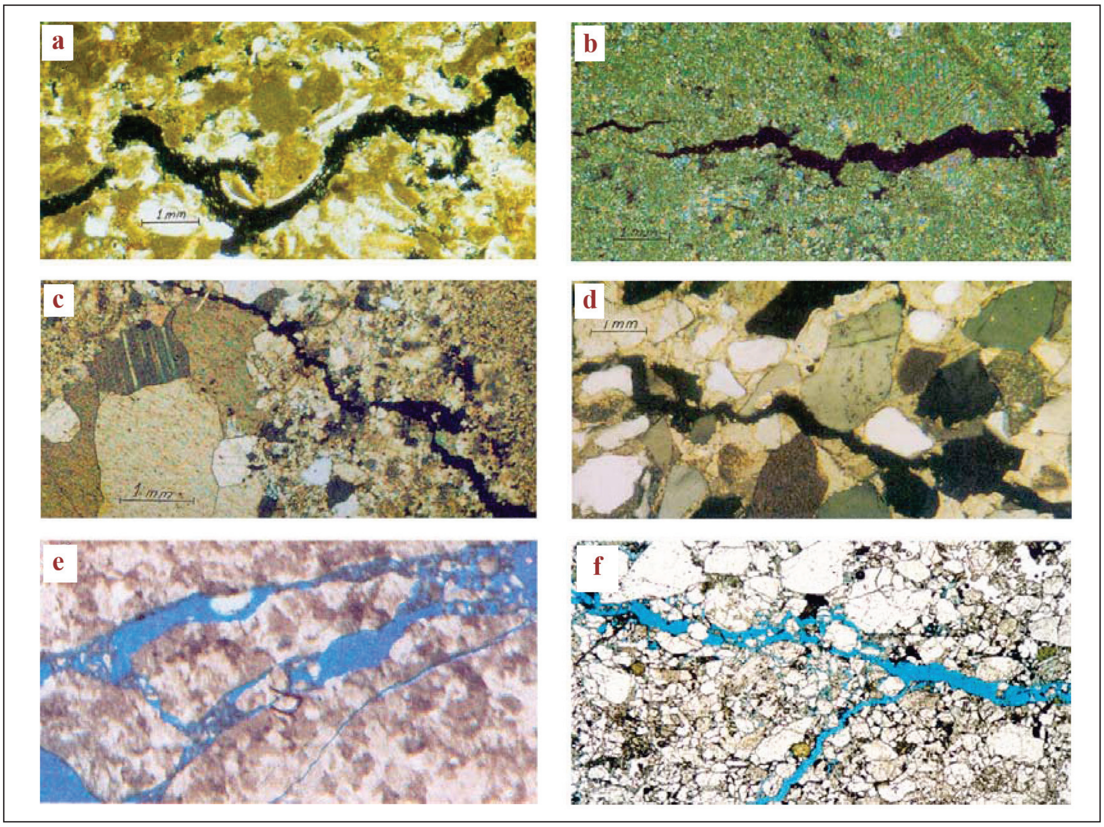

Fig. 4. Intergranular crack propagation. Organodetritic limestones: *a* – with well-preserved bryozoa from Pińczów; *b* – limestones with fine organic detritus from Suchowola; *c* – fine-detritus limestone from Piekoszów; *d* – sandstone with carbonate cement from Dwikozy (Świętokrzyskie Mts.). Flysch sandstones with carbonate cement: *e* – fragments crushed in a macrocrack, limestone from Ogrodzieniec (Kraków-Częstochowa Jurassic Upland); *f* – fragments getting stuck and displaced within a macrocrack, sandstone from Wola Komborska (Karpaty Mts.)

both the energy and signal rate increasing and decreasing due to the microcrack and macrocrack development (Pinińska, Lukaszewski, 1992; Pinińska, 2000). The dynamics of both processes, with a special emphasis on the post-critical stage, is integrally related to the rock destruction mechanism.

Destruction of rocks of a periodical structure with the polygonal mosaic and intragranular cracking mechanism is indicated on the deformation curve by regularly repeated effects of stress relaxation and concentration, both accompanied by regular oscillations of acoustic emission signals (Fig. 5a).

Destruction of rocks of a aperiodical structure with triangular mosaics is indicated by an irregular ocurrence of stress concentration and relaxation as well as by various acoustic emission effects. Both these effects of irregularity are caused by the varying energy of intergranular damage propagation (Fig. 5b).

The final failure of both types of rock structure – periodical and aperiodical – results from a rock-specific critical number of cracks required for total destruction. As is proved by DDM simulations (Napier, Peirce, 1995), the crack number required to destroy a fine-grained structure is bigger than that for a coarse-grained structure (Fig. 6).

This opinion is confirmed by photomicrographs of damaged structures (Fig. 7).

Using the total number of stress loop oscillations monitored on the deformation curve, or the total number of signals monitored on the acoustic emission path, the critical value of cracks causing the rock failure can be determined (Pinińska, 1994–2008). As shown in fig. 8, the critical number of cracks necessary for a final destruction of coarse-grained flysch sandstones from Barcice is related to approx. 160,000 signals only, while of the fine-grained sandstones from Ciężkowice to approx. 275,000 signals.

Numbers of acoustic emission signals could be a tool for estimating the degree of rock destruction by signal mobilisation ratio, recording the number of signals existing at any deformation stage, compared against their critical number. The acoustic mobilisation ratio for the critical state of stress may vary largely from case to case depending on the mechanism of rock structure destruction: for hard, intragranular cracking, coarse-grained sandstone of Ciężkowice only 9.38% of the total crack number and in fine-grained sandstone from Barcice 7.2% are mobilised in the critical state, but in an extreme case for soft intergranular cracked pellitic carbonate rocks, when fracture processes occur from early precritical stages, the acoustic emission signal ratio can be close to 50%.

A presage of an advanced damage of rock structure is dilatancy, and it differs depending on the destruction mechanism as well. As is shown in (Fig. 9 a, b), variations in the axial strain (ε_z) and volume strain (ε_v) indicate that intergranular cracking induce ductil deformation and early and significant volume deformations, whereas for intragranular damaging volume changes take a slower rate.

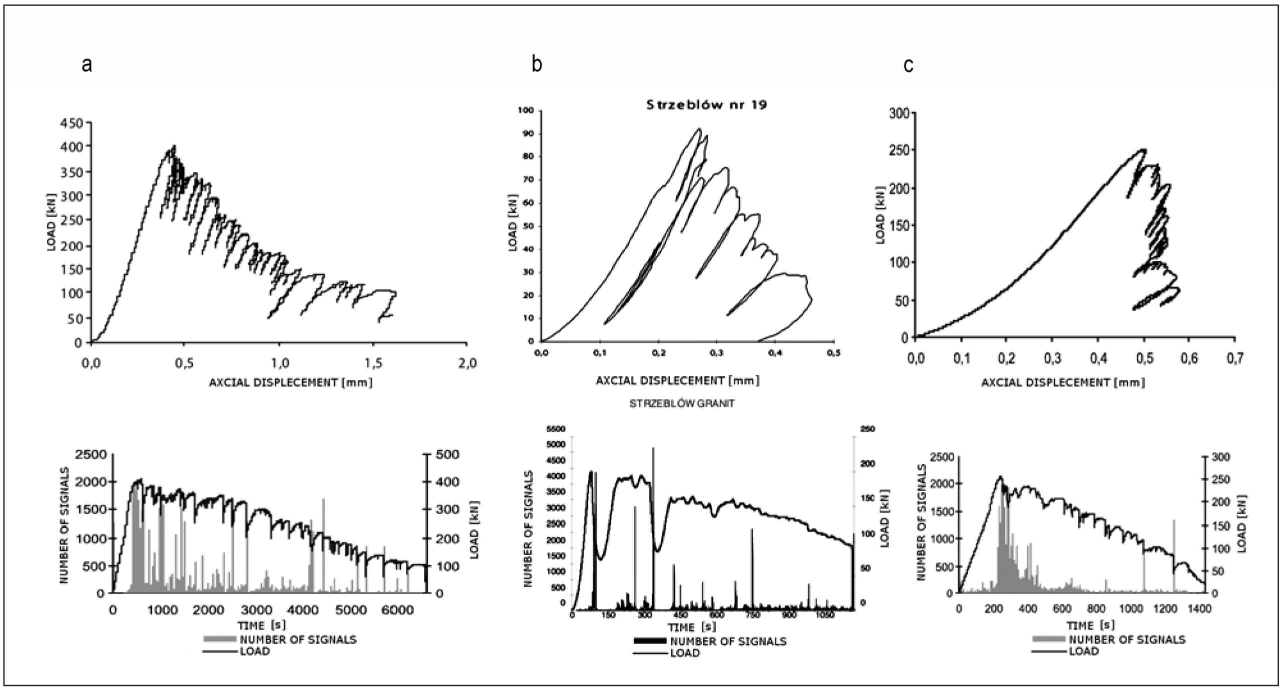

Fig. 5. Cracking effects recorded in axial deformation and acoustic emission diagrams various mechanisms of rock cracking. Regular process, intragranular cracking: *a* – sandstone with silica-carbonate cementation (from Barcice, Karpaty Mts.); *b* – granite (from Strzeblów, Sudety Mts.). Random process, intergranular cracking: *c* – sandstone with silty-carbonate cementation (from Tenczyn Górny, Karpaty Mts.)

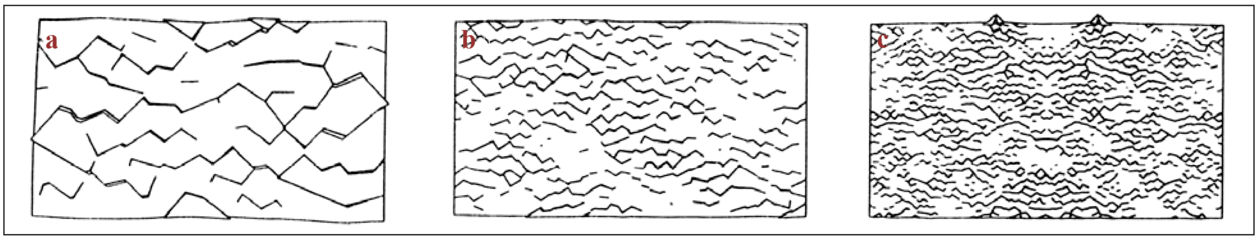

Fig. 6. Dependence of the critical crack number on grain size: *a* – coarse-grained, *b* – medium-grained, *c* – fine-grained (Napier, Peirce, 1995)

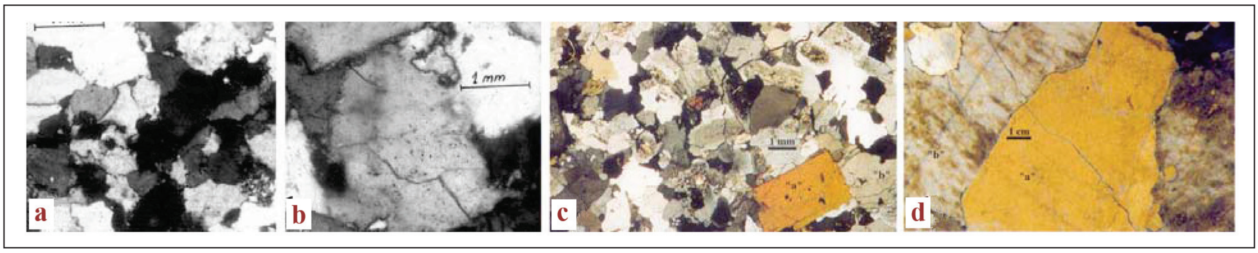

Fig. 7. Numbers of cracks in real rocks of similar origin. Quartzite sandstones (Świętokrzyskie Mts.): *a* – fine-grained (from Wiśniówka); *b* – coarse-grained (from Barcza). Granite (Sudety Mts.): *c* – fine-grained (from Zimnik), *d* – medium-grained (from Strzegom)

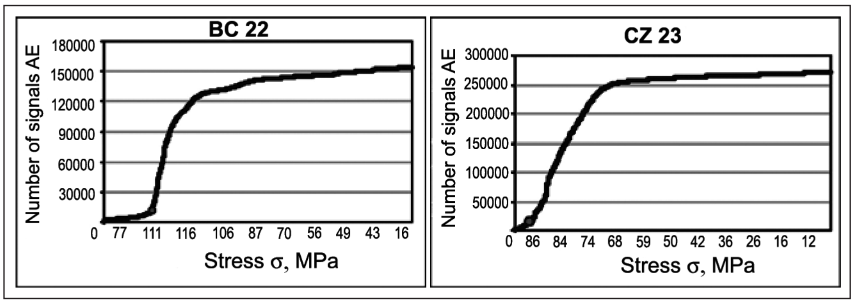

Fig. 8. Acoustic emission signal distribution against stress: *a* – fine-grained sandstone of Ciężkowice; *b* – coarse-grained sandstone from Barcice. Critical state is marked with a dot

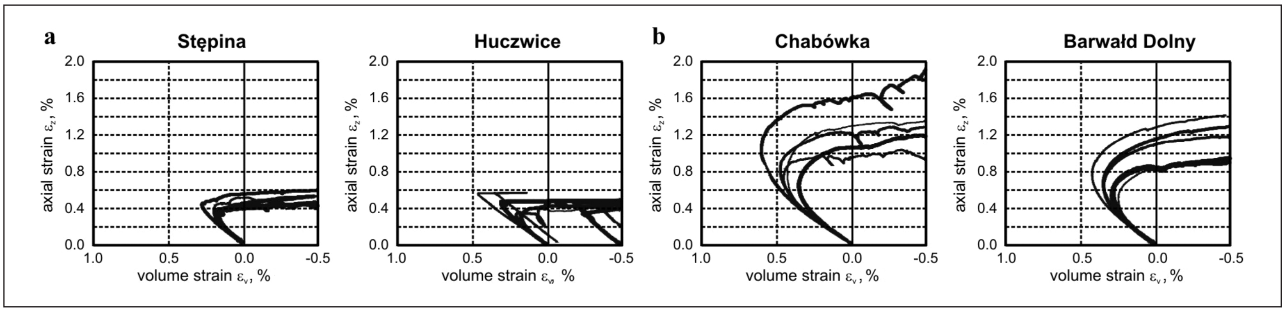

Fig. 9. Relations between axial strain (ε_z) and volume strain (ε_v) in flysch rocks from Poland (with regard to the terminology of triangular and polygonal structures given by Napier, Peirce, 1995): *a* – ductile shear deformation, volume strain increasing significantly: sandstone with carbonate cementation (triangular structure); *b* – intragranular parting fracture, slow axial and volume strain increase: sandstone with silica cementation (polygonal structure)

It could be taken into account that in inhomogeneous rocks, development of intergranular and transgranular cracks may be modified by stronger inclusions as bariers or by locally varying anisotropy of mineral grains (Fig. 10), therefore, the behaviour of the same rocks needs a deeper interpretation. In case of siliceous limestone (opoka) from Lublin region, a significant role as a barier belongs to silica sponge needles scattered in the pellitic carbonate matrix. They modify shear fracture propagation and retard the dilatancy processes, unique phenomena in weak carbonate rocks (Fig. 11 a, b).

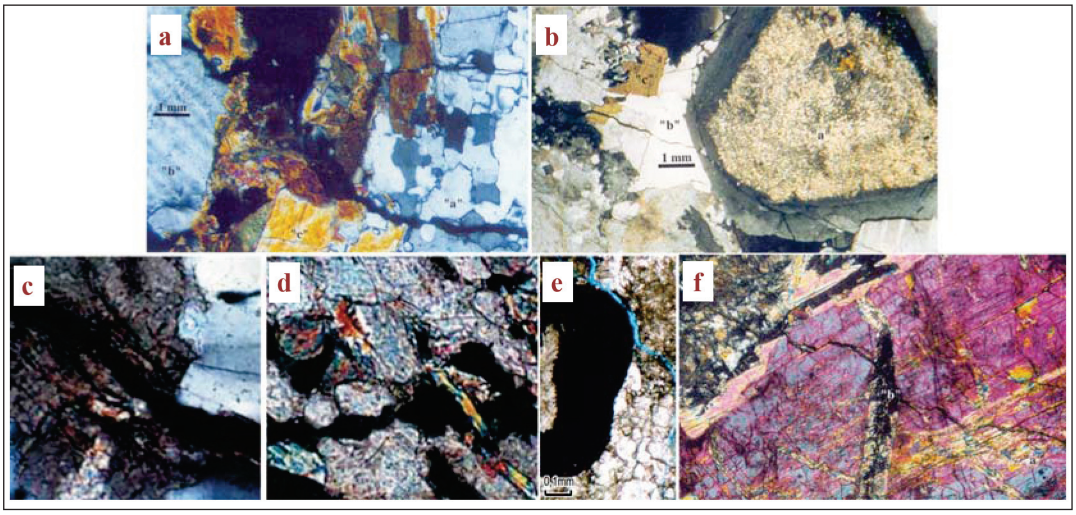

Fig. 10. Barriers across transgranular fracture propagation: *a* – olivine inside basalt from Lubań; *b* – modification by biotite and plagioclase fragments in sienite from Kośmin, *c* – sericitised plagioclase grain in granite from Michałowice; *d*, *e* – structure surfaces modified with quartz grain marble from Kletno); *f* – unidentified inclusion in gabbro from Słupiec

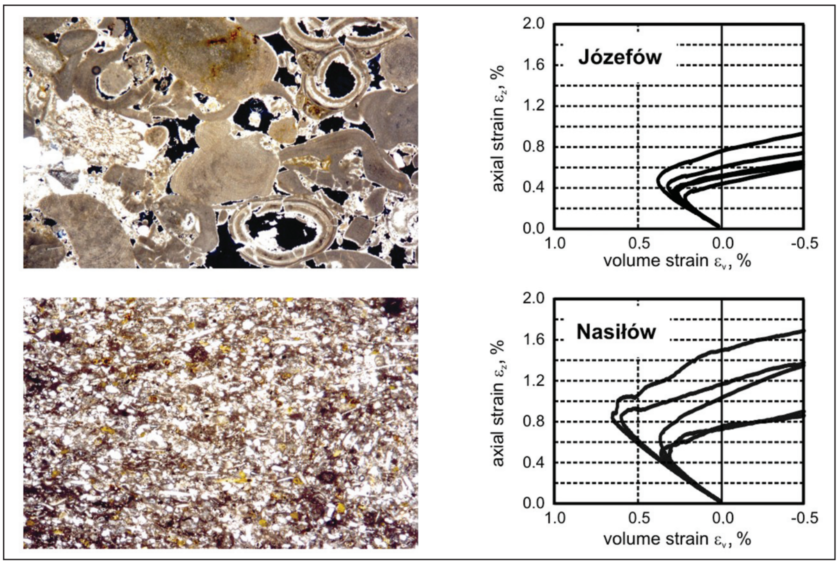

Fig. 11. Structure and volume deformations in carbonate rocks from Lublin region: *a* – limestones from Józefów; *b* – siliceous limestone (opoka) structure reinforced with sponge needles (from Nasiłów)

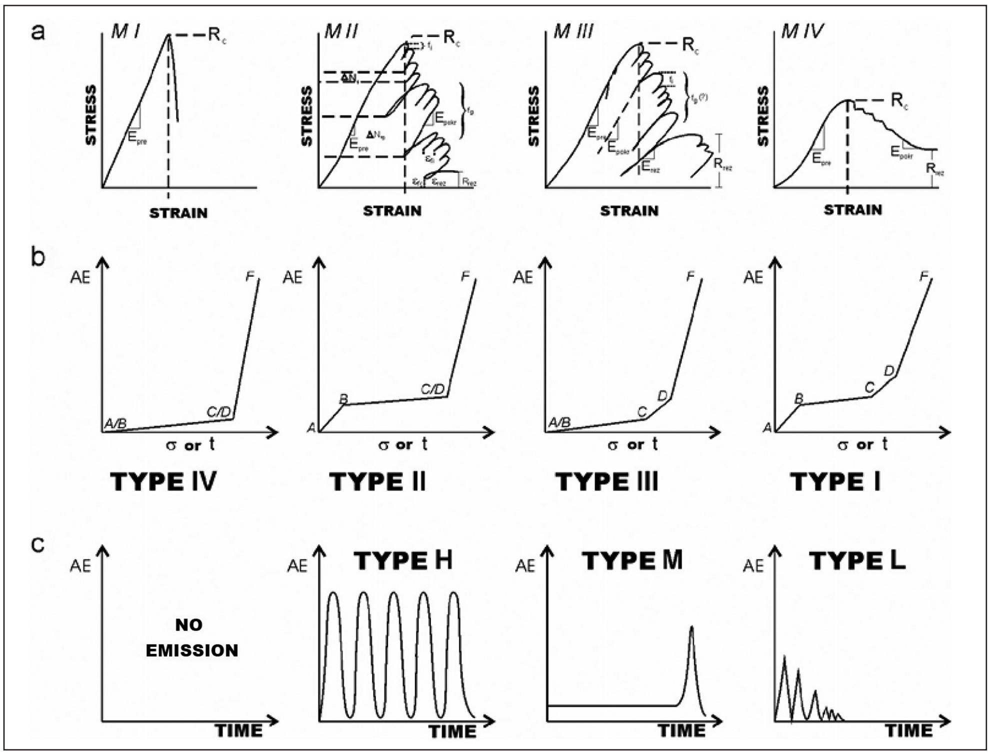

Fig. 12. Models of deformation and acoustic emission (AE): *a* – models of deformation (Pinińska, 1995); *b* – precritical accoustic emission type (Boyce et al., 1981); *c* – postcritical acoustic emission type (Pinińska, 2000)

RELATIONS BETWEEN CRACKING MECHANISM AND DEFORMATION MODEL

Rock deformation processes, with regard to destruction under external forces, may be shown using four models proposed by Pinińska (1995, 1997). These models, based on axial deformation curves (ε_z), are compared with acoustic emission types at a precritical state (Boyce et al., 1981) and with the postcritical acoustic emission types (Pinińska, 2000). They illustrate the different dynamics of fracture formation in Polish rocks depending upon their origin and lithology (Fig. 12), and they follow the brittle and ductile flow behaviour of rock damage (Mogi, 1972).

Deformation model I characterises rocks with a periodical polygonal structure and a very strong diagenesis with a high axial deformation modulus. The structure damage occurs due to a sudden high-energy transgranular macrodestruction, which is presaged by a high level acoustic emission just before the critical state. Due to the rapid structural failure, the postcritical path of the deformation curve is not developed. In Poland's conditions, this model describes the nature of high strength igneous rocks and quartzite sedimentary rocks with a strength above 200 MPa.

Deformation model II characterises rocks with a periodical polygonal structure of a lower strength (up to 200 Mpa). Deformation occurs by the integrated precritical and postcritical deformation path. Both branches of the deformation path are of a high axial strain modulus, despite damaging the rock structure by strong effects of microcracking (f_i) and macrocracking (f_g) in the postcritical state. Due to the intragranular cracking mechanism, without any clear dilatancy presage, the final structure failure is sudden and thus the residual strength, if any, is very small. The postcritical hysteresis loops are regular, showing a periodical damage of particular grains. All these phenomena are accompanied by similar nature of acoustic emission precritical paths of type II (Boyce et al., 1981) and the H type (Pinińska, 2000) very regular at the postcritical state of deformation. In Poland's conditions, this model describes the nature of high-strength igneous rocks and crystalline sedimentary rocks with a high silica content. The cracking cycle regularity depends on the sorting ratio of strong, mainly quartz, grains.

Deformation model III is specific of rocks featuring aperiodical, triangular type of structure mosaics and in Poland's conditions characterises the majority of carbonate rocks with medium and low strength. In this model, in the integrated deformation path of deformation, precritical nonlinearity of the compaction stage as well as of initial cracking may be distinguished. These precitical effects of structure damage are accompanied by the acoustic emission model type III (Boyce et al., 1981). In the postcritical state, the microcracking (f_i) and macrocracking (f_g) cycles occur irregularly depending on intergranular fracture propagation, and the axial strain modulus decreases significantly. All these phenomena follow the postcritical acoustic emission path type M (Pinińska, 2000) with a special feature of acoustic silence, associated with ductil displacements and high dilatancy. Acoustic silence ends in short-term high-energy emissions presaging the final destruction.

Deformation model IV describes weak rocks featuring aperiodical, triangular type of structure mosaics. In this model, on the integrated path of deformation, effects of damaging are very weak, and microcracking and macrocracking are hard to differentiate. The low acoustic emission in the precritical state is equal to type I (Boyce et. al., 1981) and fading monotonously in the postcritical state as type L (Pinińska, 2000). In Poland's conditions, this model is specific of very soft carbonate rocks, in particular organodetritic rocks of low diagenesis.

Compliance between the deformation and the acoustic models, together with the analysis of the rock structure damaging mechanism, acts as an indicator of rock susceptibility to fracture formation and its dynamic. The compact crystalline rocks are more stable at the precritical stage of deformation than weaker carbonate rocks, but due to their intragranular fracture of polygonal grains at the postcritical state they disintegrate rapidly with the lack of dilatancy. On the other hand, in a low-strength carbonate rocks, due to the intergranular damage of their triangular structure, the loss of stability is retarded by shearing and sliding processes occurring, particularly at the postcritical stage, along the rough surfaces of the fractures. Therefore, the model of deformation specified according to the origin and structural mosaic of the rock, together with the respective acoustic emission type, is a useful tool for the engineering-geological evaluation of rock stability status at an expected stage of stress.

CONCLUSIONS

Depending on the mineral composition and bonding material of a rock mass, uniaxial compression tests showed intragranular, intergranular or transgranular fracture formation processes operating with different dynamics. They provide for a variable long-term stability of the joint mass at the postcritical stage. The susceptibility of rocks depends on the structure and cracking mechanisms.

Basing on the analysis of the compression strength tests made for several hundreds of rock types of different lithology and originating from different locations of Poland on the thin-section structure tests, deformation curves and acoustic emission, four deformation models are proposed.

Models of deformation relate the final failure either to the intragranular cracking caused by a parting fracture of single grains, or to the intergranular cracking occurring together with shearing processes.

In case of rocks of a polygonal, periodical, cristalline structure with a strong cementation, mainly in igneous and sedimentary rocks as well as in metamorphous rocks containing quartz or silicates intragranular fracturing is observed. These rocks are characterised by a brittle damaging process. Their structure, despite a local internal destruction, for a long time remain stable but finally undergo a rapid crushing.

The irregular grain structure of soft rocks is characterised by the ductile flow. Therefore, the structure decomposition process runs slowly when a shearing and a significant residual strength are maintained. This damaging process is specific of carbonate rocks, in particular of organogenic and breccia rocks with carbonate, ferruginous and silty cementation.

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LENKIJOS UOLIENŲ DEFORMACIJOS MODELIAI PAGAL VIENAAŠIO GNIUŽDYMO TYRIMUS

Santrauka

Tiriant uolienų stiprumą vienaašiu gniuždymu, priklausomai nuo uolienų mineralinės sudėties stebėtos įvairios aižėjimo rūšys – intragranuliarinis, intergranuliarinis, transgranuliarinis. Be to, aižėjimo procesas skiriasi dinamika ir pokritinės būklės stabilumu. Pateikiami duomenys apie uolienų stiprumą ir aižėjimą, priklausantys nuo uolienų litologijos ir atskirų komponentų stiprumo. Atlikta kelių šimtų Lenkijos uolienų rūšių, pasižyminčių skirtinga litologija ir geneze, deformacijų analizė. Pagal deformacijų pobūdį bei akustinės emisijos rezultatus išskirti skirtingi deformacijų modeliai. Galutinis bandinių suirimas siejasi su intragranuliariniu dalelių trūkinėjimu dėl tempiamųjų įtampų, intergranuliarinis trūkinėjimas – dėl kerpamųjų įtampų. Tyrimai rodo, kad ryškios struktūros uolienose, pasižyminčiose stipria rišamąja medžiaga, vyksta intragranuliarinis aižėjimas. Šios uolienos kažkurį bandymo laiką yra stabilios, o vėliau suyra. Uolienose su nereguliariomis dalelėmis ir silpna rišamąja medžiaga vyrauja kerpamieji įtempiai, struktūra yra lėtai ir lieka liktinis stiprumas. Pastarasis procesas yra būdingas karbonatinėms uolienoms, ypač organogeninėms ir klastinėms su karbonatine ir geležies molio rišamąja medžiaga.

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MODELE DEFORMACJI SKAŁ POLSKI W WARUNKACH JEDNOOSIOWEGO ŚCISKANIA

Streszczenie

Procesy kruchego pękania skał pod działaniem sił zewnętrznych są inicjowane powstawaniem bądź mikro-nieciągłości intragranularnych, bądź intergranularnych przeradzających się w nieciągłości transgranularne. W zależności od rodzaju mechanizmu inicjalnego dalszy rozwój procesu uszkodzenia struktury skalnej pod obciążeniem przebiega z różną dynamiką, wskutek czego symptomy utraty wytrzymałości skały są zróżnicowane zależnie od jej składu mineralnego i charakteru wiązań strukturalnych.

Z badań wytrzymałości na jednoosiowe ściskanie kilkuset odmian skał polskich, o różnej genezie i litologii oraz różnym pochodzeniu regionalnym wynika, że procesy destabilizacji więźby skalnej w pełnym ujęciu ścieżki przedkrytycznej i pokrytycznej można przedstawić za pomocą czterech modeli deformacji (Pinińska 1995, 1997). Modele te, oparte na charakterystyce odkształceń osiowych (ε_z), są ściśle związane z modelami aktywności akustycznej opisywanymi dla stanu przedkrytycznego przez Boyce’ a et al. (1981) oraz dla stanu pokrytycznego przez Pinińską (2000), nawiązują również do modeli kruchego i ciągliwego zniszczenia skał przedstawionego przez Mogi (1972).

Modele te obrazują w jaki sposób zróżnicowany proces finalnej utraty stateczności struktury skalnej ma swe źródło we wcześniejszych stadiach bądź intragranularnego pękania rozdzielczego, pojedynczych, wytrzymałych ziaren mineralnych stykających się bezpośrednio ze sobą, bądź w pękaniu intergranularnym połączonym ze ścinaniem, w strukturach o dominacji słabego spoiwa. Stopień zróżnicowania dynamiki narastania uszkodzeń struktury, właściwy danej skale, widoczny jest tak na krzywych naprężenie / odkształcenie w obrazach kolejnych pętli histerezy jak i w towarzyszących deformacjom charakterystykach emisji akustycznej, a szczególności w zmiennej liczby sygnałów emisji stanu krytycznego w relacji do całkowitej liczby zdarzeń akustycznych scharakteryzowanych krzywą sumacyjną sygnałów akustycznych stanu przedkrytycznego i pokrytycznego.

W przypadku skał zwięzłych o poligonalnej, periodycznej strukturze, głównie skałach magmowych z wyraźnymi ziarnami kwarcu, oraz silnie scementowanych krzemionką skałach osadowych i metamorficznych pękanie inicjalne ma charakter intragranularny. Struktury te pozostają stabilne przez długi czas pomimo spękania wewnętrznego, lecz ich finalny rozpad przebiega gwałtownie i praktycznie nie zostaje zachowana wytrzymałość rezydualna (ośrodki kruche: Model I oraz Model II), a gwałtowność zjawiska rozpadu zależy od stopnia diagenezy oraz wielkości ziaren składowych. W strukturach aperiodycznych o ziarnach nieforemnych, właściwych skałom słabym, przeważa mechanizm pękania międzyziarnowego oraz ścinania, kruszenia i przesuwania odłamanych fragmentów ziaren przez co proces utraty stabilności jest powolny i zachowana jest znaczna wytrzymałość rezydualna (ośrodki ciągliwe: Model III oraz Model IV). Ten proces utraty stabilności jest właściwy skałom węglanowym, szczególnie organogenicznym oraz słabym skałom osadowym ze spoiwem węglanowym lub żelazisto-ilastym, a powolna dynamika rozwoju uszkodzeń przejawia się znaczącym rozwojem procesów dylatancji.

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МОДЕЛИ ДЕФОРМАЦИИ ПОЛЬСКИХ ПОРОД ПО РЕЗУЛЬТАТАМ ИССЛЕДОВАНИЯ НА ОДНООСНОЕ СЖАТИЕ

Резюме

При испытаниях пород одноосным сжатием в зависимости от минерального состава пород наблюдались разные виды деформаций: интрагранулярный, интергранулярный и трансгранулярный. Процесс растрескивания проявляется с разной динамикой и с разной стабильностью в закритическом состоянии. Представлены полученные данные прочности пород и процесса растрескивания, которые зависят от литологии пород и прочности отдельных компонентов. Анализ деформаций выполнен для нескольких сотен образцов польских пород, различающихся по литологии и генезису. Характер деформаций и результаты акустической эмиссии позволили установить разные модели деформации. Конечное разрушение пород тесно связано с интрагранулярным растрескиванием из-за проявления растягивающих напряжений, а интергранулярное растрескивание происходит под воздействием сдвиговых напряжений. Исследования показали, что в породах с явно проявленной структурой и прочным связывающим материалом происходит интрагранулярное растрескивание. Породы такой структуры в ходе испытания некоторое время стабильны, а затем разрушаются. В породах с нерегулярными частицами и слабым связывающим материалом преобладают сдвиговые напряжения, а структура разрушается медленно и наблюдается остаточная прочность. Данный процесс характерен для карбонатных пород и проявляется в органогенных и кластических породах с карбонатным и железисто-глинистым цементом.