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Behaviour of flysch sandstones under conventional triaxial compression

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The paper presents results of investigations on strength in the conventional triaxial compression conditions. The tests were made on flysch rocks, which regard to graining, can be divided into three types: weakly diagenesed vari-grained clastic rocks (Type I), coarse- and medium-grained clastic rocks (type II) and fine-grained clastic rocks (type III). These rocks show different behaviour under triaxial compression conditions. Destruction types for the involved rock types are described based on macroscopic and microscopic analysis.

Key words: flysch sandstones, triaxial compression, strength, deformability

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INTRODUCTION

Rock strength and strain properties should be tested under conditions as inside the earth, which means under higher temperatures and pressures. Rock behaviour under conventional triaxial compression is a very important factor, in particular in road engineering and underground engineering which are being developed currently. The selection of flysch rocks as the study material should not raise any doubt for two reasons: firstly, because these rocks are found in large parts of Poland's territory, and secondly, due to the routes of highways being designed and built in Poland.

This paper describes the behaviour of flysch sandstones under conventional triaxial compression and based on real curves for axial, circumferential and volumetric strains – stress curves. Besides critical strain values, stress at the threshold of absolute dilatancy and the critical energy value were analysed. Also, destruction types for the involved rock types were described based on macroscopic and microscopic analysis.

GEOLOGICAL CHARACTERISTIC OF THE ANALYSED ROCKS

The research material consisted of flysch sandstones with diversified graining. According to Gradziński (1986), in a flysch sediment complex, which is rather extensive, thick and relatively monotonous in the petrographic aspect, a great variability in both vertical and horizontal directions is present. From that complex of flysch rocks, three general clastic flysch rock types were selected, which differ in the graining first of all. Type I included weakly diagenesed vari-grained clastic rocks, type II included medium- and coarse-grained clastic rocks, and type III included fine-grained clastic rocks.

The weakly diagenesed vari-grained clastic rock type included Istebna Sandstones from the town of Wola Komborska and Ciężkowice Sandstones from town of Ciężkowice.

These sandstone types are specific for their varied fractional graining typical of flysch rocks. In case of Istebna Sandstones from Wola Komborska, single grains from the coarse-grained fraction are surrounded with a fine-grained mass. On the other hand, materials from the Ciężkowice quarry are a fine-, medium-, and coarse-grained sandstone, which changes into a fine-grained conglomerate, with its large grains included in a fine-grained mass. In the petrographic aspect, these sandstones are arenites, i.e. rocks with bonding material content below 15%.

The group of coarse- and medium-grained rocks included coarse- and medium-grained Godula Sandstones from the town of Brenna, medium-grained Krosno Sandstones from the town of Mucharz and medium-grained Magura Sandstones from the town of Męcina, in which separate coarse grains are located in a medium-grained mass. In the petrographic aspect, coarse- and medium-grained are wackes, i. e. rocks with bonding material content of approx. 20 up to 35%.

Type III, or fine-grained clastic rocks, includes Cergowa Sandstones from the town of Klęczany, Istebna Sandstones from the town of Rabe and – from the Lgota layers – sandstones turning into mudstone from the Targanice town.

In the petrographic aspect, the Lgota Sandstones from Targanice are located on the border between wackes and mudstones. This statement is evidenced by the content of bonding material of approx. 70%. A similar opinion holds for Klęczany Sandstones because, despite their bonding material content of 53% acc. to petrographic analysis, the microscopic image reveals fine-grained sandstone altered into mudstone. Quartzite sandstone from Rabe distinctly differs from the two latter rocks as it features an exceptionally strong compaction as well as a very small share (5%) of siliceous bonding material.

METHODS

Strength tests under conventional triaxial compression were made at the laboratory of the Department of Geomechanics, Warsaw University. A rigid-structure MTS 815 strength testing press was applied, which was fitted with an MTS 656.05 triaxial cell. The triaxial vessel design as well as attachments for the sample slenderness ratio of 2 we as shown in earlier papers by the same author (Łukaszewski, 2007).

For flysch sandstones, single classic triaxial tests were made featuring a two-stage test run (Kovari et al., 1983). In stage one, a specified confining pressure, $p = \sigma_2 = \sigma_3$, was applied; in stage two, the sample was loaded axially until sample failure. In our tests, three pressures were applied: 30, 60, and 90 MPa, respectively. The pressures increased at a constant rate of 3.3 MPa/s. Once the final pressure was reached, the samples were loaded further at a constant piston displacement rate of 0.05 mm/min.

Sensors were applied to record the following parameters: force, confining pressure, piston displacement as well as the axial and circumferential strain. The volumetric strain (ε_v) was calculated based on the measurement of the axial strain (ε_a) and circumferential strain (ε_c) according to the formula:

$$\varepsilon_v = \varepsilon_a + 2\varepsilon_c. \qquad (1)$$

Based on the relation between the differential stress and axial, circumferential and volumetric strains, parameters were determined for each sample as follows: maximum differential stress $(\sigma_1 - \sigma_3)_{max}$, critical axial strain ε_{acr}, critical circumferential strain ε_{ccr}, critical energy γ_{cr} and differential stress for the threshold of absolute dilatancy $(\sigma_1 - \sigma_3)_D$ (Fig. 1).

In order to fully analyse the behaviour of flysch sandstones under high pressures, results for conventional triaxial compression were complemented with results for uniaxial compression (with the confining pressure equal to zero).

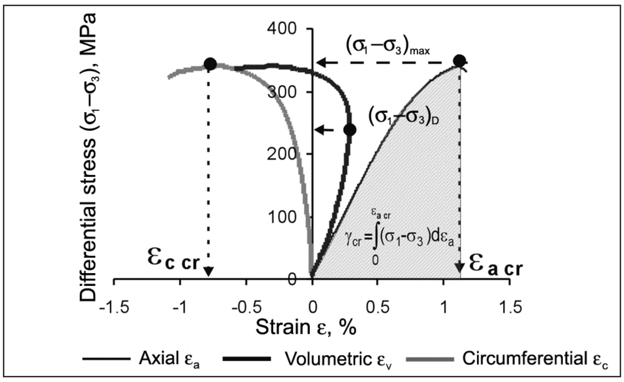

Fig. 1. Scheme of the method of determination of the parameters under analysis

RESULTS

Strength test results for three types of clastic rocks, i. e. sandstones from the towns of Ciężkowice, Mucharz and Klęczany, are shown in the differential stress–strain curves for a series of confining pressure values (Fig. 2).

On analysing the strain curve families, an observation may be made that the greater the confining pressure, the bigger the vertical and horizontal curves. In the general case, the increase of confining pressure is accompanied by increasing the rock compressive strength, ductility, inclination of the stress–strain curve, and the post-failure stress reduction. Besides, a distinct growth of critical values for axial and circumferential strains can be seen, as well an increase of Young's modulus and Poisson's ratio along with the increasing confining pressure.

Based on the stress–strain model characteristics as presented by Mogi (1972) for rocks featuring brittle, transitional, or ductile strain, the rock destruction character can be determined

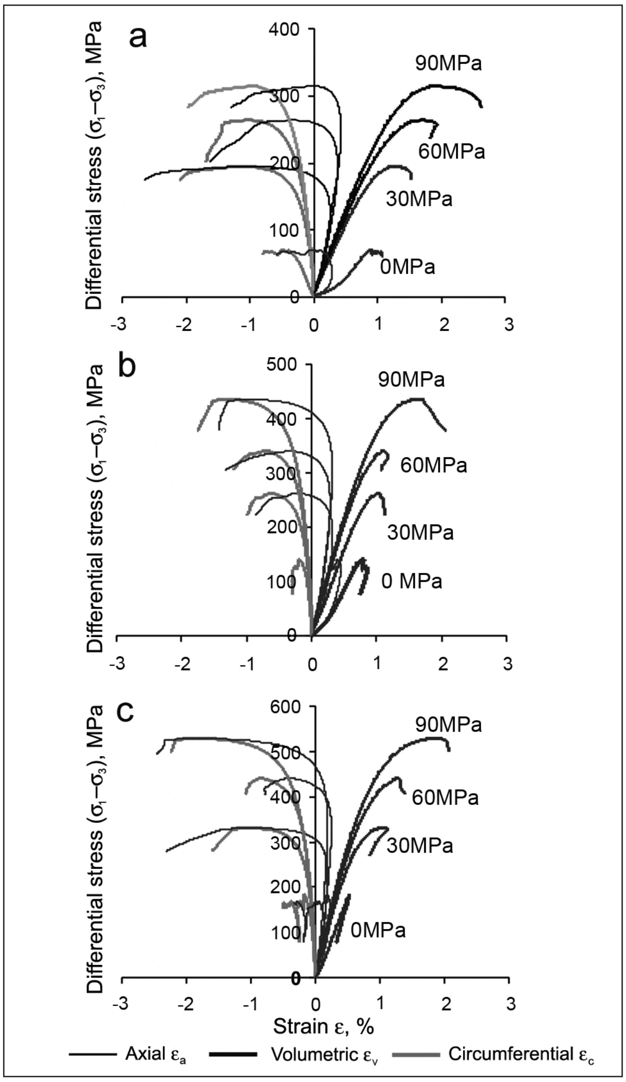

Fig. 2. Typical differential stress-strain characteristics for different confining pressures
a – weakly diagenesed and vari-grained Ciężkowice sandstone,
b – medium-grained Mucharz sandstone,
c – fine-grained Klęczany sandstone

in the same way. While analysing differential stress – axial strain characteristics for weakly diagenesed clactic rocks (type I), an observation can be made that at 90 MPa confining pressure these rocks undergo a transitional strain (T). Under the same pressure, coarse- and medium-grained as well as fine-grained clastic rocks (types II and III) continue to experience a brittle strain (B). This is evidenced by a low strain value as well as a rapid and significant stress reduction once the ultimate failure strength has been exceeded.

For weakly diagenesed clastic rocks, at a confining pressure of $p = 90$ MPa, the ultimate failure strength does not exceed the value of 3.5 p determined by Kwaśniewski (2002) for sandstone alteration from the brittle status to the transitional status. This is clearly visible for flysch sandstones in the analysis of the ultimate failure strength dependence on the confining pressure, with the line $(\sigma_1 - \sigma_3)_{max} = 3.5$ p separating the brittle behaviour field from the transitional (between brittle and ductile) behaviour field as shown in Fig. 3. In this figure, values below this line are only valid for the ultimate failure strength for weakly diagenesed clastic rocks and only at a 90 MPa confining pressure. Thus, these rocks undergo a transitional strain at this pressure value.

This thesis is confirmed with a macroscopic analysis of failed samples. On adopting the rock failure types as proposed by Hoshimo et al. (1972), one can see that brittle strain rocks fail by means of a single shear crack (S). In this case, the failure features a rock material consistency loss as a result of shearing along a plane inclined at approx. 30° towards the largest stress direction. This was the reason for failure of coarse- and medium-grained and fine-grained clastic rocks (types II and III) as well as for weakly-diagenesed clastic rocks (type I) at confining pressures of 30 and 60 MPa.

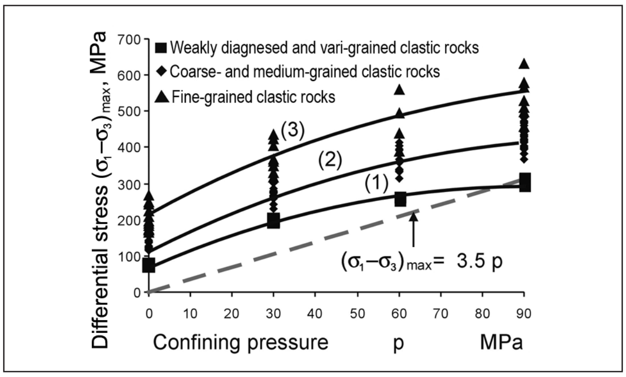

Fig. 3. Ultimate strength for flysch sandstones which show, depending on confining pressure, brittle or transitional behavior:
(1) $(\sigma_1 - \sigma_3)_{max} = -0.027\,p^2 + 4.86\,p + 90$; $R^2 = 0.94$;
(2) $(\sigma_1 - \sigma_3)_{max} = -0.025\,p^2 + 5.58\,p + 121$; $R^2 = 0.91$;
(3) $(\sigma_1 - \sigma_3)_{max} = -0.025\,p^2 + 5.58\,p + 203$; $R^2 = 0.90$

Contrary to the case described above, transitional-strain rocks fail by flowing (F). This failure features a uniform macroscopic strain without consistency loss, and occurs by cataclastic flow. It should be emphasised that in this case, the term 'cataclastic flow' is understood as a process occurring inside the rock under pressure and consisting in mineral grain straining, cracking and crushing without any chemical and crystallographic changes. This is the failure process for weakly diagenesed rocks at a confining pressure of approx. 90 MPa.

Macroscopic observations were confirmed by a microscopic image of thin plates made at a right angle to the sample axis and exactly at a half of the height. In this microscopic image, two objects are clearly visible: a single shear crack (Fig. 4a) after a brittle failure, and a zone of disintegration of the bonding material and grains showing 'cataclasis' (Fig. 4b) after a transitional failure.

A detailed description of flysch sandstones under conventional triaxial compression was made based on a correlation between certain strength parameters and strain parameters (defined in Fig. 1) as determined for the three selected rock types at various confining pressure values.

Under a conventional triaxial compression, i. e. under the increasing confining pressure, stress and strainability also increase. This is clearly seen while observing the dependence of critical differential strain on the critical axial and circumferential strain (Fig. 5). An increase of strength and strainability is observed for all the selected rock types for which distinctive dependencies exist and have the same logarithmic curve shape. It is clearly seen in the analysis of results for selected confining pressures that for the relation $(\sigma_1 - \sigma_3)_{max} - \varepsilon_a$, non-overlaying data sets were obtained, whereas, for higher confining pressure values, higher stress and strain values were obtained. On the other hand, for the relation $(\sigma_1 - \sigma_3)_{max} - \varepsilon_c$, and for the confining pressure values 30, 60, 90 MPa, partially overlaying data sets were obtained. While analysing results for a single confining pressure value, it is also seen that for weakly diagenesed clastic rocks (type I), large strains are related to low strength values, whereas, for fine-grained clastic rocks (type III), smaller strains are related to higher strength values. This tendency is typical of both axial and circumferential strains.

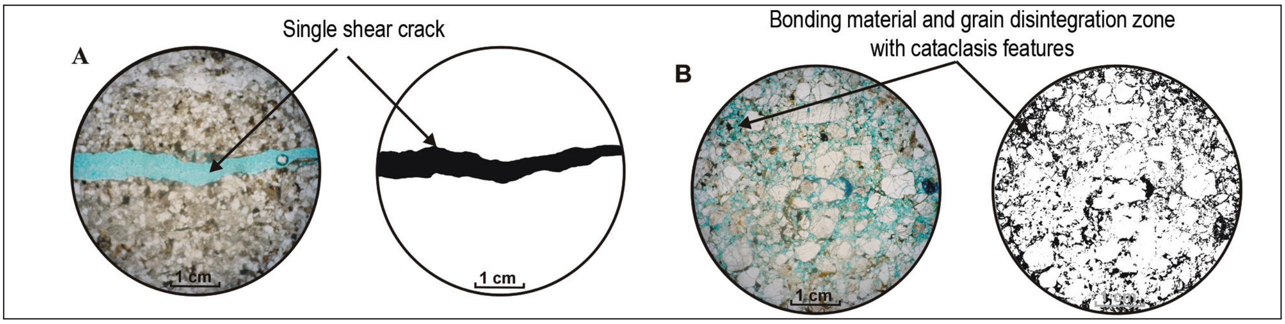

Fig. 4. Sample failure type. *A* – brittle – single shear crack; *B* – transitional – bonding material and grain disintegration zone with cataclasis features

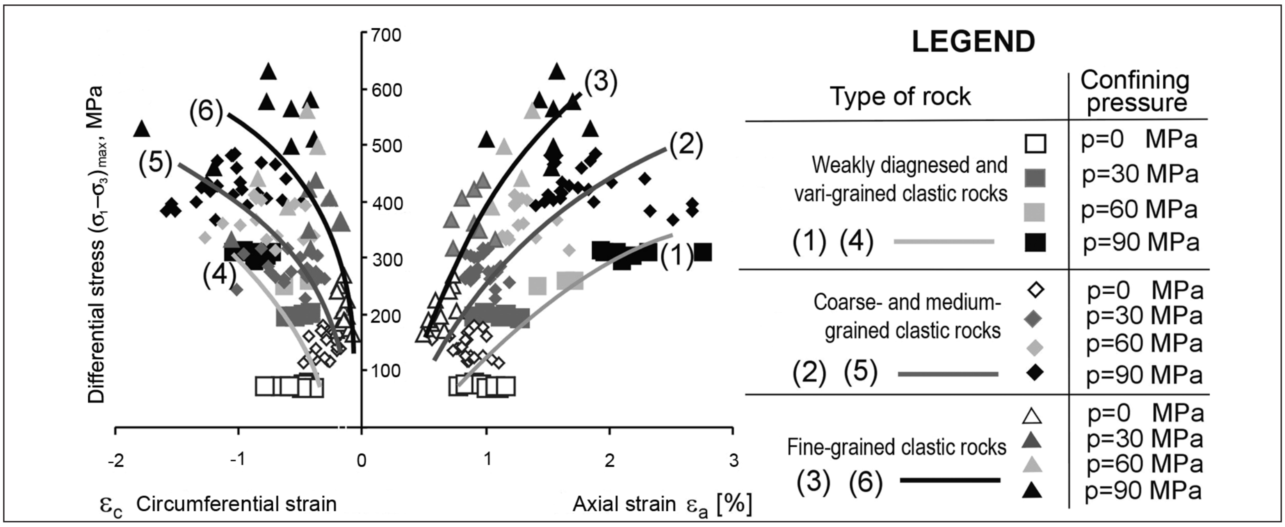

Fig. 5. Relationship between differential stress and axial and circumferential strain at different confining pressure for clastic rocks under analysis:
(*1*) $(\sigma_1-\sigma_3)_{max} = 239\ln(\varepsilon_a) + 125$; $R^2 = 0.77$;
(*2*) $(\sigma_1-\sigma_3)_{max} = 265\ln(\varepsilon_a) + 259$; $R^2 = 0.63$;
(*3*) $(\sigma_1-\sigma_3)_{max} = 347\ln(\varepsilon_a) + 396$; $R^2 = 0.85$;
(*4*) $(\sigma_1-\sigma_3)_{max} = 220\ln(-\varepsilon_c) + 297$; $R^2 = 0.46$;
(*5*) $(\sigma_1-\sigma_3)_{max} = 163\ln(-\varepsilon_c) + 389$; $R^2 = 0.64$;
(*6*) $(\sigma_1-\sigma_3)_{max} = 148\ln(-\varepsilon_c) + 540$; $R^2 = 0.59$

It is not only strength but also accumulated critical energy that increases along the confining pressure (Fig. 6). This is clearly seen in observations of the dependency of critical energy on the critical differential stress. Typical exponential relations were obtained for rock types featuring different graining. It is obvious in the analysis for a single confining pressure value that lower energy values are specific of weakly diagenesed clastic rocks (type I), whereas higher energy values are shown by fine-grained clastic rocks. This tendency is common for all confining pressure values analysed.

The last parameter the differential stress for the absolute dilatancy threshold $(\sigma_1 - \sigma_3)_D$, was normalised in relation to the maximum differential stress $(\sigma_1 - \sigma_3)_{max}$ and converted to % in order to make the analysis easier. Under uniaxial compression ($p = 0$ MPa), the highest values of the normalised differential pressure for the absolute dilatancy threshold $(\sigma_1 - \sigma_3)_D / (\sigma_1 - \sigma_3)_{max}$ (Fig. 7) were also obtained for fine-grained clastic rocks, and the lowest values – for weakly-diagenesed vari-grained clastic rocks. Along the increasing confining pressure, this parameter decreases significantly for fine-grained clastic rocks, whereas, for weakly-diagenesed clastic rocks this parameter decreases. For coarse- and medium-grained clastic rocks, this parameter does not change and remains on a constant level which is typical of these rocks.

This means that along the increasing confining pressure, an uncontrolled and self-sustaining process of unstable crack propagation (on the strain curve) commences either earlier than under uniaxial compression, which is the case for fine-grained clastic rocks, or later than under uniaxial compression, this being the case for weakly diagenesed clastic rocks.

CONCLUSIONS

Despite the identical petrographic composition of the analysed rocks, the strength test results presented in this paper are a proof of a different behaviour of various rock types under a conven-

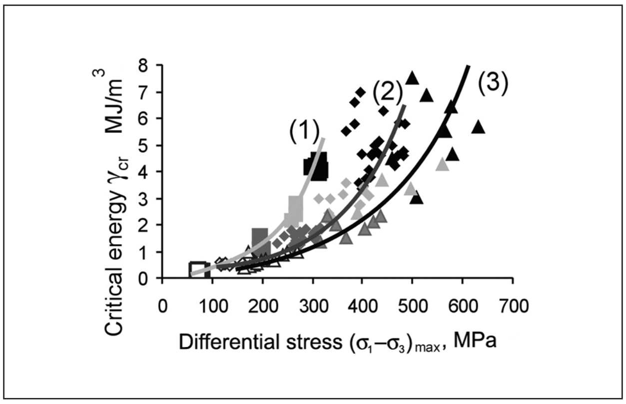

Fig. 6. Relationship between critical energy and differential stress (legend as in Fig. 5):
(*1*) $\gamma_{cr} = 0.123\exp\{0.0114\,(\sigma_1-\sigma_3)_{max}\}$; $R^2 = 0.99$;
(*2*) $\gamma_{cr} = 0.212\exp\{0.0071\,(\sigma_1-\sigma_3)_{max}\}$; $R^2 = 0.93$;
(*3*) $\gamma_{cr} = 0.205\exp\{0.0059\,(\sigma_1-\sigma_3)_{max}\}$; $R^2 = 0.91$

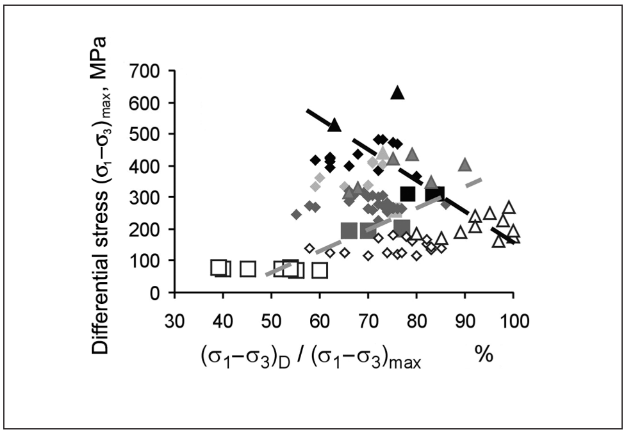

Fig. 7. Relationship between differential stress and $(\sigma_1-\sigma_3)_D/(\sigma_1-\sigma_3)_{max}$ (legend as in Fig. 5)

tional triaxial compression. Weakly diagenesed vari-grained porous clastic rocks of low strength feature a high strainability: even as early as at a 90 MPa confining pressure, these rocks undergo a transitional strain which is visible due to three indicators: the shape of the stress-strain curve, on a macroscale – the failure type, and on the microscale – cataclastic flow zones.

On the other hand, fine-grained massive cataclastic rocks of high strength feature a low strainability; until 90 MPa, these rocks undergo a brittle cracking process with a single shear crack visible on both the macro- and microscale. Besides, it is interesting that with increasing the confining pressure, the normalised differential pressure values (for the absolute dilatancy) increase for weakly diagenesed clastic rocks, and the same properties decrease for high-strength fine-grained clastic rocks. Under a conventional triaxial compression, i. e. along the increasing confining pressure, and in dependence on rock lithology, in particular on the graining and diagenesis extent, an unstable cracking process on the strain curve can commence either earlier or later than under uniaxial compression.

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FLIŠO SMILTAINIO MECHANINIAI POKYČIAI PAGAL TRIAŠIO GNIUŽDYMO TYRIMUS

Santrauka

Tirtos trijų tipų flišo uolienos: įvairiagrūdės (I tipas), stambiagrūdės ir vidutingrūdės (II tipas) bei smulkiagrūdės (III tipas). Nustatyti skirtingi įvairių tipų smiltainio mechaniniai pokyčiai. Pirmo tipo uolienos pasižymi mažu stipriu gniuždant ir didele deformacija. Esant 90 Mpa slėgiui, uolienos laikinai deformuojasi. Šis procesas stebimas pagal įtempių deformacijų priklausomybės pobūdį, taip pat kataklastinio takumo zonų makro- ir mikroskalėse. Trečiojo tipo uolienoms būdingas didesnis stiprumas gniuždant ir mažos deformacijos. Esant 90 Mpa slėgiui, šio tipo uolienose matomi atskiri makro- ir mikrotrūkinėjimai. Visuose mėginiuose, didėjant kameros slėgiui, normalinio įtempio vertės didėja menkiau diagenezės paveiktose uolienose, ypač III tipo mėginiuose. Sutartinio triašio gniuždymo atveju, kai kameros slėgis didėja, trūkinėjimo procesas deformacijos kreivėje priklausomai nuo litologijos ir diagenezės laipsnio gali prasidėti anksčiau arba vėliau negu vienaašio gniuždymo atveju.

Paweł Łukaszewski

ZACHOWANIE SIĘ PIASKOWCÓW FLISZOWYCH W WARUNKACH KONWENCJONALNEGO TRÓJOSIOWEGO ŚCISKANIA

Streszczenie

W artykule przedstawiono wyniki badań wytrzymałościowych w warunkach konwencjonalnego trójosiowego ściskania. Badaniom poddano skały fliszowe, w których ze względu na uziarnienie wydzielono trzy typy skał: słabo zdiagenezowane, różnoziarniste skały klastyczne (typ I), grubo i średnioziarniste skały klastyczne (typ II) oraz drobnoziarniste skały klastyczne (typ III). Skały te w warunkach trójosiowych różnie się zachowują.

Słabo zdiagenezowane i różnoziarniste skały klastyczne charakteryzujące się niską wytrzymałością cechują się dużą odkształcalnością. Przy ciśnieniu okólnym 90 MPa skały te odkształcają się przejściowo. Widoczne jest to zarówno po charakterze krzywej naprężenie odkształcenie, jak również w makroskali poprzez typ zniszczenia oraz w mikroskali poprzez strefy płynięcia kataklastycznego.

Drobnoziarniste masywne skały klastyczne o wysokiej wytrzymałości cechuje z kolei mała odkształcalność. Przy ciśnieniu do 90 MPa skały te odkształcają się krucho poprzez pojedyncze pęknięcie ścięciowe widoczne zarówno w makro- jak i mikroskali.

Interesujące jest również, że wraz ze wzrostem ciśnienia okólnego, wartości znormalizowanego naprężenia różnicowego dla progu dylatacji właściwej rosną dla słabo zdiagenezowanych skał klastycznych, a maleją dla mocnych, drobnoziarnistych skał klastycznych. W warunkach konwencjonalnego trójosiowego ściskania czyli wraz ze wzrostem ciśnienia okólnego w zależności od litologii, a w szczególności od uziarnienia i stopnia diagenezy, proces pękania niestabilnego na krzywej deformacji może zachodzić wcześniej lub później niż w warunkach jednoosiowych.

Павел Лукашевски

МЕХАНИЧЕСКОЕ ПОВЕДЕНИЕ ПЕСЧАНИКОВ ФЛИША ПРИ ИСПЫТАНИЯХ ТРЕХОСНЫМ СЖАТИЕМ

Резюме

Проведены испытания флишевых пород трех типов: разнозернистой (I тип); крупнозернистой и разнозернистой (II тип); мелкозернистой (III тип). В ходе испытаний у разных типов песчаников наблюдалась различная механика. Для пород первого типа характерны небольшое сопротивление сжатию и значительные деформации. Под давлением 90 MPa породы временно деформируются. Этот процесс наблюдается по характеру кривой напряжений и деформаций как в макро-, так и в микрошкале в зонах катакластической текучести. Повышенное сопротивление сжатию и незначительные деформации характерны для пород III типа. Под давлением 90 MPa хрупкие породы деформируются по микро- и макротрещинам. Установлено, что при повышении давления в камере значения нормализованного напряжения увеличиваются в слабо литофицированных и уменьшаются в прочных мелкозернистых породах. В условиях конвенционального сжатия в зависимости от литологии и степени литификации процесс нестабильного трещинообразования возникает раньше или позже, чем при испытаниях одноосным сжатием.