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THE EFFECT OF TEMPERATURE ON THEIR PERMEABILITY TO GAS FLOW OF NON-STRESSED ROCKS

WPŁYW TEMPERATURY WYGRZEWANIA SKAŁ NIEOBCIĄŻONYCH NA ICH PRZEPUSZCZALNOŚĆ W PRZEPŁYWIE GAZU

An investigation of the permeability of sandstone from Tumlin together with fine and coarse-structured granites from Strzelin was conducted using a steady flow of nitrogen and helium.

The permeability values were determined for samples cut from solid rock-masses, firstly at ambient temperature and subsequently at temperatures of 100°C, 200°C, 300°C and 500°C.

Heating the Tumlin sandstone up to 100°C resulted in its evident drying up and the desorption of all the gases contained in it; therefore the permeability increased more than eight-fold. Further heating to 300°C caused a decrease in permeability whilst on raising the temperature to 500°C the permeability again increased somewhat, due to both a slightly greater level of rock destruction, by the removal of the bonded water and other changes in its illitic binding material. Both Nitrogen and Helium showed similar temperature-related flow-patterns.

The progressive changes in permeability accompanying the heating, measured from the flow of both gases, were observed to be qualitatively identical for the fine-grained and coarse-structured-grained granites. A monotonic increase in permeability was observed, which was much higher than in the case of sandstone. This was due to the dehydration of the granite and, possibly, to the preferential direction of the thermal expansion of the rock material, resulting from the directional array of the biotite plates in the granite.

Key words: granite, sandstone, heating up, flow of nitrogen and helium, permeability

Badania przepuszczalności w przepływie gazów prowadzone były w trzech próbkach skalnych: piaskowcu z Tumlina (obrzeże Gór Świętokrzyskich) oraz drobnoziarnistym i gruboziarnistym granicie ze Strzelina (Dolny Śląsk).

Do badań używane były wycinane próbki walcowe skał o średnicy 22 mm i wysokości około 40 mm. Badano próbki piaskowca i granitu w stanie niewygrzewanym oraz wygrzewane w temperaturze 100, 200, 300 i 500°C. Badania przepuszczalności piaskowca i granitu w przepływie azotu i helu prowadzono w permeametrze, do którego wpływał gaz (azot lub hel) pod zadanym ciśnieniem.

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Badania przepływów stosowanych gazów w próbkach skalnych wykonywano do wartości ciśnienia wejściowego 0,8 MPa. Przepuszczalność w przepływie gazu wyliczano ze wzoru Darcy'ego dla gazów.

Początkowy przebieg zmian przepuszczalności przy zadanym ciśnieniu średnim gazu dla azotu pokazuje znaczny spadek przepuszczalności (sorpcja) (rys. 1). W przepływie helu, następującym po przepływie azotu, obserwuje się wzrost przepuszczalności spowodowany desorpcją azotu znajdującego się w próbce i ustalaniem się warunków przepływu. Im wyższa temperatura wygrzewania próbek piaskowca i granitu, tym szybciej ustalają się zachodzące w nich przepływy azotu i helu (lepsza dostępność struktury próbek wygrzewanych dla przepływu).

Przepuszczalności wyznaczone w ustalonym przepływie azotu i helu dla skał niewygrzewanych, a następnie wygrzewanych kolejno w temperaturze 100, 200, 300 i 500°C zebrano na rysunkach zbiorczych dla każdego gazu.

Ogrzanie próbki piaskowca Tumlin do 100° C powoduje wyraźne jej osuszenie (usunięcie wody wolnej obecnej w makroporach spoiwa) i desorpcję wszystkich zawartych w niej gazów (ponad 8-krotny wzrost przepuszczalności) (rys. 2a). Ogrzewanie piaskowca do 200°C, a szczególnie do 300°C, wiąże się ze spadkiem przepuszczalności. Możliwe, że wzrost temperatury wygrzewania wpływa na ilaste spoiwo piaskowca i prowadzi do zatykania kanałów dotychczas drożnych dla przepływu gazu. Według Gustkiewicza (2001) wpływ temperatury na porowatość mikrospękań jest w piaskowcu niewielki: do 300°C wynosi zaledwie około 0,5‰, a przy 500°C osiąga 2‰. Niewielki wzrost przepuszczalności przy ogrzewaniu piaskowca do 500°C (do 0,3 mD) może być zatem spowodowany zarówno nieco większą destrukcją i pękaniem ziaren, jak też usunięciem wody związanej w ilastym spoiwie piaskowca.

Zmiany przepuszczalności piaskowca pod wpływem wygrzewania w przypadku przepływu helu przebiegają zupełnie podobnie (rys. 2b). Uzyskane wówczas liczbowe wartości przepuszczalności są o około 50% wyższe od odpowiednich wartości w przepływie azotu.

Podczas ogrzewania granitu drobnoziarnistego jego przepuszczalność wzrasta w sposób monotoniczny (rys. 5). Przy ciśnieniu średnim przepływającego azotu 150 kPa dla 100°C przepuszczalność wynosi 0,0015 mD, dla 200°C — 0,0088 mD, dla 300°C — 0,0222 mD, a dla 500°C — 0,109 mD. Wzrost ten spowodowany jest osuszeniem granitu (usunięcie wody wolnej w temperaturze 100°C) i zapewne uprzywilejowanym kierunkiem termicznego rozszerzania się materiału skalnego, który wynika z kierunkowego ułożenia blaszek biotytu obecnego w granicie. Przepuszczalność tego granitu w przepływie azotu wzrosła podczas jego wygrzewania do 500°C prawie 260 razy dla wejściowego ciśnienia azotu 0,2 MPa, podczas gdy dla piaskowca Tumlin wzrost ten był mniej niż 4-krotny. Ze wzrostem temperatury (szczególnie powyżej 200°C) Gustkiewicz i in. (2001) obserwowali bowiem wyraźny wzrost odkształceń oraz porowatości spękań granitu. W badanym przez nich zakresie temperatur zmiany te były kilkudziesięciokrotnie większe dla granitu niż dla piaskowca. Również Nowakowski i Konečny (2002) pokazali, że zmiany piaskowca Tumlin w wyniku jego podgrzania do temperatury 500°C były niewielkie w porównaniu ze zmianami w granicie drobnoziarnistym. Wpływ wygrzewania próbek badanego granitu drobnoziarnistego Strzelin na jego przepuszczalność w przepływie helu jest zupełnie podobny.

Dla granitu gruboziarnistego przebiegi i sekwencje zmian przepuszczalności z temperaturą wygrzewania są takie same jakościowo w przepływie obu gazów jak dla granitu drobnoziarnistego (rys. 6). Próbki niewygrzewane gruboziarnistego granitu charakteryzują się niezwykle małą przepuszczalnością w przepływie obu gazów. Przepuszczalności próbek wygrzewanych w 300 i w 500°C są dużo wyższe niż dla granitu drobnoziarnistego. Wyniki te pozostają w dobrej zgodności z badaniami Homand-Etienne i Houperta (1989). Znacznie większy wzrost gęstości spękań i porowatości dla granitu gruboziarnistego niż drobnoziarnistego wynika z jego niższego modułu sprężystości i wytrzymałości na rozciąganie.

Słowa kluczowe: granit, piaskowiec, wygrzewanie, przepływy azotu i helu, przepuszczalność

1. Introduction

The permeability of rock to the flow of gases and liquids is one of the essential parameters characterising its filtering properties. Permeability depends on the structure and condition of the rock medium, that is, the shape and size of pores, the humidity (Skawiński et al. 1991), the internal rock stresses (Somerton et al. 1975; Lingard et al. 1984) as well as on the constitution and the pressure of the gas flowing through it (Harpalani and Chen 1993; Terschüren 1979; Skawiński et al. 1987). Thus, the relationship between the permeability to gas flow and the structure and pressure of the gas depends on both the chemical and the mechanical state of the rock. Temperature is another important factor that affects the properties of the rock since thermal variations can cause significant structural changes in the rock material (an increase in the number of fractures), which may alter its filtering properties, (Danek et al. 2001; Nowakowski and Konečny 2002).

An increase in the temperature of a rock mass can occur in many ways. This issue is important in connection with diverse serious problems concerning gas and rock outbursts, fires in tunnels or underground waste storage.

Information about rock permeability, especially at great depths, becomes extremely important when the underground storage of radioactive materials is being contemplated (Skoczylas and Henry 1995). The effect of temperature on the permeability of the rock is an essential consideration in this case, since fissile materials are thermally active and their presence can lead to an increase in the pressure on the fluid flowing out of the waste, as a result of a combined thermo-poro-mechanical effect. In order to control and limits such flow enlargement, the waste must be stored in geologically stable rocks of low permeability, such as mineral salts., shales, argillites and granites. Skoczylas and Henry describe the measurement of the permeability of granite to the flow of argon and neon for rock in both stressed and unstressed states. Even at a pressure of 25 MPa the granite remained permeable (6.2×10^{-18} m^2), which indicates that during the loading the rock fractures were not completely closed and a flow through them was still possible (at 5 MPa the permeability was equal to 7.75×10^{-18} m^2).

The study by Danek (2001) presents the results of tests on grandiorite, both unheated and heated to a temperature of 1000°C. The research was aimed to investigate the dependence of strain and acoustic emission as well as rock permeability on the axial compressive force. As was observed in microscopic examinations, an increase in temperature was accompanied by the occurrence of a large number of new micro-cracks. As a result of intensive micro-damage in the thermally treated areas, the properties of the granidiorite had changed. In uni-axial compression, the compressive strength of the rock dropped by one order of magnitude and Young's modulus by two orders. In triaxial compression this decrease is smaller because of the occlusion of micro--fractures. At the same time, the permeability of the thermally treated samples was measured. The heated samples showed a distinctly higher permeability, caused by the micro-damage in the thermally treated areas, even if the permeability was measured in a tri-axial stress-state.

A study by Nowakowski and Konečny (2002) presents the results of testing rock permeability in the tri-axial state of stress, where the samples had been previously heated up to a maximum temperature of 500°C. For samples prepared in this way, the velocity of a longitudinal sound wave going through the sample was also measured. Whilst in the case of granite an increase in permeability was observed for temperatures exceeding 300°C, sandstone did not show any reaction to being heated. The changes in the longitudinal sound wave velocity were also considerably higher for granite than for sandstone.

The effect of temperature on the mechanical properties of granite samples has also been presented in a work by Homand-Etienne and Houpert (1989). Both fine-and coarse-grained granites were heated at 200°C, 400°C, 500°C and 600°C. The micro--cracks created by the process were observed according to the SEM method and statistically analysed. The research results thus obtained indicate that the length of fractures does not change whereas their breadth grows relative to the temperature. The intensity.of thermal treatment also leads to an increase in the density of cracks. Coarsely-grained granite exhibits a more intense reaction to elevated temperatures in this respect, both in fracture-density and porosity than granite with a finer structure. Both the modulus of elasticity and the tensile strength are lower than in the case of the fine-grained granite and their decrease with the rise of temperature is more pronounced.

The problem of the influence of temperature on rock properties has also been discussed in a work by Pinińska (1980), which describes changes in physico-mechanical properties in of sandstones from the Krosno region in relation to their thermal treatment temperature and including measurement of the velocity of longitudinal sound waves.

2. Experimental research

The object of this work is to investigate the effect of heating temperature on changes in the permeability of non-loaded rock samples of sandstone and granite to the flow of nitrogen and helium.

2.1. The rocks examined

The investigation of permeability to the flow of gases was conducted in three kinds of rock: sandstone from Tumlin (at the border of the Świętokrzyskie mountains region) and fine-grained and coarse-grained granites from Strzelin (Lower Silesia).

The sandstone from Tumlin is a Lower-Triassic, medium-grained rock with grains of quartz, sometimes touching one another, of sizes ranging from 40 to 400 μm. It is characterised by a macroscopically cherry-red colour and directional texture, parallel and accentuated by a streaked colouring of the binding material or matrix. This colouring results from the presence of iron compounds. The quartz grains, sharp-edged in places, are cemented by a silico-ferruginous or silico-illitic binding agent. Occasionally, in the matrix, chips of silicaceous minerals, can be found, with diameters reaching 8 mm. The matrix content of the rock-sample may be in excess of 15%.

Granite is a magmatic rock of holomorphic crystalline structure, built of crystals of quartz, feldspars, biotite and scarce chlorites. Potassium feldspar is represented in granite by microcline and plagioclases by orthoclase. Its characteristic feature is an evident predominance of oligoclase over potassium feldspar. The fine-grained (gneiss) granite contains 26.5% of quartz, 23.5% of microcline, 45% of oligoclase and 6% of biotite. The coarse-grained (so-called "natural") granite is "younger" than the fine-grained one. The specimen examined consisted of 29.5% quartz, 27.6% microcline, 36.2% oligoclase and 5.5% of biotite.

All the rocks subject to investigation are thermally an-isotropic media. Particular grains or mineral crystals contained in them respond to an increase in temperature to a different degree. In the case of granite a directional texture sometimes occurs because of the possibility of a directional array of biotite plates. Such an arrangement of plates will probably be aligned with the preferential direction of the thermal expansion of the rock material. The streaked colouring of the binding agent in the Tumlin sandstone is possibly an indication that it has a directional texture. The high content of quartz in the sandstone can be connected with the high coefficient of conductivity of the rock. On the other hand, sandstones with a high quartz content are more porous media, showing a decrease in thermal conduction.

This contradiction becomes even more distinctly marked if an increase in temperature results in rapid destruction of the rock and an the appearance of numerous cracks in it. On the other hand, if a porous rock is exposed to slight and gradual heating, the coefficient of conductivity may increase due to the inward expansion. Thus, the effect of an increased temperature on rock materials can be ambiguous and requires careful experimental investigation.

For research purposes, rock samples of a cylindrical shape, cut out as cores, were used, with a diameter of 22 mm and a height between 41 and 44 mm. Sandstone and granite samples were first tested at ambient temperature and were then heated to temperatures of 100°C, 200°C, 300°C and 500°C. A detailed description of the procedure for preparing such the samples is presented in a work by Nowakowski and Konečny (2002).

2.2. The methods of research

The investigation to measure the permeability to a flow of nitrogen and helium in sandstone and granite was performed using apparatus designed in the Porous Media Flow Laboratory in the Strata Mechanics Research Institute of the Polish Academy of Sciences (Żółcińska and Dyrga 1996). The test sample was placed in a permeameter into which the gas (nitrogen or helium) was flowing at a preset pressure. At the inlet of the permeameter the pressure and temperature of the inflowing gas was measured. Having passed through the apparatus the gas was released into the atmosphere. The flows of gases applied in rock samples were usually tested with inlet pressure set to a value of

0.8 MPa. The amount of gas flowing through a sample was determined by flow-meters (SAGA 400, ERG 10, calibrated capillary).

The permeability was determined on the basis of the gas pressure at the inlet and the flow of gas through the sample as well as at the flow discharge. It was calculated according to Darcy's formula for gases with the assumption of a viscous flow of gas and a linear dependence of the velocity of flow on the pressure gradient of the flowing gas. The permeability values determined for the rock samples tested ranged from 2×10^{-20} m^2 to 5×10^{-16} m^2 (that is, from 2×10^{-5} mD to 0.5 mD).

3. Measurements

The permeability measurements derived from in the flow of gases through the rock sample are presented as a relation of the permeability to the mean pressure of the flowing gas. They are all characterised by a similar sequence of qualitative changes; that is, a drop in permeability corresponds to an increase in the pressure of the flowing gas. Nevertheless, there are quantitative differences. For this reason Fig. 1 should only be regarded as an example; it depicts the change in permeability of the coarse-grained granite from Strzelin in response to an increase of nitrogen and helium pressure. The permeability of nitrogen flow was first to be tested in every sample.

The initial pattern of permeability changes at a preset inlet pressure (at a mean pressure of about 150 kPa) shows a significant decrease of permeability whilst applying nitrogen. This probably results from the sorption of the flowing gas in a the sample;

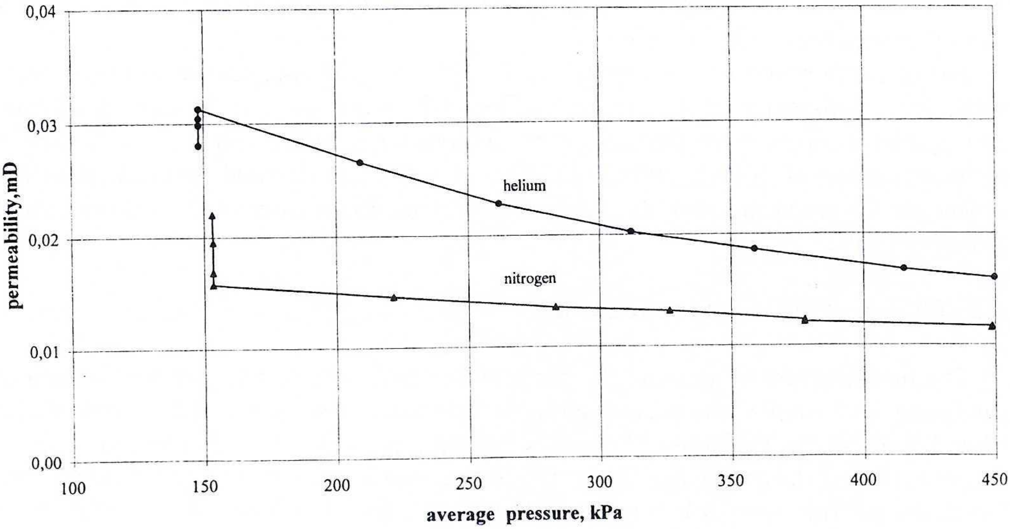

Fig. 1. The change permeability to nitrogen and helium flow in coarse-grained granite

Rys. 1. Zmiana przepuszczalności granitu gruboziarnistego w przepływie azotu i helu a similar phenomenon has been reported for coal by Harpalani and Chen (1993). On the other hand, when introducing helium after the nitrogen flow, an increase in permeability was observed. This was caused by the desorption of nitrogen in the sample as well as by the stabilisation of the flow conditions. It was also noticed that a steady state was more rapidly when He flowed.

After the stabilisation of the permeability value, the pressure of the gas at the inlet was raised, which made it possible to determine the permeability of the rock over a whole range of test pressures. With the increase in pressure of the flowing gas, the stabilisation of the flow (i.e. its reaching a steady permeability value) was also established more rapidly faster. It was also observed that higher sample temperatures resulted in a quicker stabilisation of nitrogen and helium flows in them in all cases. This is due to the flowing gas having increased accessibility to the internal structures of the samples. The relationships between permeability, gas-flow rates and the mean pressure has been predicted by the theory of gas flows in a porous medium (Harpalani and Chen 1993). This relation is of a hyperbolical character; deviations from the predicted pattern depend on the sorption of gas by the rock (the stronger the sorption, the greater the deviation). Discrepancies in the permeability of the porous medium under investigation using the flow of different gases can might be due to a dissimilar interaction of a gas with the surface of the pore walls (as in the slippage effect, also called Klinkenberg's effect) or the properties of the medium, such as density or viscosity, which can affect the velocity field the in porous area.

The permeability values determined for a steady flow of nitrogen and helium, first for unheated rocks and then for rocks heated, sequentially to temperatures of 100°C, 200°C, 300°C and 500°C are presented in collective diagrams for each gas.

Fig. 2a illustrates changes in the permeability of the Tumlin sandstone in a flow of nitrogen over the whole range of applied pressures; Fig. 2b presents the same for helium.

The unheated sandstone exhibits, at a mean nitrogen flow- pressure of 150 kPa, a permeability of 0.074×10^{-15} m^2 (0.074 mD), which indicates a considerable rock porosity. Heating a sample to 100°C results in its apparent dehumidification and the desorption of all gases contained in it. Its structure becomes very easily accessible to the flowing nitrogen, which is reflected in a noticeable increase of the permeability, that is, up to 0.61 mD (over eight times as great as the initial value). According to Homand and Duffaut (in the monograph Manuel de Mécanique des Roches [Manual of Rock Mechanics] 2000), the drying up of sandstone mostly concerns its binding material.

A considerable amount of gravitational water appearing in the macropores of the illitic binder is removed by heating to temperature of 100°C, while the water of crystallisation in its hydrated minerals can only be released at a temperature exceeding 500°C. The heating of sandstone up to 200°C and particularly in the 200–300°C range, is connected with a decrease in its permeability (respectively 0.56 mD and 0.22 mD). This seems rather surprising, as the research by Gustkiewicz et al. (2001) concerning the effect of temperature on permanent changes in rocks showed that an increase in temperature led to the appearance of micro-cracks in the rock. A rock is a material composed of minerals of different coefficients of thermal expansion. Different physical changes in adjacent components produces internal thermo-elastic stresses in the rock, which lead to such fractures. It is possible that in sandstone, which is a clastic rock with a grainy structure, such a rise in temperature can result in closing the cracks

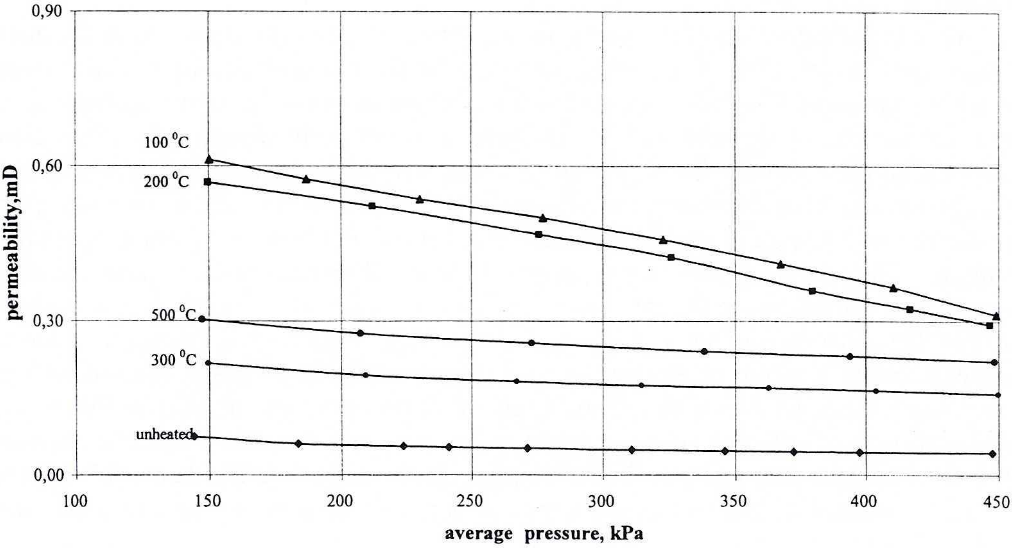

Fig. 2a. The change sandstone permeability to nitrogen flow in response to heating

Rys. 2a. Zmiana przepuszczalności wygrzewanego piaskowca w przepływie azotu

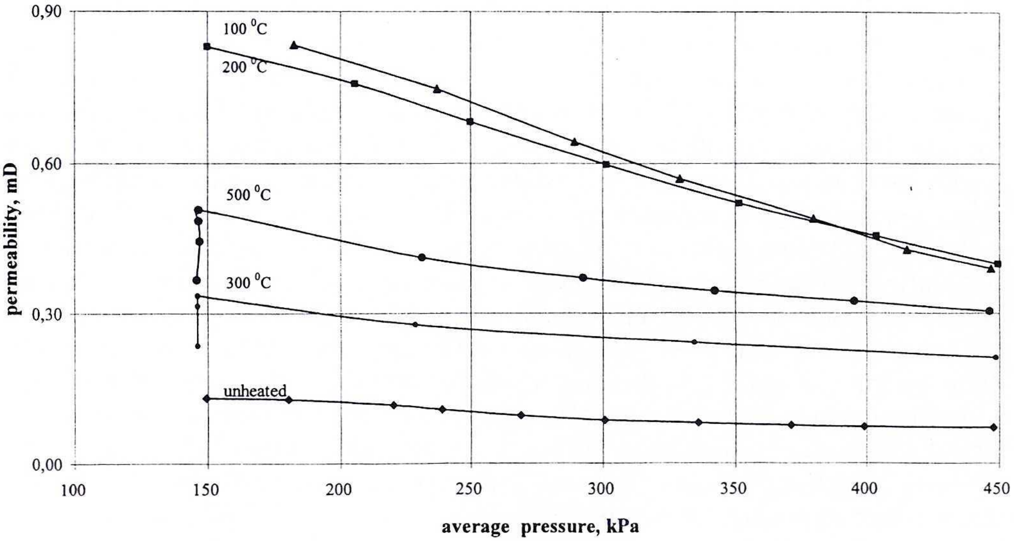

Fig. 2b. The change sandstone permeability to helium flow in response to heating

Rys. 2b. Zmiana przepuszczalności wygrzewanego piaskowca w przepływie helu (i.e. a reversible deformation and relative movement of the grains leading to their tighter and irreversible packing). Possibly, temperature can also affect the binding material of sandstone, thus causing the clogging of channels hitherto permeable to gas flow. According to Gustkiewicz (2001), the influence of temperature on the porosity of micro-cracks in sandstone is small; below 300°C it is only about 0.5‰, which at 500°C may rise to as much as 2‰. Therefore the slight increase in permeability (up to 0.3 mD) of the Tumlin sandstone) when heated up to 500°C, can be attributed to slightly greater destruction of that rock as well as by the removal of water and other changes in the rock matrix.

Changes in the permeability of sandstone as a result of heating in the case of helium-flow are very similar (Fig. 2b). The numerical values of permeability obtained for the flow of helium are about 50% higher than the equivalent values for nitrogen. In the flow of this inert and non-sorptive gas with small particles the total change in permeability may be ascribed solely to the slippage effect of helium particles on the pore walls of the tested material.

A better illustration of the temperature effect on changes in the filtering properties of sandstone (i.e. a change in its permeability) is presented in Fig. 3.

The diagram presents the permeability values corresponding to the steady states of nitrogen and helium flows at mean flow pressures of 150 kPa and 450 kPa. It can be clearly seen that the initial increase in temperature (up to 100°C) causes a considerable increase in the sandstone's permeability but later it works in the opposite direction, though to a lesser degree. It is only the further heating (up to 500°C) that leads to another slight increase in permeability, caused by the superimposition of two factors: the removal of the water of crystallisation and other changes occurring in the matrix.

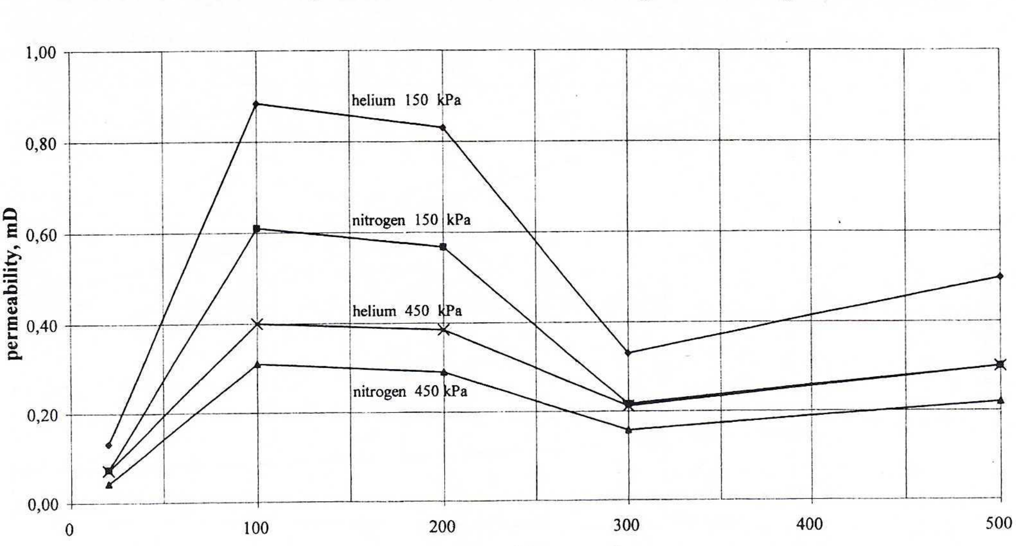

Fig. 3. The change in Tumlin sandstone permeability in relation to its temperature

Rys. 3. Zmiana przepuszczalności piaskowca Tumlin w zależności od temperatury jego wygrzewania

Analogous dependencies of changes on the temperature were obtained for the fine-grained granite from Strzelin. Fig. 4a shows changes in permeability for unheated granite as well as for granite exposed to temperatures increases up to 500°C, over

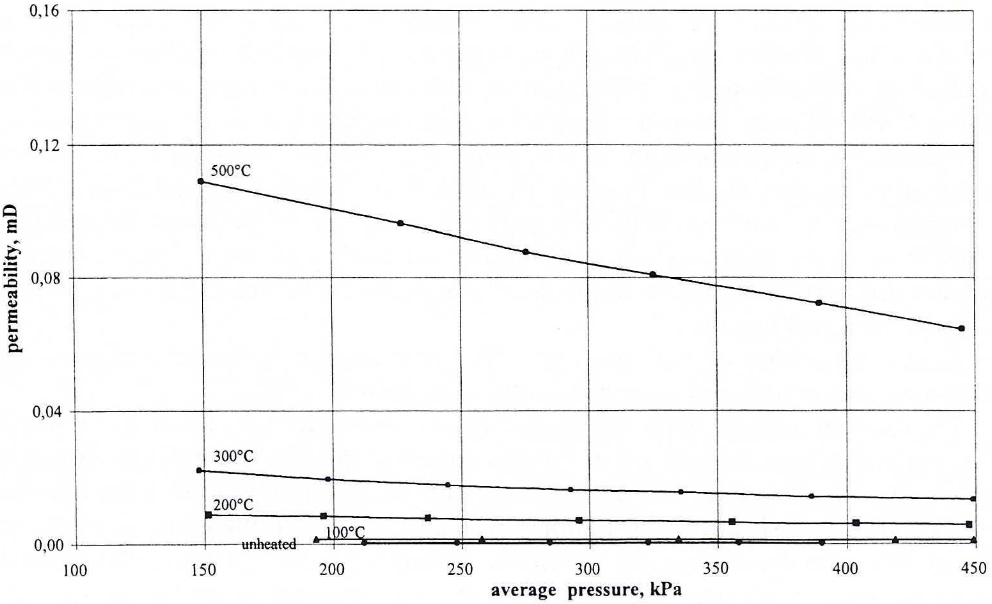

Fig. 4a. The change fine-grained granite permeability to nitrogen flow in response to heating

Rys. 4a. Zmiana przepuszczalności wygrzewanego granitu drobnoziarnistego w przepływie azotu

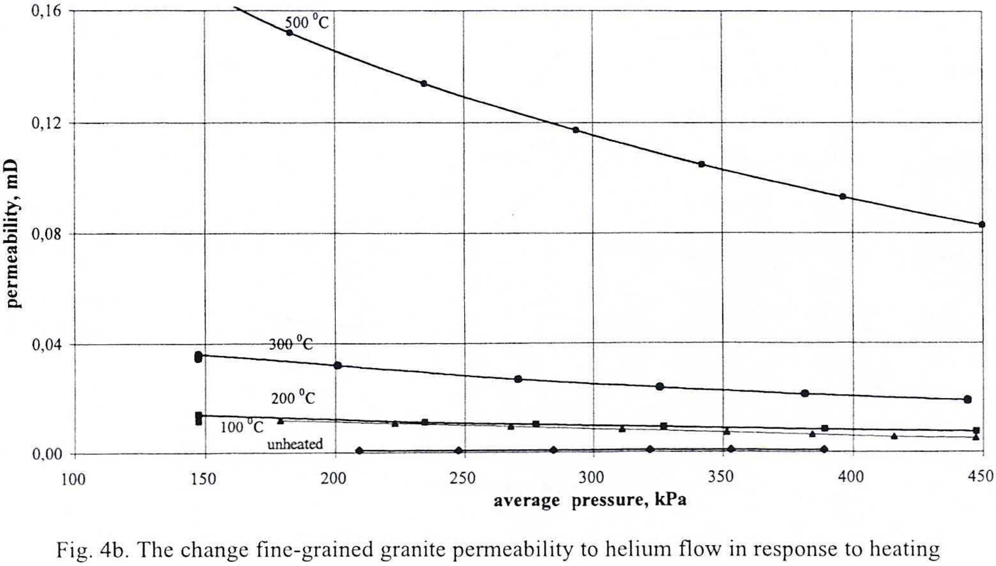

Fig. 4b. The change fine-grained granite permeability to helium flow in response to heating

Rys. 4b. Zmiana przepuszczalności wygrzewanego granitu drobnoziarnistego w przepływie helu the whole range of pressures applied to the flowing nitrogen. At a mean pressure of nitrogen of 150 kPa, an unheated granite sample shows a permeability of 4.2×10^{-19} m^2 (0.00042 mD), showing its resistance to flow. In comparison with sandstone the permeability of this rock is much lower. During the heating of the granite its permeability gradually increases from at through to; its value is 0.0015 mD for 100°C, 0.0088 mD for 200°C, 0.0222 mD for 300°C and 0.109 mD for 500°C. This increase is caused by the dehydration up of granite (i.e. the removal of the free water at 100°C) and possibly by the preferential direction of the thermal expansion of the rock material, resulting from the directional array of biotite plates appearing in the granite. Gustkiewicz et al. (2001) observed a distinct increase in strains and porosity of granite with as the temperature rose, especially above 200°C. Within the range of temperatures examined by them, such changes were many (20–100) times greater for granite than for sandstone.

Those observations correlate fairly well with the measurements obtained in this test-programme. The permeability of the fine-grained granite in the nitrogen flow during its heating up to 500°C increased nearly 260 times with an initial nitrogen pressure of 0.2 MPa, whereas in the case of the Tumlin sandstone it was less than four times. Nowakowski and Konečny (2002) also showed that the changes resulting from heating Tumlin sandstone up to 500°C were small in comparison with the changes in the fine-grained granite; it was found that the permeability of the sandstone lacked a regular relationship with the temperature in a tri-axial stress-state. The changes in the longitudinal sound wave velocity, caused by the heating of a sample, are also small in the case of sandstone as compared to those measured for granite.

The effect of heating the samples of the fine-grained granite from Strzelin on its permeability to a flow of helium is quite similar (Fig. 4b). Because of the smaller size and chemically inert character of the particles of this gas, the numerical permeability values in its flow are about 50% higher than the values obtained for nitrogen flow under identical conditions. In the case of nitrogen the change in the permeability did not directly indicate the dehydration up of the granite sample at 100°C. At the mean gas pressure of 150 kPa, the permeability increased about four times. In a helium flow the change in the permeability is considerable; for a sample heated up to 100°C its value is 0.012 mD and for an unheated sample it is equal to 0.00086 mD, that is, it increases fourteen times.

As for sandstone, the change in the permeability of the fine-textured granite in relation to its temperature is presented in Fig.5.

Changes in permeability of the fine-grained granite, corresponding to steady flows of nitrogen and helium at mean pressures of 150 kPa and 450 kPa, increase monotonically as the temperature of the samples rises. While at the temperature of 100°C, the granite is mostly dehydrated; further heating is accompanied by its volumetric expansion as well as a significant increase in strains and the number of cracks in the test-sample (Gustkiewicz et al. 2001).

For the coarse-grained granite the progress and sequences of changes in permeability with the increases of temperature are identical in quality for either gas as those for the fine-grained granite (Fig. 6).

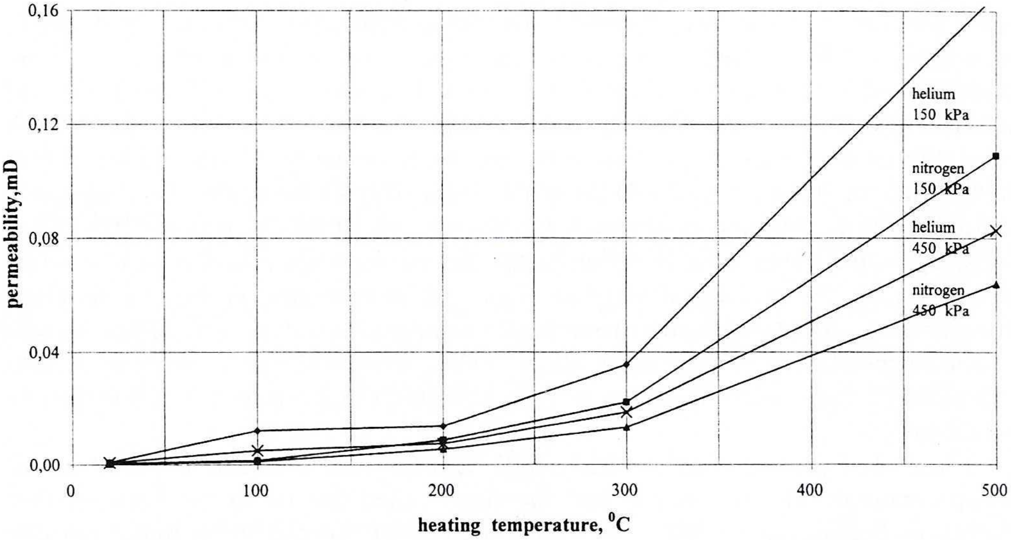

Fig. 5. The change in the Strzelin fine-grained granite permeability in relation to its temperature

Rys. 5. Zmiana przepuszczalności drobnoziarnistego granitu Strzelin w zależności od temperatury jego wygrzewania

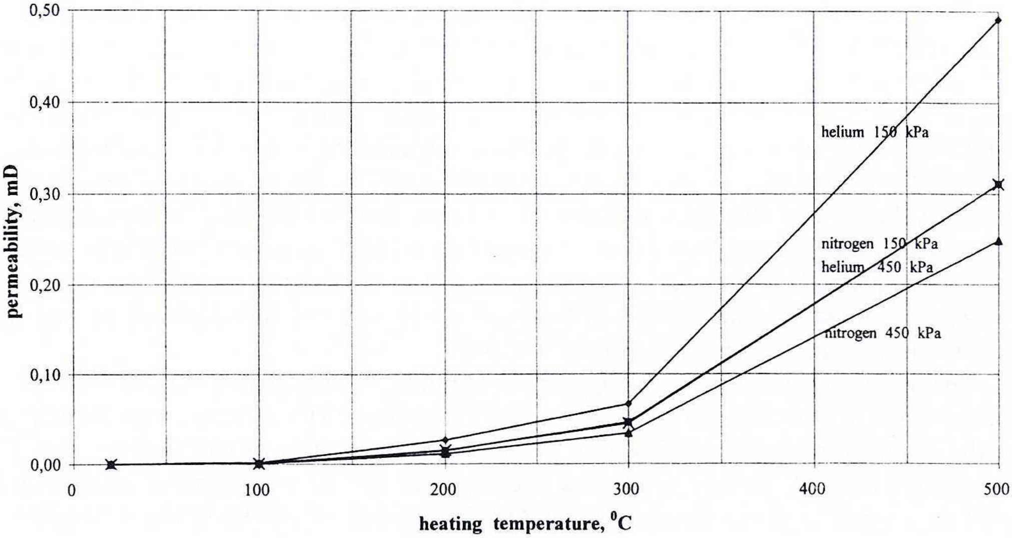

Fig. 6. The change in the Strzelin coarse-grained granite permeability in relation to its temperature

Rys. 6. Zmiana przepuszczalności gruboziarnistego granitu Strzelin w zależności od temperatury jego wygrzewania

Unheated samples of the coarse-grained granite are characterised by an extremely low permeability in the flow of both gases; being, however, nearly one order of magnitude lower than in the case of the fine-grained granite. Only after heating the samples to above 200°C do numerous cracks appear in the rock. The permeability values of samples heated to 300°C and 500°C are much higher than the respective values for the fine-grained granite. The permeability of nitrogen flow when the temperature was raised to 500°C increased over 5000 times in relation to the permeability of an unheated sample. In an analogous situation the permeability of the fine-grained granite increased 260 times. A similar effect of temperature elevation on the changes in permeability was also observed for helium.

These results are fairly consistent with those obtained by Homand-Etienne and Houpert (1989). In their research samples of fine-grained and coarse-grained granites heated up to temperature of 600°C indicated an increase in the concentration of the temperature-induced cracks. They found that for the coarse-grained granite a considerably higher increase in the creation of cracks and porosity was observed as compared with fine-structured grained granite. This is considered to be due to a lower modulus of elasticity and tensile strength of the rock.

4. Conclusions

The investigation of the permeability in the flow of gases was conducted in sandstone from Tumlin and samples of fine and coarse crystalline granite samples from Strzelin.

The investigation of the permeability of sandstone and granite to the flow of nitrogen and helium has been conducted both in unheated sandstone and granite samples and samples subsequently heated to stage temperatures of 100°C, 200°C, 300°C and 500°C. The effect of temperature on rock permeability is essential, since waste stored in rocks is frequently thermally active and its presence, as a result of a combined thermo-poro-mechanical effect, can lead to an increase in the pressure of the fluid flowing from the waste. In the investigation described it was observed that the higher the temperature of the sandstone and granite samples, the quicker the stabilisation of both flows of nitrogen and helium flows are stabilised.

Heating Tumlin sandstone 100°C desiccation; that is the removal of free water present in the macropores of the binding material and a more than eightfold increase in the permeability of the whole. Heating the sandstone to 200°C and, more significantly, to 300°C leads to a decrease in the flow of gas, which is assumed to be caused by a decrease in permeability. Heating the sandstone to 500°C causes a slightly increased destruction of the rock as well as a removal of the water retained within the illitic binding agent of the sandstone; hence a slight increase in permeability can be observed. Using helium, the changes in the permeability of the sandstone, caused by its being heated, are very similar. The numerical permeability values are about 50% higher than the comparable values obtained for nitrogen flow.

Heating the fine-grained granite results in a monotonic increase of its permeability. This is attributable to the desiccation of the granite as well as the preferential direction of its expansion (i.e., the array of biotite plates). The permeability of that granite in a nitrogen flow increased during heating up to 500°C by nearly 260 times, at an initial nitrogen pressure of 0.2 MPa whereas for the Tumlin sandstone the permeability increased by less than four times. The effect of heating samples of the Strzelin fine-grained granite on their permeability in the flow of helium is very similar.

For coarse-grained granite, the progress and sequences of permeability changes with the temperature in the flow of both gases are identical in quality to those occurring in the case of the fine-grained granite. Unheated samples of coarse-grained granite exhibit an extremely low permeability in the flow of both gases. However, the permeability values of samples heated to 300°C and 500°C are considerably higher than in the case of the fine-grained granite. The above results are fairly consistent with those obtained by Homand-Etienne and Houpert in their research (1989).

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