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# CHANGES OF SELECTED STRUCTURAL AND MECHANICAL PROPERTIES OF THE STRZELIN GRANITES AS INDUCED BY THERMAL LOADS

# WPŁYW OBCIĄŻEŃ TERMICZNYCH NA ZMIANY NIEKTÓRYCH STRUKTURALNYCH I MECHANICZNYCH WŁAŚCIWOŚCI GRANITÓW STRZELIŃSKICH

Temperature is one of the basic factors influencing physical and structural properties of rocks. A quantitative and qualitative description of this influence becomes essential in underground construction and, in particular, in the construction of various underground storage facilities, including nuclear waste repositories. The present paper discusses the effects of temperature changes on selected mechanical and structural parameters of the Strzelin granites. Its authors focused on analyzing the changes of granite properties that accompany rapid temperature changes, for temperatures lower than 573ºC, which is the value at which the $\beta - \alpha$ phase transition in quartz occurs. Some of the criteria for selecting the temperature range were the results of measurements carried out at nuclear waste repositories. It was demonstrated that, as a result of the adopted procedure of heating and cooling of samples, the examined rock starts to reveal measurable structural changes, which, in turn, induces vital changes of its selected mechanical properties. In particular, it was shown that one of the quantities describing the structure of the rock – namely, the fracture network – grew significantly. As a consequence, vital changes could be observed in the following physical quantities characterizing the rock: primary wave velocity ($v_p$), permeability coefficient ($k$), total porosity ($n$) and fracture porosity ($\eta$), limit of compressive strength (${}^R\sigma_1$) and the accompanying deformation (${}^R\varepsilon_1$), Young's modulus (E), and Poisson's ratio ($v$).

**Keywords:** rock properties, rock structure, thermal load, cracks, sound wave velocity, porosity, permeability, compressive strength, Young modulus, Poisson ratio

Wśród wielu czynników wpływających na właściwości fizyczne i strukturalne skał jednym z najważniejszych jest bez wątpienia temperatura. Jej podwyższenie lub obniżenie może prowadzić do zmian struktury, spowodować przemiany fazowe składników, zmieniać skład chemiczny a wreszcie, stan skupienia skały. Procesy te mogą więc w istotny sposób zmienić właściwości fizyczne skały, co jest istotne między innymi z punktu widzenia szeroko rozumianego budownictwa podziemnego. Zmiany temperatury skały mogą wynikać z warunków naturalnych, w jakich się ona znajduje lub być konsekwencją działalności człowieka. Szczególnym przypadkiem takiej działalności jest budowa różnego typu składowisk pod-

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ziemnych czy to magazynowych (np. magazyny paliw płynnych) czy też „podziemnych śmietników" na różnego rodzaju odpady, także promieniotwórcze.

Artykuł skupia się na badaniach wpływu zmian temperatury na wybrane parametry mechaniczne i strukturalne granitów ze Strzelina. Autorzy skoncentrowali się na analizie zmian właściwości tych skał towarzyszących szybkim zmianom temperatury, w zakresie od temperatury pokojowej do 573ºC, czyli do temperatury, przy której zachodzi przemiana fazowa kwarcu $\beta - \alpha$.

Badania prowadzono na dwóch odmianach granitoidów z masywu Strzelin-Żulowa. Jedna z nich to odmiana „młodszą", tzw. normalna, o charakterze adamellitu a druga to odmiana „starszą" wykazującą podobieństwo do gnejsów. Na potrzeby niniejszej pracy granit normalny nazywano granitem gruboziarnistym, a granit gnejsowaty – drobnoziarnistym.

Procedura badawcza polegała na tym, że walcowe próbki skal umieszczano w piecu nagrzanym do zadanej temperatury, celem wywołania „szoku" termicznego. Stosowano temperatury 100, 200, 300 i 500 stopni Celsjusza. Po upływie 60 minut piec, w którym znajdowała się próbka wyłączano i stygł on wraz z próbką do temperatury pokojowej. Przyjęty czas wygrzewania miał zapewnić równomierne nagrzanie próbki w całej jej objętości. Wyznaczony on został na podstawie pomiarów przewodnictwa temperaturowego.

Wyniki badań mikroskopowych przeprowadzone dla granitów wygrzewanych w opisany sposób wskazują, że istotną zmianą strukturalną jest powstanie nowych i (lub) rozrost już istniejących spękań. W pracy zaprezentowano wyniki badań ilościowych, które świadczą o tym, że zastosowana procedura grzania szokowego pociąga ze sobą wzrost spękań rozumiany zarówno jako wzrost ich długości jak i rozwartości a w konsekwencji ich powierzchni (patrz rys. 6), Ponadto spękania te są praktycznie niezauważalne pod mikroskopem optycznym i uwidaczniają się dopiero pod mikroskopem skaningowym, Analizując dwie odmiany granitu zauważono, że zdecydowanie większy wzrost spękań występuje w granicie gruboziarnistym. Jakkolwiek rozrost istniejących i powstanie nowych spękań nie są jedynymi zmianami strukturalnymi zauważonymi w podgrzewanych skałach (porównaj rozdział 3.1 i 3.2), to w rezultacie zaprezentowanych wyników badań przyjęto, że są one tym procesem, który wywiera największy wpływ na właściwości fizyczne badanych skał.

W badanych nie zaobserwowano przemian fazowych. Zwrócono natomiast uwagę na niewielkie zmiany chemiczne. Ich przykładem może być np. oksydacja skaleni i biotytu, czego efektem jest opisana zmiana barwy biotytu (patrz rys. 5).

Badania dylatometryczne, których wynik zaprezentowano na rys 17 pokazały, że względny przyrost wymiarów liniowych próbek skał towarzyszący zmianom temperatury w przyjętym zakresie osiąga 0,085% dla granitu drobno- i 0,11% dla gruboziarnistego. Zakładając, że granity można uważać za skały jednorodne i izotropowe można w tym momencie oszacować, że ich trwała zmiana objętości (dylatancja) będąca wynikiem grzania szokowego wyniesie odpowiednio 0,255% i 0,33%. Są to wartości tego samego rzędu, co pokazane wcześniej (rys. 16) wartości porowatości spękań.

Potwierdzeniem przypuszczeń o związku pomiędzy przyjętą procedurą obróbki termicznej skały a powstawaniem w niej spękań są wyniki badań przepuszczalności oraz badań porozymetrycznych pokazane w rozdz. 4.2. Zależności widoczne na rys. 8, 9 i 10 pokazują, że dla badanych granitów wraz ze wzrostem temperatury grzania szokowego następuje wyraźny wzrost przepuszczalności i porowatości. Należy przy tym wziąć pod uwagę, że zarówno badania porozymetryczne jak i badania przepuszczalności dostarczają jedynie informacji na temat spękań otwartych, połączonych ze sobą i z brzegami próbki. Nie dają one natomiast żadnych informacji na temat spękań izolowanych.

Analizując wyniki testów jednoosiowego ściskania stwierdzić należy, że dla badanego materiału wraz ze wzrostem temperatury grzania szokowego zaobserwowano spadek wytrzymałości oraz sztywności próbki (rys. 11 i 13) połączony ze wzrostem jej odkształcalności (rys. 12). Przyczyny takiego zachowania badanych próbek granitowych można powiązać zpojawianiem się – w wyniku procedury grzania szokowego – nowych oraz rozrostem istniejących już w próbce mikrospękań.

W rozdziale 4.3 zaprezentowano wyniki pomiarów współczynnika Poissona. Dla badanych granitów trudno dopatrzyć regularności w zależności $\nu(T_g)$, co może być konsekwencją trudności związanych ze stosowaną techniką pomiaru odkształceń poprzecznych Wydaje się jednak, że anomalia zilustrowana na rys. 14 jest zjawiskiem fizycznym polegającym na tym, że deformacja poprzeczna szkieletu próbki podczas jej jednoosiowego ściskania powoduje zamykanie się w próbce tych spękań, które są odchylone od kierunku siły obciążającej.

Reasumując należy stwierdzić, że w pracy wykazano, że wskutek przyjętej procedury ogrzewania i chłodzenia próbek w badanych granitach zachodzą mierzalne zmiany strukturalne pociągające za sobą istotne zmiany wybranych właściwości mechanicznych. W szczególności wykazano, że spośród wielkości

charakteryzujących strukturę skały znaczącemu rozrostowi uległa sieć spękań. Konsekwencją tych zmian były znaczące zmiany takich charakteryzujących skałę wielkości fizycznych jak: prędkość podłużnej fali akustycznej ($v_p$), współczynnik przepuszczalności ($k$), porowatość całkowita ($n$) i porowatość spękań ($\eta$), granica wytrzymałości na ściskanie (${}^{R}\sigma_1$) i towarzyszące jej odkształcenie (${}^{R}\varepsilon_1$), moduł Younga ($E$) i współczynnik Poissona ($v$).

**Słowa kluczowe:** właciwości skał, struktura skał, obciążenie termiczne, spękania, prędkość fali dźwiękowej, porowatość, przepuszczalność, wytrzymałość na jednoosiowe ściskanie, moduł Younga, współczynnik Poissona

# 1. Introduction

Temperature is undoubtedly one of the most important factors influencing physical and structural properties of rocks. Its rise or drop may bring about changes in a rock's structures, effect phase transitions of the its ingredients, or change its chemical composition, as well as its state of matter. Thus, these processes may change physical properties of a rock in a significant manner, which is of vital importance in broadly defined underground construction industry. Possible changes of rock temperature may have their source in natural conditions affecting the rock, or in human activity. A particular example of the latter is construction of various underground storage facilities, such as storage tanks (e.g. for liquid fuels) or “underground dumping sites” for different types of waste. In the case of liquid fuel storage tanks, determining the influence of temperature changes on selected properties of reservoir rocks – as demonstrated by Araújo et al. (1997) – might prove to be essential. In the case of nuclear waste repositories, one should take into account the fact that containers with such waste, placed in a stratum, are powerful sources of heat. The results of measurements of stratum temperature, carried out at the nuclear waste repository in Yucca Mountain in the U.S. state of Nevada (Boyle & Datta, 1999), showed an up to ca. 200°C increase in the temperature of the rock in the direct vicinity of the repository. The significance of the impact of temperature in underground storage facilities on rock properties is also emphasized by Hudson (1999) in his work summarizing twenty years' worth of the British rock mechanics' experience in the field of exploitation of underground nuclear waste repositories. According to Hudson, the imperative to take thermal effects in a rock mass into consideration is one of the fundamental conclusions reached in the course of all the projects related to this particular science that have ever been undertaken in the United Kingdom. Riekkola and Salo (1999), discussing corresponding experiences of Finnish scientists, emphasize the importance of laboratory and *in situ* investigations in the process of designing and exploiting a storage facility, while at the same time paying special attention to the question of tightness of rocks around it.

When attempting to analyze the influence of changes in the temperature of a rock on its properties, one needs to realize that a rock as such is not a homogenous material but an aggregate composed of minerals whose coefficients of thermal expansion differ from each other. Additionally, these minerals frequently display significant anisotropy of the coefficient in question. These differences may induce thermal stresses within the rock, which can lead to emergence of new fractures and enlargement of the already existing ones. Comprehensive studies on the topic were published by Wong and Brace (1979) and Alm et al. (1985). Homand-Etienne and Houpert (1989), in turn, demonstrated how the porosity of the fractures in selected rocks changes with an increase in the temperature of sample heating, and David et al. (1999) analyzed the impact of temperature-induced fractures on the microstructure and selected physical properties of the

La Peyratte granite. Development of thermal fractures in granite was also observed – by means of an ongoing monitoring of acoustic emission – by Calleja and Ruiz de Argandona (1984) and Jansen et al. (1993). The results obtained by these researchers showed that microfractures can be observed as early as when the temperature value exceeds 80°C, and they can subsequently join together, forming structures that are macroscopic in their nature. Chaki et al. (2008), in their study of the impact of an increase of temperature to the value of 600ºC on selected properties of granite rocks, introduce the notion of "thermal damage", i.e. a significant increase in the number of fractures resulting from changes in the rock temperature.

The aforementioned changes of temperature occurring in the vicinity of radioactive waste repositories, discussed by Boyle and Datta (Boyle & Datta, 1999), may have serious consequences – namely, significant changes in rock permeability (cf. Skoczylas & Henry, 1995). The importance of the issue in question (i.e., of the temperature-induced changes in rock permeability) has been repeatedly stressed by such authors as Heard and Page (1982), Vogele and Brace (1985), Darot et al. (1992), Lin and Daily (1990), and Danek et al. (2001). All of them also referred to the impact of thermal fractures on broadly defined filtration properties of a rock.

When analyzing papers that investigate the relation between the temperature of a given rock and the mechanical properties of this rock, one can come to the conclusion that this question is often studied not as a separate issue, but as one connected with the influence exerted by pressure. It is advisable to begin an overview of these works with a series of papers written by Griggs. The first one (Griggs et al., 1951) discusses a very narrow scope of temperature values (up to 150°C) – however, in the next ones (Griggs et al., 1960; Griggs & Handin, 1960), the authors go further, providing us with a description of behavior of certain rocks and minerals subjected to temperature values of up to 800°C. Such laboratory investigations are seldom carried out, as they require the usage of triaxial apparatuses, which make it possible to apply pressure values of several hundred megapascals and temperature values reaching up to 1000ºC. Still, one can mention in this context a paper by Brace and Kohlstedt (1980), as well as a more recent one by Jiang et al. (2000). It is also worth mentioning that there exist works analyzing the impact of temperature increasing with depth, in the context of exploitation carried out in underground mines (Taufer et al., 2010), or of physical and chemical properties of coal and their influence on work safety (Wierzbicki & Dutka, 2010).

Polish authors have also tackled the subject in question. The most significant of their works are, among others, papers by Chmura, devoted mainly to studies of rocks extracted from Polish hard coal basins (Chmura, 1970; Chmura & Myrcha, 1980; Chmura & Chudek, 1999). Single chapters discussing the subject can be found in textbooks by Hobler (1977) and Ryncarz (1993). The influence of temperature on rock properties was also of interest to Pinińska, whose two papers (Pinińska, 1980a, 1980b) discuss the results of studies into the impact of high temperatures on physical properties of the Krosno sandstones. A comprehensive monograph upon the subject was also written by Nowakowski et al. (2003), who in this way summarized the outcomes of a three-year-long research project financed by the State Committee for Scientific Research (KBN). The topic is also discussed at country-level conferences on geomechanics, as shown by works of Nowakowski and Konečný (2002), Nowakowski (2003), and Młynarczuk and Ratajczak (2003).

## 2. Research material

The research was conducted on two varieties of granites from the Strzelin-Žulowa massif – the first one being the so-called normal, "younger" variety, adamellite-like in nature; the other – the "older" variety, revealing similarity to gneisses. These granitoids are igneous (magmatic) rocks that have a holocrystalline structure consisting of quartz crystals, feldspars, biotites, and sparse chlorites. Another feature of these rocks is that quartz found in them assumes the form of grains. The Strzelin normal granite is even-grained, light grey, with black, disorderly scattered biotite. The potassium feldspar found in it is microcline, and the plagioclases occur there as oligoclase. The Strzelin gneiss-granite is fine-grained. The plagioclase occurring in it tends to dominate the potassium feldspar to an extent greater than in the case of the normal granite. Locally, the Strzelin gneiss-granite reveals a parallel texture marked by streak-like arrangement of the biotite plates. Table 1 presents the mineral composition of the granite varieties which constitute the research material employed in the present study.

TABLE 1

The mineral composition of the granites used in the present study

| **Minerals** | **Normal granite "coarse-grained granite"** | | **Gneiss-granite "fine-grained granite"** | |
|---|---|---|---|---|
| | **Volume ratio [%]** | **Size [mm]** | **Volume ratio [%]** | **Size [mm]** |
| quartz | 29.5 | 0.4-2.0 | 26.0 | 0.2-1.0 |
| potassium feldspar | 27.6 | 0.5-5.0 | 23.0 | 0.2-2.0 |
| plagioclase | 36.1 | 0.5-5.0 | 43.5 | 0.2-2.0 |
| biotite | 5.5 | 0.5-3.0 | 6.5 | 0.1-1.0 |
| chlorites | 1.2 | 0.5-1.0 | 0 | - |

The reasons for which these rocks were chosen as research material were their similar mineral composition and a significant difference in the size of minerals, which should be demonstrated by differences in their thermal expansion. Thus, from now on, the normal granite (the "younger" one) shall be referred to as "coarse-grained granite", and the gneiss-granite (the "older" one) – as "fine-grained granite".

For research purposes, cylinder-shaped samples of the diameter $\phi = 22$ mm and the height-diameter ratio (slenderness ratio) $\lambda = 2$ were made. The samples were then placed in a furnace preheated to a given temperature so that "thermal shock" would occur. The applied temperature values were 100, 200, 300, and 500 centigrades, and they were selected with respect to the results of temperature measurements in a nuclear waste repository as provided by Boyle and Datta (1999). It was also assumed that the research would be conducted with a temperature of less than 573ºC, which is the value at which $\beta$-quartz transforms to $\alpha$-quartz. The furnace with the sample was turned off after 60 minutes and left to cool down (together with the sample) until it reached room temperature. Such a time span was adopted in order to ensure even heating of the sample in its entire volume, and was determined on the basis of temperature conductivity measurements (cf. Nowakowski et al., 2003).

# 3. Analysis of structural changes

## 3.1. Microscopic observations

A microscopic inspection of thin sections made of granite samples subjected to a thermal load indicates that the first structural damage occurs when rocks are heated to 300°C. Locally, quartz aggregates disintegrate into separate grains. Under the temperature of 500°C, however, disintegration occurs for most such aggregates (Fig. 1). Starting with the temperature of 300°C, gradual oxidation of feldspar grains and biotite grains can be observed. During oxidation of silicates containing ferrous oxides (FeO), ferric oxides ($Fe_2O_3$) are formed, as decomposition products. In the case of feldspars, one can observe an increase in their opacity, caused by the products of the decomposition in question (Fig. 2). Under the temperature of 500°C, due to the oxidation process, biotite changes its pleochroic color from olive-honey to darker one, almost black in parts. It was also observed that, under the very same temperature of 500°C, relocation of biotite borders occurs, which is manifested by a greater distinctness of its contours. Additionally, the cleavage fractures in biotite get thicker, and non-oriented transcrystalline fractures, running through feldspars, are formed. However, a definite majority of the observed fractures, formed in the aftermath of thermal stresses, are intercrystalline in nature (as confirmed by observations of Mendez et al. (1999)). It needs to be emphasized that such changes are mostly perceived more easily when the rock being inspected is a coarse-grained granite. In a fine-grained granite, certain arrangement of the biotite plates testifies to a privileged direction of the expansion of the rock material, which is sometimes observed as a network of fractures issuing from the plates (Fig. 3). All the changes described above are submicroscopic changes, which are often difficult to discern with an optical microscope. In particular, this concerns observations of the forming fractures and relocation (expansion) of intergranular borders. The presence of such discontinuities can only be confirmed by means of a scanning microscope. Fig. 4 presents examples of inter- and transcrystalline fractures in a coarse-grained granite, formed as a result of heating the sample to the temperature of 500°C.

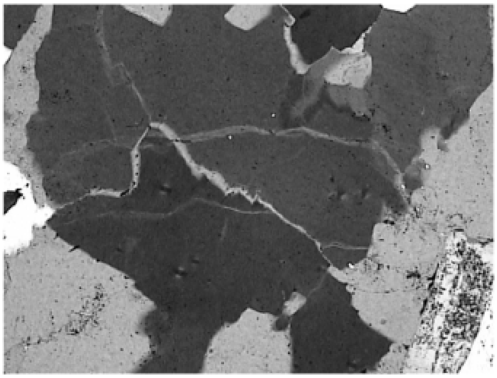

Fig. 1. Disintegration of quartz aggregates (coarse-grained granites, temperature 500°C, magnification 100×, crossed nicols)

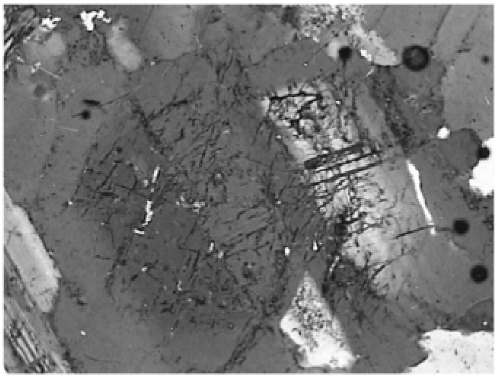

Fig. 2. Decomposition of the feldspar structure (fine-grained granite, temperature 500°C, magnification 100×, 1 nicol)

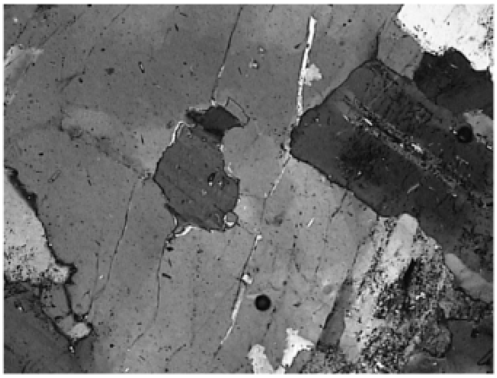

Fig. 3. Fractures issuing from the expanded biotite (fine-grained granite, temperature 500°C, magnification 100×, crossed nicols)

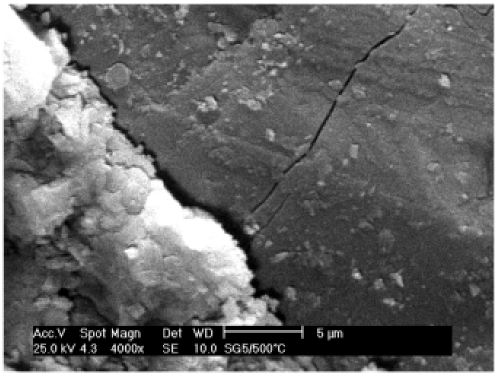

Fig. 4. Fractures in coarse-grained granite, SEM microscope, magnification 4000×, temperature 500°C

## 3.2. Quantitative assessment of the biotite color change in the Strzelin granites

During the research process, it was observed that gradual oxidation of biotite and feldspars in the studied granites starts at 300°C. This leads to a change in the intensity of the pleochronic color, from olive-honey to darker one, almost black in parts. In order to provide a quantitative description of these changes, nine randomly chosen fields with biotite, placed on thin sections of the studied granites, were registered with an optical microscope (magnification 100×, polarized light, one polarizer). Due to the fact that biotite is a pleochronic mineral which changes its color depending on the positioning of the sample in relation to the polarizer, each observed field was registered five times, with five various positions of the rotary table, within the range of 0-90 degrees. The aim of this was to register both the minimum and the maximum brightness values for each biotite.

The analysis of the biotite color consisted in measuring the profile of the levels of greyness along the lines drawn in each registered field. The lines were drawn arbitrarily; however, they were contained only in the biotite grains and, whenever possible, encompassed their full width. Along these lines, on the images of the same field registered at various positions of the polarizer, measurements of the values of the pixel greyness levels were carried out. As the final outcome of the analysis could have been influenced by such factors as the thickness of the thin section, the amount of the microscope light, or the quality of the camera, the acquisition was carried out in such a way that all the images were registered with the same settings of the microscope light intensity. In order to describe the changes in the biotite brightness, the mean values of the component L from the HLS color model (Fig. 5) were analyzed. As can be seen in the graph presented in Fig. 5, up to the temperature of 200°C, the level of brightness of the biotite grains remains more or less the same. However, the biotite grains do darken significantly when subjected to shock heating to the temperature of 500°C. This confirms, in a quantitative manner, subjective observations suggesting that, with an increase in the temperature of heating, oxidation of the biotite grains occurs, which causes them to darken.

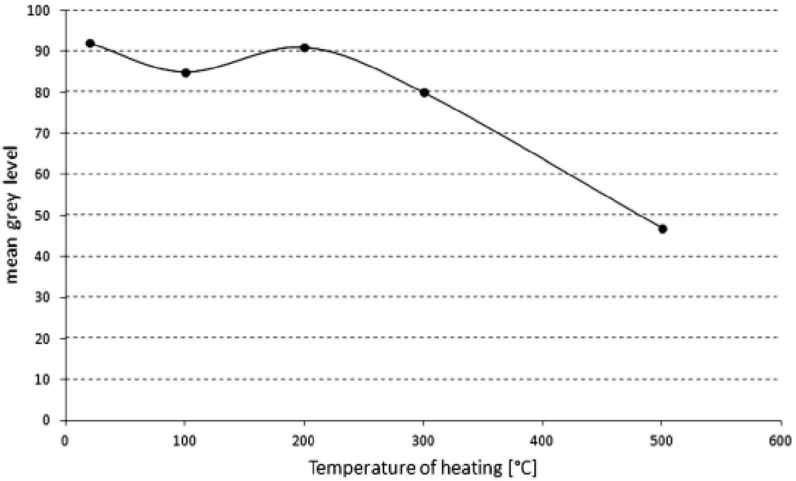

Fig. 5. Change of the mean greyness levels of the lumination component for biotite in relation to the temperature of the shock heating of samples (the scope of the greyness levels is 255 (white) – 0 (black))

## 3.3. Quantitative description of thermally induced fractures

A lot of scientists is of the opinion that changes in the mechanical properties of rocks subjected to thermal loads are caused mainly by fractures, which, in turn, are formed due to these loads (Alm et al. (1985), Hommand-Etienne and Houpert (1989), Menendez et al. (1999)). Therefore, microscopic observations were carried out in order to verify the existence of such a correlation, as well as to determine whether it could be described in a quantitative manner.

For a quantitative determination of the impact of temperature on the expansion of fracturing, the coefficient of fracturing ($S_L$) – describing the relation of the area of fracture traces to the area of the field observed on the investigated rock – was applied.

$$S_L = \frac{\sum_i S_{Fi}}{S} \cdot 100\% \tag{1}$$

where: $S_{Fi}$ – area of the fracture $i$, $S$ – area of the investigated rock.

The analysis of the values of the $S_L$ coefficients, measured for various magnifications of both the optical and the scanning microscope, proved that the parameter in question is strongly dependent on the adopted magnification. Additionally, a definite increase in the $S_L$ value was observed, which occurred within the 1000×–4000× magnification range. This might indicate that, as a result of shock heating (in the analyzed case, for $T_g = 500°C$), a substantial number of fractures appears, and that these fractures become observable only when such a magnification scale is assumed.

Further observations were carried out with a scanning microscope (the magnification being 4000×). For each investigated rock, three samples were analyzed: a sample not subjected to heating, a shock-heated sample with $T_g = 300°C$, and a shock-heated sample with $T_g = 500°C$. For each of them, 25 evenly distributed fields were registered. Subsequently, the $S_L$ parameter was measured in every image. Its changes, together with the temperature change, were depicted in Figure 6.

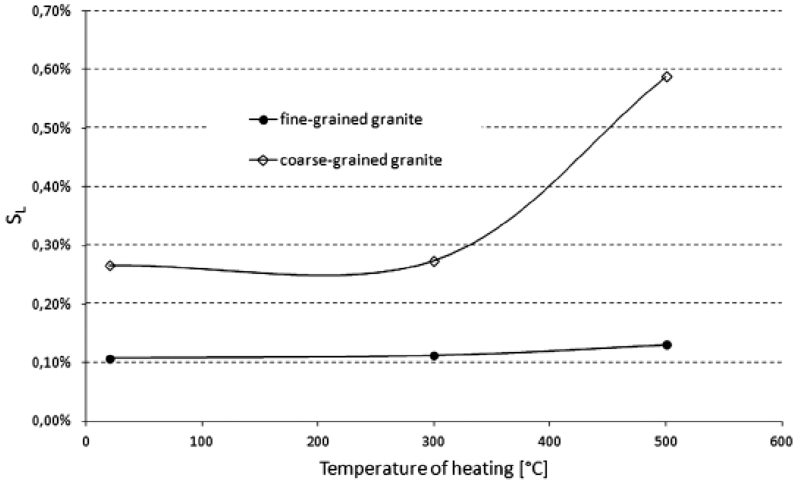

Fig. 6. The coefficient of fracturing for the investigated granites as observed under a SEM microscope at the magnification of 4000×

A summary of the obtained results leads us to a conclusion that microfractures appear in rock samples when the latter are shock-heated to the temperature of 300°C and 500°C. The microfractures are almost invisible under an optical microscope; however, they can be observed and measured under a scanning microscope. Although some structural distortions can be observed already at 300°C, the number of fractures increases significantly only when samples are shock-heated to 500°C. It can also be observed that coarse-grained granite reveals greater susceptibility to formation of fractures than fine-grained granite.

## 3.4. Some remarks on measurement accuracy in automatic (digital) image analysis

In a broad sense, measurements carried out by means of the automatic image analysis method are a two-stage procedure. In the first stage, the objects that are of interest to us, visible in the pictures, should be segmented. Most commonly, the segmentation consists in transforming a colorful or a grey image into one or several binary images, where all the objects being of interest to the researcher are properly projected. The second stage involves automatic measurements of the quantities peculiar to the segmented objects. The most crucial factor as far as the accuracy of automatic measurements is concerned is the outcome of the first stage, i.e. of the automatic segmentation of the objects in question. Any errors made at this stage might distort the end result of the measurement by several dozen or even several hundred percent. For a change, the stage of the measurement proper practically does not generate errors. In a lot of papers discussing the application of the automatic image analysis in the process of quantitative rock description that have been written to date, a rule was adopted that the extent of the automatic method error is the deviation of the result obtained by means of this method from the result arrived at due to the application of standard stereological methods (Młynarczuk, 1999, 2004). In those papers, the conformity of the results obtained by means of both methods was substantial. They also lead us to conclude that, if visual inspection of the outcome of the segmentation indicates that the objects were identified correctly, the automatic measurement procedure will also return a correct result (i.e. approximating the result obtained in the course of a standard stereological analysis).

# 4. Changes of physical properties of the investigated granites

The results of microscopy research discussed above demonstrated that the adopted manner of a rock's "thermal processing" would bring about noticeable changes to its structure. The next step involved identifying the effects of the observed structural changes, manifesting themselves as quantitative changes of selected mechanical properties of rocks. In particular, the subject matter of the study was the way in which the applied shock-heating procedure influenced the following:

- the velocity of the primary wave passing through the sample,
- the permeability and the porosity of the sample,
- the result of the uniaxial compression test,
- the result of the compressibility test.

## 4.1. Changes in the velocity of the primary wave passing through the sample

Measuring the velocity of the primary wave passing through the sample ($v_p$) is a standard non-destructive testing procedure, whose basic objective is to evaluate the degree of the homogeneity of the samples to be used in experiments. For the sake of the discussed research plan,

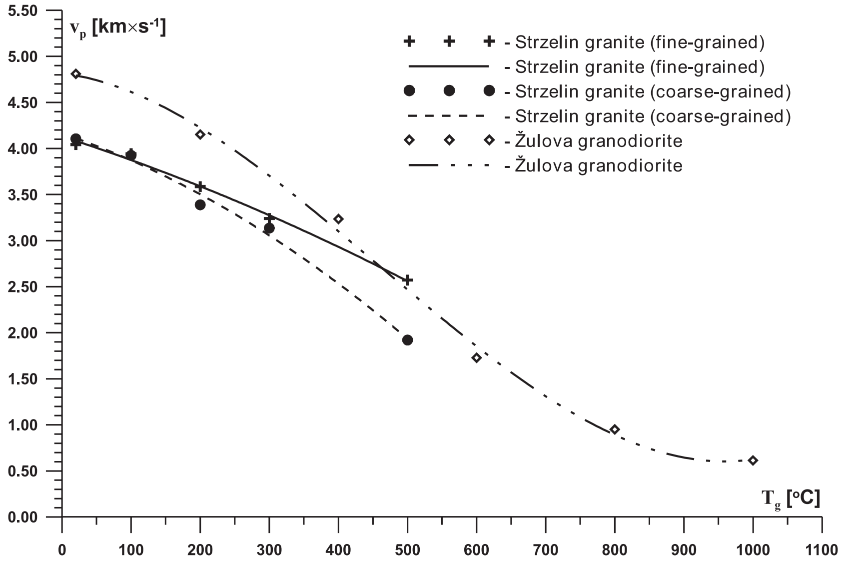

Fig. 7. Comparison of the results of studies into the relationship between the primary wave velocity and the heating temperature for the Strzelin granites and the Žulova granadiorite; the granadiorite part after Kožušnikova (1999)

this test was also carried out in order to determine whether the applied shock heating procedure caused any changes to the samples.

Fig. 7 shows the results of the study on granite samples, depicted as a relation between the value of $v_P$ and the shock heating temperature ($T_g$). For the sake of comparison, it also shows the results obtained by Kožušnikova (1999), who studied (for $T_g \leq 1000°C$) the Žulova granodiorite, a rock whose texture resembles strongly the one of the Strzelin granites, and which can be found in the very same massif. It is clearly visible that the value of the primary wave velocity measured in the sample decreases with a rise in the shock heating temperature.

## 4.2. Permeability and porosity of the sample as relating to the shock heating temperature

Investigations into the granite permeability in the flow of nitrogen and helium were carried out on equipment developed at the Strata Mechanics Research Institute of the Polish Academy of Sciences (Żółcińska & Dyrga, 1996). A detailed description of the methodology applied, together with the obtained results, can be found in a paper by Żółcińska and Dyrga (2003).

Fig. 8 and 9 show the relations between the permeability index (k) of the investigated sample and the shock heating temperature, for nitrogen and helium, as well as for the minimum (150 kPa) and maximum (450 kPa) mean gas pressure flowing through a sample. As can be seen, for both types of granite, the shock heating process results in a monotonic increase of their permeability index. The increase is one of several orders of magnitude. Differences between granites are basically only quantitative ones: the nonheated samples of coarse-grained granite show significantly low permeability for the flow of gases, whereas the permeabilities of the samples heated in the temperature of 300 and 500°C are much higher than they are in the case of fine-coarsed granite. The results are compatible with those obtained by Homand-Etienne and Houpert (1989).

In order to determine changes in the rock porosity, porosimetry tests were performed. Their results are depicted in Figure 10, which also shows a sudden increase in the total porosity ($n$)

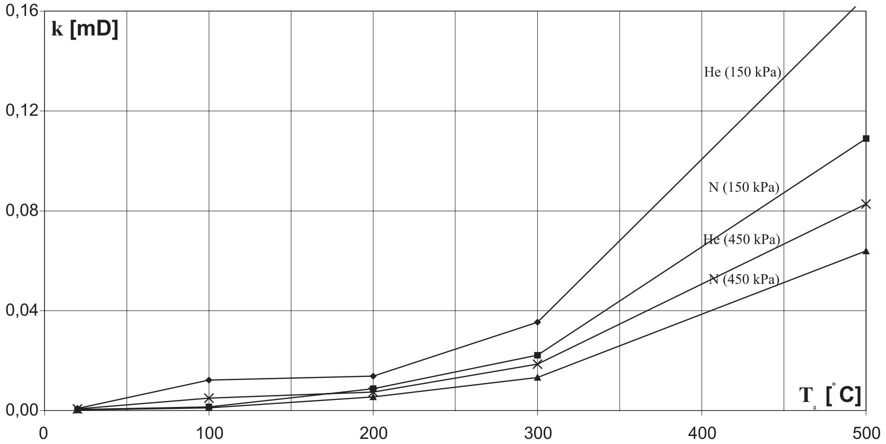

Fig. 8. Permeability coefficient of the sample in relation to the shock heating temperature; the Strzelin fine-grained granite; after Żółcińska and Dyrga (2003)

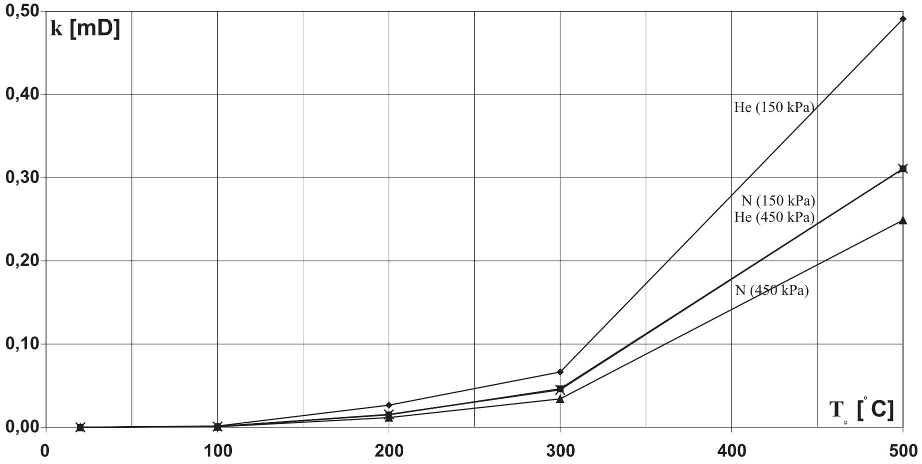

Fig. 9. Permeability coefficient of the sample in relation to the shock heating temperature; the Strzelin coarse-grained granite; after Żółcińska and Dyrga (2003)

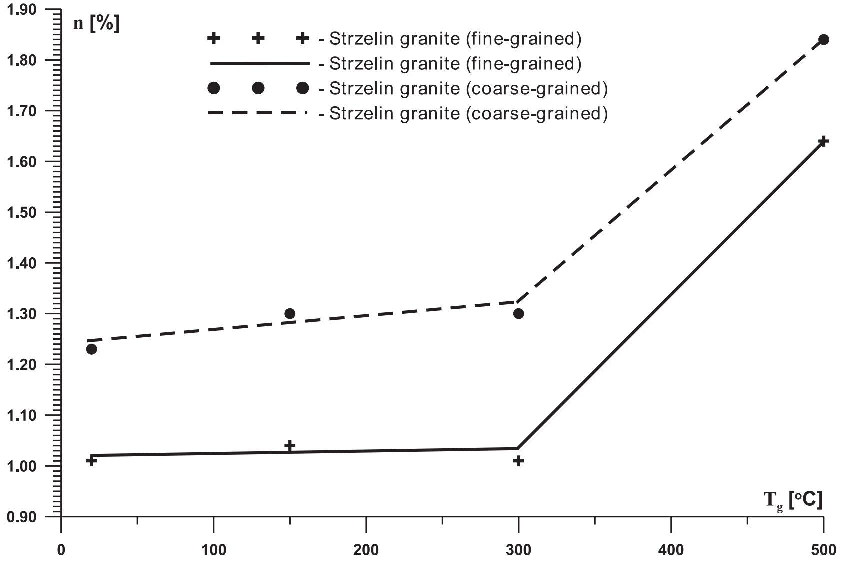

Fig. 10. Total porosity coefficient of the sample in relation to the shock heating temperature

for the samples heated to the temperature of 500°C. It seems that one can assume that, for 20ºC $\leq T_g \leq$ 300°C, changes in the sample porosity are minor – and are not detected by the applied measuring device.

## 4.3. Influence of the shock heating temperature on the results of the uniaxial compression test

The uniaxial compression test was performed with the INSTRON 8500 Rock Testing System machine (cf. Nowakowski, 1994), with the constant axial strain rate $10^{-5}$ $s^{-1}$. During the test, the loading force was registered, together with the changes in the height of the sample and in the length of its circumference.

These two quantities were used to produce graphs showing relationships between the axial stress within the sample ($\sigma_1$) and its deformations: longitudinal ($\varepsilon_1$), transverse ($\varepsilon_3$), and volumetric ($e$) one. The graphs then served to determine the following material constants: the uniaxial compressive strength limit of the sample (${}^R\sigma_1$) together with the corresponding deformation (${}^R\varepsilon_1$), Young's modulus ($E$), and Poisson's ratio ($v$). The $E$ and $v$ constants were determined with just the rising sections of the proper relationships between the stress and the deformation (the loading-unloading loop was omitted), which is a procedure accepted by International Society of Rock Mechanics (cf. Brown, 1981; Pells, 1993). Fig. 11-14 depict the relationships between the determined material constants and the shock heating temperature, obtained for the examined samples.

The above figures provide a fairly clear picture of the rock being the object of the study, as it can be noticed that, for the examined granite samples, a rise in temperature $T_g$ is accompanied by a decrease in strength and stiffness, illustrated by a decrease in the value of ${}^R\sigma_1$ and E (Fig. 11 and 13). The latter, in turn, is accompanied by an increase in ductility, translating into a rise in the value of ${}^R\varepsilon_1$ (Fig. 12). A problematic issue, however, is determining what happens to Poisson's ratio (Fig. 14). It needs to be emphasized here that – for all the samples for which the uniaxial compression test was carried out – the relationship between the stress within the sample and its transverse deformation $\sigma_1(\varepsilon_3)$ was nonlinear in its nature. As a result, the value of $v$ was estimated

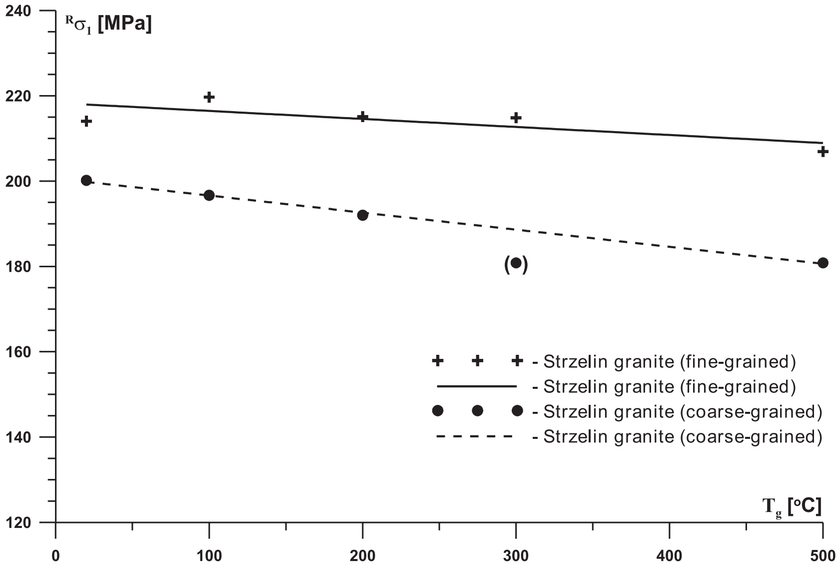

Fig. 11. Relationship between the uniaxial strength limit of the sample and the shock heating temperature

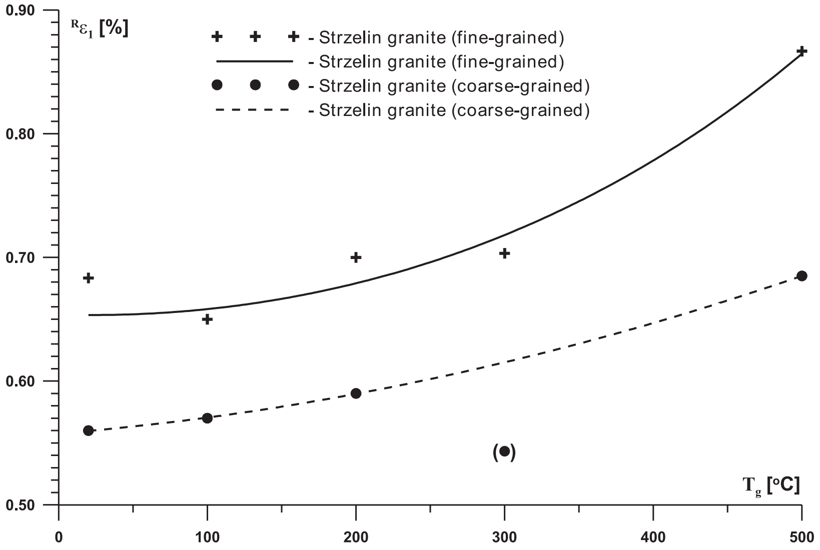

Fig. 12. Relationship between the strain at uniaxial strength limit and the shock heating temperature

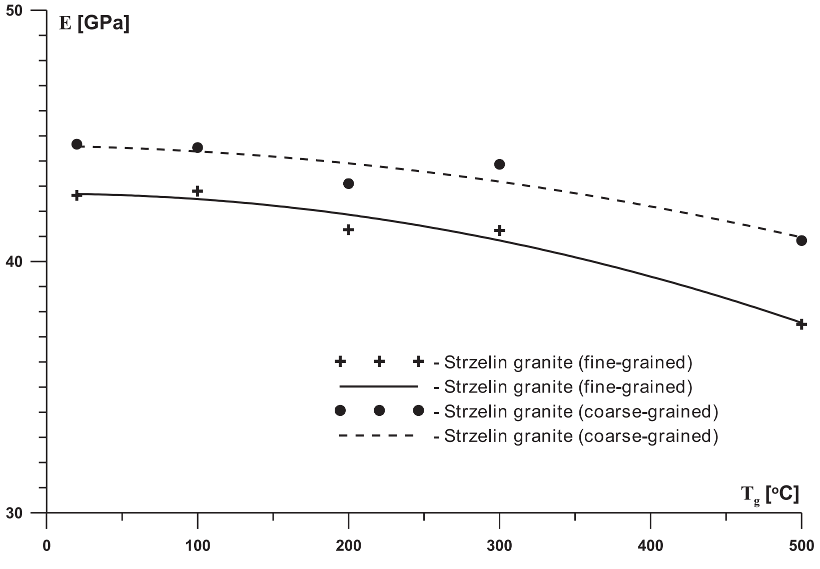

Fig. 13. Relationship between Young's modulus of the sample and the shock heating temperature

using a tangent to the curve $\sigma_1(\varepsilon_3)$ at the point $\sigma_1 = 0{,}5\,^R\sigma_1$ (as it is done in the case of determining the so-called tangent Young's modulus for curves $\sigma_1(\varepsilon_1)$). Such a method of determining the value of $v$, although acceptable, is more error-prone than the standard procedure, and reduces the reliability of the result itself. Additionally, in the case of samples that were subjected to shock

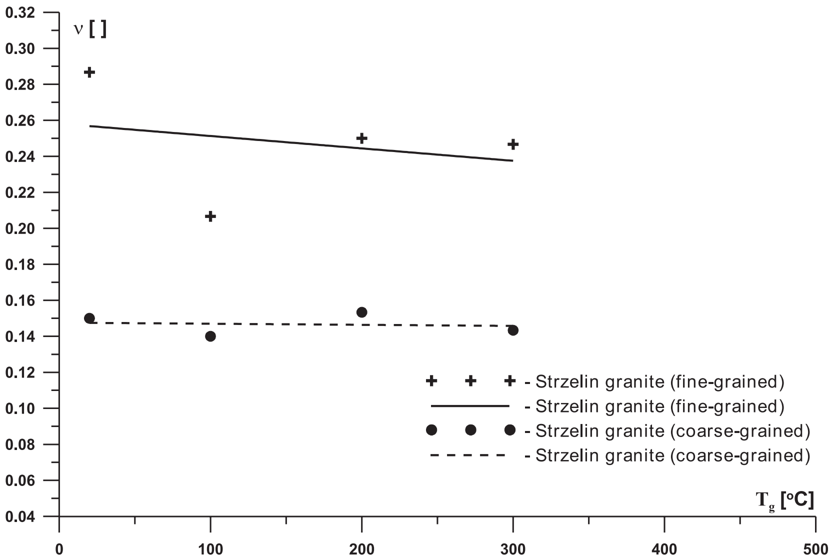

Fig. 14. Relationship between Poisson's ratio of the sample and the shock heating temperature

heating in the temperature of 500°C, the transverse deformations would initially reveal the material contraction, which meant that the value of Poisson's ratio was below zero. Thus, for the samples heated in the temperature of 500°C, the value of *v* was not determined. The possible reasons for the occurrence of such a phenomenon will be discussed in Chapter 5 of the present paper.

## 4.4. Temperature of the shock heating of the sample as relating to the result of the compressibility test

The objective of the compressibility test was to determine the relationship between the hydrostatic pressure of the medium surrounding the sample and the change in the sample's volume (cf. Gustkiewicz, 1989, 1996). During the experiment, the hydrostatic pressure would change from 0 to 300 MPa. The deformations of the sample were measured by means of an inductive transducer, which was described in a paper by Nurkowski (1998). On the basis of the obtained relationship curves, depicting the relationship between the hydrostatic pressure and the change of the sample's volume, the sample's coefficient of volumetric compressibility – $K$ – was determined, as well as its fracture porosity – $\eta$ (cf. Walsh, 1965; Gustkiewicz, 1989). Subsequently, the relationships between these constants and the temperature of shock heating of the sample were investigated. Relevant relationships were presented in Fig. 15 and 16.

The results presented below prove that shock heating of the sample has little influence on its volumetric stiffness, whose measure is compressibility coefficient $K$. The distribution of measurement results shown in Fig. 15 does not indicate the existence of a visible trend for any of the investigated rocks; rather, it suggests some oscillations about a certain constant value. The result remains in contrast with the outcome of the uniaxial compression test (see above: Chapter 4.3, Fig. 13), where the linear stiffness of granite samples (measured by the E module) decreased

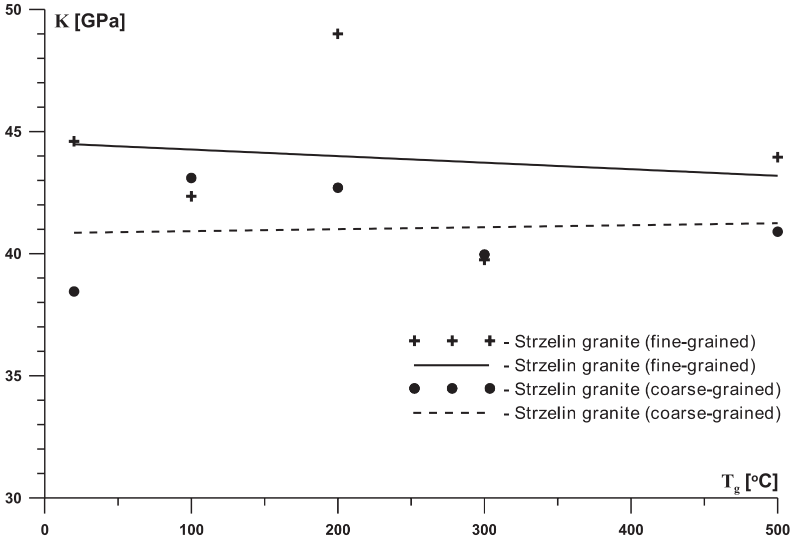

Fig. 15. Relationship between the compressibility modulus of the sample and the shock heating temperature

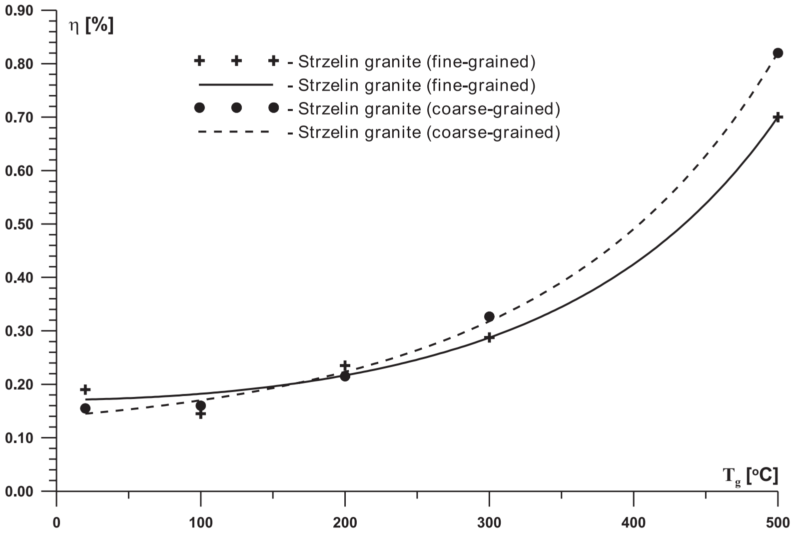

Fig. 16. Relationship between the porosity of sample fracturing and the shock heating temperature

visibly together with an increase in the heating temperature. This can perhaps be explained by the hydrostatic pressure present during the compressibility test, which closes the fractures and "stiffens" the sample. A separate issue is the question of porosity of rock fractures, which – for the granites being the object of the study – rises together with $T_g$ (Fig. 16).

## 4.5. Representative character of the results of strength tests

Fig. 7-16 present, in the form of graphs, a series of relationships between the shock heating temperature and the values of selected quantities describing the examined rock. When attempting to evaluate their representativeness, one should take into consideration the fact that each point in Fig. 7-16 is a result obtained for one sample, only. Thus, it is impossible to carry out a standard estimation of the value of measurement uncertainty, which requires performing more experiments. The results of the strength tests presented above should therefore be treated merely as certain information of a qualitative type, indicating the directions of changes occurring to the analyzed rock properties – and they must not be regarded as a basis for drawing any quantitative conclusions.

At the same time, the question arises as to why the authors did not decide to perform more experiments. It needs to be explained that the authors, when approaching the subject in question, were presented with a choice between two strategies: they could narrow down the scope of experiments and perform each of them for a greater number of samples – or broaden this scope substantially, which, however, would reduce the number of samples used in each testing procedure. The adopted deadline for research completion made it impossible to carry out the tests in the scope presented in this paper for a greater number of samples.

The authors chose the second strategy (i.e. more experiments with fewer samples used in each procedure), hoping that it would facilitate the interpretation of the obtained results. These hopes were fulfilled only partially, which is why some of the performed experiments were not discussed in this paper (among others, this concerns the results of the conventional triaxial compression tests).

# 5. Discussion of the obtained results

A synthetic discussion and interpretation of the obtained study results requires in the first place putting an emphasis on certain structural and textural properties of the granites from the Strzelin – Žulowa massif. The granites in question are rocks with fully crystallized grains, where the contact areas between crystals are developed in the sense that virtually the whole area of a given crystal is in contact with the areas of the neighboring crystals. These properties are of the essence as far as the analysis of the rock “reaction” to thermal load is concerned.

1) The related results of the microscopy research prove that a vital structural change caused by shock heating is the emergence of new fractures and (or) expansion of the already existing ones. The quantitative research was carried out in order to establish if and how the number and size of fractures changes with an increase in temperature. In its course, it was established that:
    a) the applied shock heating procedure entails a growth of fractures, defined as an increase in their length as well as their width, and, what follows, their area,
    b) the fractures are virtually imperceptible under an optical microscope, and can be observed only under a scanning microscope,
    c) the analysis of the two types of granite revealed that the growth of fractures is decisively bigger in the case of the coarse-grained granite,
    d) the area of fractures increases rapidly in the samples subjected to shock heating in the temperature of 500°C.

When interpreting the described results, one should remember that they present the measurements of just these fractures which were visible at the magnification of 4000×. Thus, the relatively small changes of the coefficient of fracturing, observed up to temperature $T_g = 300^{o}C$, can be attributed to the fact that the fractures formed in such temperature were too small to be observed and measured. Nonetheless, the outcomes of some other research procedures, such as studies of porosimetry, and permeability, do indicate the formation of fractures for $T_g \leq 300^{o}C$. What is beyond doubt, however, is a very significant growth of fractures for $T_g = 500^{o}C$, the effects of which are manifested in most of the measurements presented in this paper.

2) Although the expansion of the already existing fractures and the formation of the new ones are by no means the only structural changes observed in heated rocks (cf. Chapters 3.1 and 3.2), it was assumed (due to the presented study results) that, out of all structural changes, fractures are the one that exerts the biggest influence on the physical properties of the examined rocks. Other authors, such as Hommand-Etienne and Houpert (1989) and Menendez i et al. (1999), reached a similar conclusion.
3) No phase transformations were observed in the investigated rocks; however, minor chemical changes were noticed. Examples of such changes can be oxidation of feldspars and biotites, the effect of which is the change of the biotite color, described in a quantitative manner.
4) Fig. 17 shows permanent linear deformations ($\Delta l \times l_0^{-1}$) of the examined granites in relation to temperature $T_g$, obtained in the course of dilatometric tests. These tests demonstrated that a relevant increase in the linear dimensions of the rock samples that accompanies the changes of temperature within the assumed range is 0,085% for the fine-grained

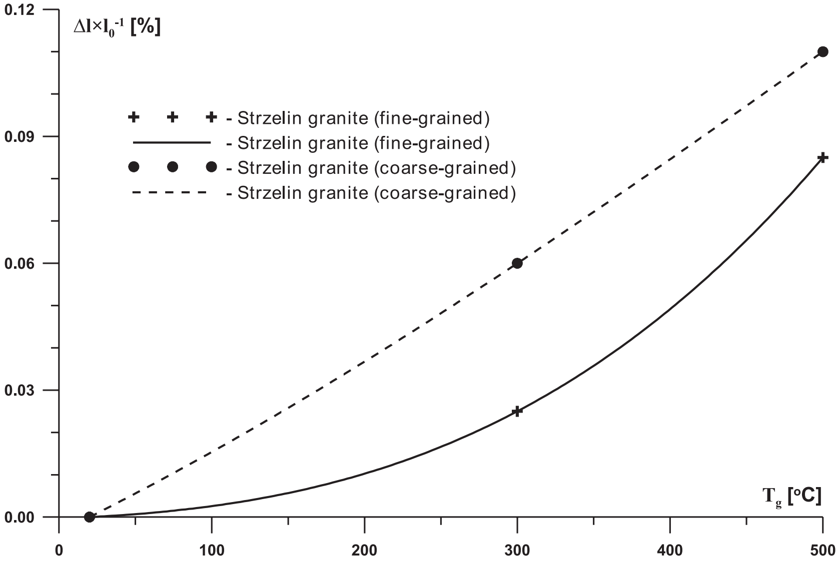

Fig. 17. Permanent linear deformations of the investigated rocks in relation to the applied heating temperature; results of dilatometric studies

granite and 0,11% for coarse-grained granite. Assuming that granites can be regarded as homogenous and isotropic rocks, it can be estimated that their permanent volume change (dilatancy), being the result of shock heating, will be 0,255% and 0,33%, respectively: these values are of the same order of magnitude as the values of fracture porosity quoted above (Fig. 16).

Such a reaction of rock samples is most probably due to the fact that in the discussed granites – where any crystal is usually tightly compressed by adjacent crystals – induced thermal stresses can be sufficiently high to cause crystal cracking and fracturing. This is why the quantitative research – which was to establish if and how the number and size of fractures changes with an increase in temperature – was carried out. The research was performed with a scanning microscope, and its detailed description, together with the results, was presented in Chapters 3.3 and 3.4.

5) Suppositions concerning the existence of a relationship between the adopted procedure of thermal processing of the rock and the formation of fractures find their confirmation in the results of the permeability studies and porosimetric studies presented in Chapter 4.2. The relationships depicted in Fig. 8, 9, and 10 demonstrate that, for studied granites, an increase in the temperature of shock heating of samples is accompanied by a clear increase in permeability and porosity. This is consistent with the conclusions drawn from dilatometric tests. At the same time, one needs to take into consideration the fact that both the porosimetric and permeability tests provide information only as to open fractures, linked to each other and to the sample borders – but they are not revealing when it comes to isolated fractures.
6) The analysis of the results of uniaxial compression tests brings us to the conclusion that, for the investigated material, an increase in the shock heating temperature is accompanied by a decrease in the strength and stiffness of the sample (Fig. 11 and 13), combined with an increase in its deformability (Fig. 12). This might also be explained by the formation of new microfractures and the expansion of the already existing ones (caused by shock heating of the sample). Alm et al. (1985) and Homand-Etienne and Houpert (1989) drew similar conclusions from their study results.
7) The list of the material constants discussed in Chapter 4.3 closes with Poisson's ratio. At the end of that chapter, the author indicated that, for the examined granites, it is hard to notice any regularities in relationship $\nu(T_g)$, which can be attributed to difficulties connected with the applied method of transverse deformation measurements. It seems, however, that the anomaly depicted in Fig. 14 is not a consequence of a measurement error, but a physical phenomenon consisting in the fact that the transverse deformation of the sample's frame, caused by uniaxial compression, results in the closing of these fractures that are deflected from the direction of the loading force. In such a situation, a measuring transducer installed on the side surface of the sample shows minor deformations – or their absence. When there is a sufficient number of fractures, the sensor of transverse deformations might even show a transverse contraction of the sample – this happens when swelling would rather be expected. Such a situation is presented in Fig. 18, which shows relationship curves concerning the relation between the axial stress within the sample and its transverse deformation, obtained for samples of the "Strzelin" coarse-grained granite.

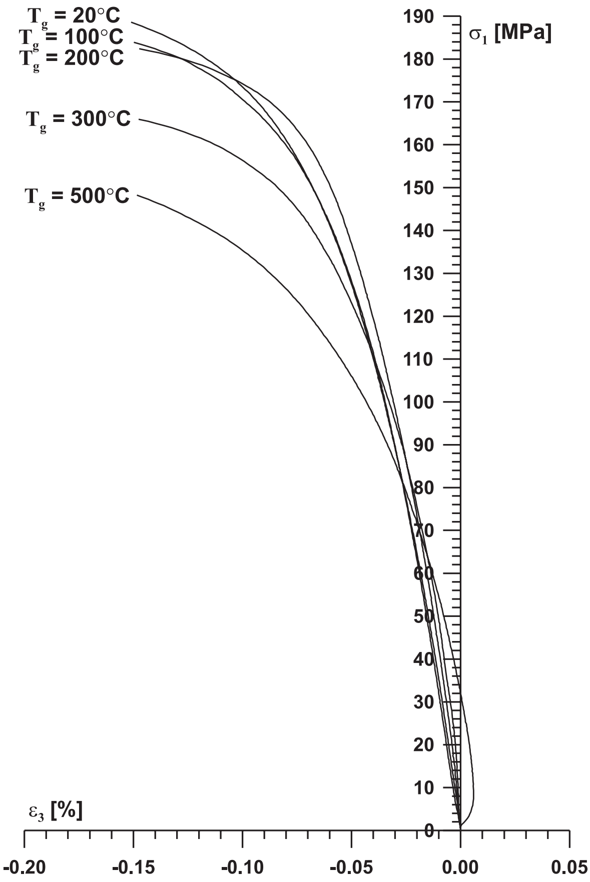

Fig. 18. Relationship $\sigma_1(\varepsilon_3)$ for various values of $T_g$; the Strzelin coarse-grained granite

Various reference papers describe similar situations in relation to the "Stripa" granite (Alm et al., 1985) and the "Remiremont" granite (Homand-Etienne and Houpert, 1989). In the case of both these granites, for heating temperatures exceeding 300°C, the degree of fracturing was so substantial that, at the initial stage of the experiment, deformation transducers indicated a contraction of the sample instead of its swelling – and relationships $\sigma_1(\varepsilon_3)$ were nonlinear within the entire stress range. As a result, it turned out that the higher the temperature of sample heating, the greater the number of fractures, and the lower the registered values of transverse deformations. As a consequence, an increase in $T_g$ reduces the value of Poisson's ratio.

## 4. Final remarks

The objective of the conducted and described research was to analyze the influence exerted on granite rocks by temperatures lower than phase transformations temperatures. The research was carried out at the Strata Mechanics Research Institute of the Polish Academy of Sciences, beginning in 2001. During that time, a lot of rocks were studied. The focus of the present paper, however, is just the two varieties of the Strzelin granite: the fine-grained and the coarse-grained granite.

Considering that rock properties are influenced not only by the value of temperature, but also the speed with which it changes and the time of rock heating, the adopted procedure of thermal processing of samples was the so-called shock heating. It involved placing a rock sample in a furnace preheated to a given temperature and keeping it there for a period of time necessary for leveling the temperature field in the sample. Afterwards, the furnace was turned off so that the sample would cool down to room temperature. The samples subjected to such a procedure would then be studied with respect to their structural and strength properties.

It needs to be emphasized that the results obtained for both types of granite reveal certain quantitative differences. The primary wave velocity (Fig. 7) decreased by 2,2 $\text{km} \times \text{s}^{-1}$ for the coarse-grained granite, whereas for the fine-grained granite it decreased by 1,5 $\text{km} \times \text{s}^{-1}$, which is 53,5% and 37,0% of the values obtained for nonheated samples, respectively. These results suggest that the fine-grained type of granite is less responsive to the adopted method of thermal processing.

One can arrive at similar conclusions when analyzing the results of permeability tests (Chapter 4.2). In room temperature, both granite types are virtually impermeable (cf. Fig. 8 and 9), but their permeability increases once they have been subjected to thermal processing in the temperature of 500°C (for example, their permeability in the flow of helium, at the pressure of 450 kPa, is, respectively: 0.07 mD – the fine-grained type, and 0.32 mD – the coarse-grained type). It can be seen that the permeability of the coarse-grained granite is 4.5 times greater.

The described differences in the responsiveness of the two types of granite are most probably caused by differences in the size of grains of which they are built. The mineral composition of the studied rock, presented in Table 1 (Chapter 2), shows that the maximum grain size in the coarse-grained granite is two (quartz) – three (biotite) times greater than in the fine-grained granite. Since the thermal deformation of a grain is directly proportional to its length, it is obvious that thermal stresses induced in the coarse-grained granite are going to be greater than in the fine-grained type. As a result, the coarse-grained granite cracks to a significantly greater extent than the fine-grained granite, which is confirmed by the results of structural tests (cf. Fig. 6).

Summing up these remarks, it needs to be stressed that the procedure of shock heating adopted for research purposes eliminated one of the most crucial factors – namely, the time of the exposition of the rock to temperature. Still, the results presented in this work prove that even relatively small temperature changes can lead to significant transformations of the structure and the chemical composition of the rock, and, what follows, its physical properties. At the same time, the direction of the possible further research into the changes of physical and structural properties of rocks subjected to the influence of temperature is an interesting question.

Naturally, a researcher is tempted to further explore the impact of time understood as an important factor in such a study. This can be done in at least two ways. The first one would involve changing the time of heating the sample and studying the changes of the rock sample properties in relation to the period of its exposition to the increased temperature. The other method would focus on the process of heating, making it possible to study the changes of the properties of the examined material in relation to the speed with which the temperature would rise.

The value of applied temperatures remains a separate issue. From the perspective of geotechnical problems encountered in engineering practice, the temperature range of up to 500°C, adopted in this study, can be regarded as sufficient. On the other hand – from the cognitive perspective, it would be interesting to move beyond that range, which would enable researchers to analyze, among other things, the effects of phase transformations. It would also accentuate the consequences of the fracture formation and expansion, as well as the results of chemical transformations occurring in rocks, i.e. the subject matters of the present paper.

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