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HIGH TEMPERATURE VERSUS GEOMECHANICAL PARAMETERS OF SELECTED ROCKS – THE PRESENT STATE OF RESEARCH

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Abstract
This paper presents the current state of knowledge concerning the examination of the impact of increased temperatures on changes of geomechanical properties of rocks. Based on historical data, the shape of stress-strain characteristics that illustrate the process of the destruction of rock samples as a result of load impact under uniaxial compression in a testing machine, were discussed. The results from the studies on changes in the basic strength and elasticity parameters of rocks, such as the compressive strength and Young's modulus were compared. On their basis, it was found that temperature has a significant effect on the change of geomechanical properties of rocks. The nature of these changes also depends on other factors (apart from temperature). They are, among others: the mineral composition of rock, the porosity and density. The research analysis showed that changes in the rock by heating it at various temperatures and then uniaxially loading it in a testing machine, are different for different rock types. Most of the important processes that cause changes in the values of the strength parameters of the examined rocks occured in the temperature range of 400 to 600°C.

Keywords
high temperature, geomechanical parameters of rocks, stress-strain characteristics, compressive strength, Young's modulus

1. INTRODUCTION

Temperature is one of the factors that has a significant impact on the change in value of the geomechanical parameters of rock. Since ancient times, man has been interested in the possibility of strengthening or weakening rocks under the influence of temperature. Probably the first time this phenomenon was brought into light was during the firing of clay and kaolin (Dimitriyev et al. 1969). It was noted that rocks exposed to high temperatures increased their resistance several times with a simultaneous reduction of their plasticity.

Since the 1970s, the development of geoengineering has resulted in a number of studies on the effects of high temperatures on the mechanical behaviour of rocks. This is an important research issue in such projects as: deep storage of nuclear waste, exploitation of geothermal deposits and crude oil, underground coal gasification, or the development of underground infrastructure of large cities (Mao et al. 2009; Tian et al. 2009; Chen et al. 2012; Zhang et al. 2013). Understanding the thermal phenomena in the rock mass also aids in understanding many processes which take place in the Earth's crust (Ranjith et al. 2012; Heuze 1983).

Most of the data associated with the change of geomechanical properties of rock according to their heating at various temperatures comes from studies carried out by Chinese scientists. In Europe, research on the effects of high temperatures on rocks are undertaken more rarely. In recent decades, this topic is becoming more and more popular because of the development of technologies where temperature affects the rock mass. It is important here to introduce technology concerning underground coal gasification (Dengina, Kazak, Pristash 1993; Hettema, Wolf, Pater 1993; Tian et al. 2009; Korzeniowski, Skrzypkowski 2012).

Under the influence of high temperatures in the rock, thermal stress appears which gives rise to numerous microcracks, which then gradually expand as the temperature rises. This leads to a weakening of the rocks' strength and their gradual destruction (Pinińska 2007; Mao et al. 2009; Keshavarz, Pellet, Loret 2010; Małkowski, Kamiński, Skrzypkowski 2012). This paper presents the results from studies focused on the effects of high temperatures on the values of uniaxial compressive strength and the elasticity of: granite, sandstone, limestone, marble and clay rocks subjected to a uniaxial compression test.

2. BEHAVIOUR OF ROCKS IN HIGH TEMPERATURES

Rock strength is determined on the basis of such factors as: mineral composition, structural and textural characteristics, including porosity, fracturing, the strength of given mineral constituents and the nature of the bonding between them. The same factors determine the strength of rocks in increased temperatures (Dimitriyev et al. 1969; Chmura, Chudek 1992; Pinińska 2007; Małkowski, Kamiński, Skrzypkowski 2012).

In the case of a high-temperature impact on rock, an additional factor which influences its strength is the thermal expansion of minerals included in the composition of the given rock. Under the influence of temperature, depending on the coefficient of the thermal expansion of mineral components, an increase of the contact surfaces between particles takes place. This leads to structural changes that have an impact on the change of the values of strength parameters and the bulk density of the rock (Pinińska 2007; Małkowski, Kamiński, Skrzypkowski 2012; Zhi-jun et al. 2009). In addition to structural deformation, there are changes in the physical properties (shape change, volume, mass, velocity of propagation of elastic waves through the rock medium) caused among others by the hydration or dehydration and decarbonisation of rocks. Moreover, chemical changes take place, the result of which is polymorphic transformation, melting and the disappearance of certain minerals (Dengina, Kazak, Pristash 1993; Pinińska 2007; Małkowski, Skrzypkowski, Bożęcki 2011; Wu et al. 2013). Some researchers on the basis of the undertaken study found that the period of heating rocks can be divided into three stages (Dimitriyev et al. 1969; Pinińska 2007). In the first, the rock's strength is dependent on the thermal stability of the minerals and their expansion. In the second stage, the strength depends on the nature of its intergranular contact, the state of the boundaries between them and the reaction to the resulting stress. The third stage makes the rock's strength dependent on the minerals' resistance to destruction. On this basis, a classification was made which determined the nature of changes in the strength of the different types of rocks into two groups (Dimitriyev et al. 1969):

- Group I – crystalline rocks and clastic rock, in which in the first stage of heating, the mineral composition is substantially unchanged. In the next step increasing the contact surfaces of the minerals take place, leading to the initial increase in rock strength compared to the strength at room temperature. In the third stage of heating, the relaxation phenomena develops at the interface between minerals and structural defects which are then formed, resulting in a reduction in strength and rock destruction. Additionally, it has been noted that an increase in rock strength parameters is present in a certain typical temperature range (Dimitriyev et al. 1969) – usually from 400 to 600°C. Dengina (Dengina, Kazak, Pristash 1993) indicates the critical temperature beyond which plastic deformation occurs in rocks (Mao et al. 2009; Zhang Mao, Lu 2009; Zhi-jun et al. 2009; Ranjith et al. 2012).
- Group II – carbonate rocks, in which the decomposition of minerals occurs at relatively low temperatures, and the bonding between the minerals exhibit a very slight resistance, causing a decrease in strength from the start of heating (Dimitriyev et al. 1969; Pinińska 2007; Zhi-jun et al. 2009). Soviet studies have shown that chemical changes also contribute to this, e.g. for limestone, the main component of which is $CaCO_3$, a decrease in strength is also related to the decomposition and emission of CO_2 (Dimitriyev et al. 1969). Figure 1 shows the graphs of dependence of the compressive strength on the temperature of the selected rocks of both groups.

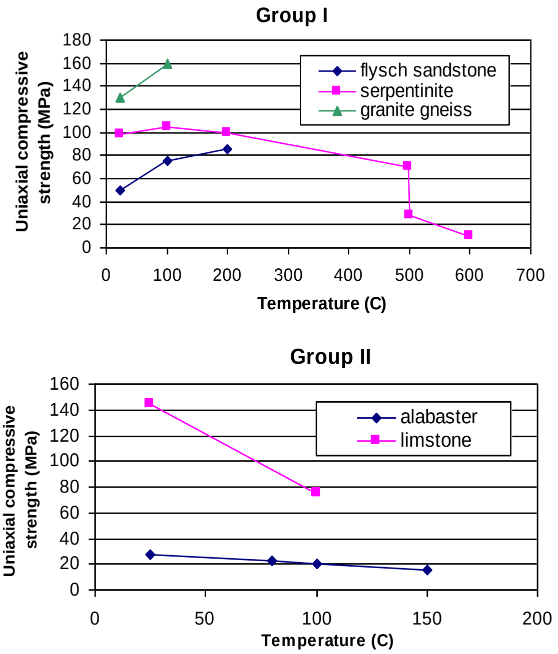

Figure 1. Dependence of uniaxial compressive strength on the temperature: a – crystalline rocks and sedimentary clastic rocks, b – carbonate sedimentary rocks (Pinińska 2007)

Pinińska (2007) notes that, in addition to mineral composition, an important factor influencing the strength of rock is the grain size and porosity. In fine-grained sandstone and sandstone of lower porosity, an increase of compressive strength occurs earlier and is longer than in coarse-grained sandstones of greater porosity. This behaviour is attributed to changes of thermal expansion of minerals. Similar findings in his study is described by Dengina (Dengina, Kazak, Pristash 1993). He adds that in coarse-grained sandstones, strength decreases more rapidly compared to the fine-grained sandstones, in which the decrease of strength takes place more smoothly. The reason for this behaviour which he gives, among others, is intergranular fractures and cracks passing through the pores in the rocks of coarse graining. Zhi-jun with a team (2009) found that in the case of sandstone, high porosity minimizes cracking due to the expansion of minerals, causing an increase in the density of the rock and its temporary reinforcement. Research on mudstones confirms this phenomenon (Zhang et al. 2013). Ranjith et al. (2012) have shown that porosity and particle size have an impact on the transition from a brittle to a plastic state as the result of the load. Particle size also affects the elastic properties of rocks (Małkowski, Kamiński, Skrzypkowski 2012). The research shows that fine-grained sandstones have reduced their elasticity more than coarse-grained sandstones.

Numerous experiments have shown that apart from the temperature, acting pressure is also significant in the change of rock strength parameters (Hettema, Wolf, Pater 1993; Pinińska 2007; Zhi-jun et al. 2009; Małkowski, Kamiński, Skrzypkowski 2012). Pinińska (2007) in her study conducted on crystalline rocks proved that with the acting confining pressure, rock strength also decreases with increasing temperature; however, the differences compared to the results obtained in room temperature are insignificant. Hettema (Hettema, Wolf, Pater 1992) in the triaxial compression tests conducted on argillaceous schist, notes the substantial increase in strength above 200°C at a confining pressure of 14.2 MPa. With temperatures above 600°C, this phenomenon disappears, whereas when the temperature ranges up to 200°C, it does not cause major changes. In an axisymmetrical state of stress when the condition $\sigma_1 > 0$ and $\sigma_2 = \sigma_3$ is met, the increase in the value of pressure causes the transition from the brittle to a ductile state at high confining pressures. In the post-failure part of the stress-deformation curve the value of stress decreases, which means that when the confining pressure increases the value of residual stress increases, and the post-failure curve is more gently inclined in relation to the axis of deformation (Bukowska 2012).

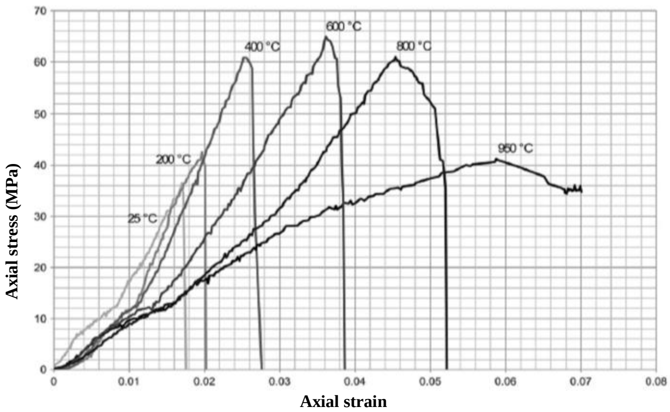

Figure 2. Stress-strain curves of sandstone for temperatures 25–950°C (Ranjith et al. 2012)

3. CHANGES OF THE VALUES OF GEOMECHANICAL PARAMETERS OF ROCKS AS A RESULT OF HIGH TEMPERATURES

Most of the studies carried out so far on the changes of the mechanical properties of rocks under the influence of different temperatures refer to uniaxial compression tests of rock samples after the heating process at a previously set temperature. Based on the post-failure curve, obtained on the basis of rock compression in the testing machine, changes in the geomechanical parameters are determined.

3.1. Stress-Strain Characteristics of Selected Rocks as a Result of High Temperatures

Figure 2 shows the stress-strain characteristics of sandstone in the temperature range from 25 to 950°C. From the post-failure curve, a gradual increase in the damaging stress (maximum) to 600°C can be seen. When this temperature is exceeded, damaging stress falls down to about 63% of maximum value. The pre-failure stress-strain curve indicates that up to the temperature of 400°C, the curves do not differ in shape and show considerable elastic deformation, and the values of Young's modulus do not differ significantly. In the temperature range of 400–950°C, the values of Young’s modulus visibly decrease, and at 950°C plastic deformation dominate the sandstone. It follows that increasing temperature changes sandstone destruction – brittle fractures turns into a ductile rock destruction model. This is reflected in the shape of the stress-strain curves. The change of the sandstone destruction model compressed uniaxially from brittle to ductile results from the dehydration of kaolinite, forming a part of the sandstone’s binding agent, and from the transformation of goethite into hematite.

Similar behaviour in the course of the stress-strain curves have been shown by sandstone samples tested at temperatures ranging from 20 to 1200°C by Wu et al. (2013). The course of the curves in Figure 3a indicates that:

- generally, by increasing the heating temperature of sandstone samples (20–400°C) the value of the maximum stress increases (the damaging one equal to uniaxial compressive strength)
- while increasing temperature in the range of 20–200°C the value of the critical strain also increases (the strain corresponding to the maximum strain)
- changes in the value of Young's modulus in the temperature range between 20–200°C are not marked significantly.

The courses of stress-strain curves shown in Figure 3b illustrate the destruction manner of sandstone samples heated at 1200°C (Wu et al. 2009). According to these researchers, sandstones exhibit a pronounced elasticity up to a temperature of about 800°C. The graph shows that at higher temperatures sandstone exhibits higher values of axial-failure strain and total deformation (Fig. 3b).

In more recent studies of Zhang, with a team (2013) studied mudstone samples in the temperature range of 25 to 800°C. It has been shown that chemical changes in the mineral composition of the rock under the influence of temperature cause changes in the shape of stress-strain characteristics at different temperatures. Up to the temperature of 400°C, the mineral composition is stable thus the course of the stress-strain curves is not much different from that at 25°C, showing the typical course of brittle destruction (pre-failure phase, the elastic deformation phase, post-failure phase with a clear decrease of stress to the values close to zero) (Fig. 4a, b). In the temperature range from 600 to 800°C, under a compressive load, with gradual transition into the ductile state, the samples displayed the residual strength (Fig. 4c, d). The authors argue that the mineral transformations of feldspar, the dehydration and the transformation of kaolinite to illite occurs. These processes contribute to the deterioration of the homogeneity and orientation of the pores. This leads to the formation of numerous cracks and a more diverse course of the curve at 800°C than at lower temperatures.

With the destructive tests of granite heated to a temperature of 800°C, a decrease in the value of the maximum axial stress from the beginning of heating with a simultaneous increase of axial strain was shown (Chen et al. 2012). The authors note a similar shape of curves, distinguishing in their course three phases: the tightening of pores and fissures, in which due to external loads micro-cracks tighten, the elastic deformation stage, in which the characteristics until reaching the maximum axial stress, have an almost linear course and the stage of brittle deformation, in which the post-destruction (post-failure) characteristics decline sharply, and the residual strength is equal to zero. The increase in axial deformation above the temperature of 400°C, with a significant drop in the strain is assigned to the fast pace of dehydration with temperatures ranging from 200 to 400°C before the formation and propagation of micro-cracks. In the samples heated to a temperature above 400°C, and then compressed uniaxially in a testing machine, a rapid growth of cracks was observed which resulted in their disintegration.

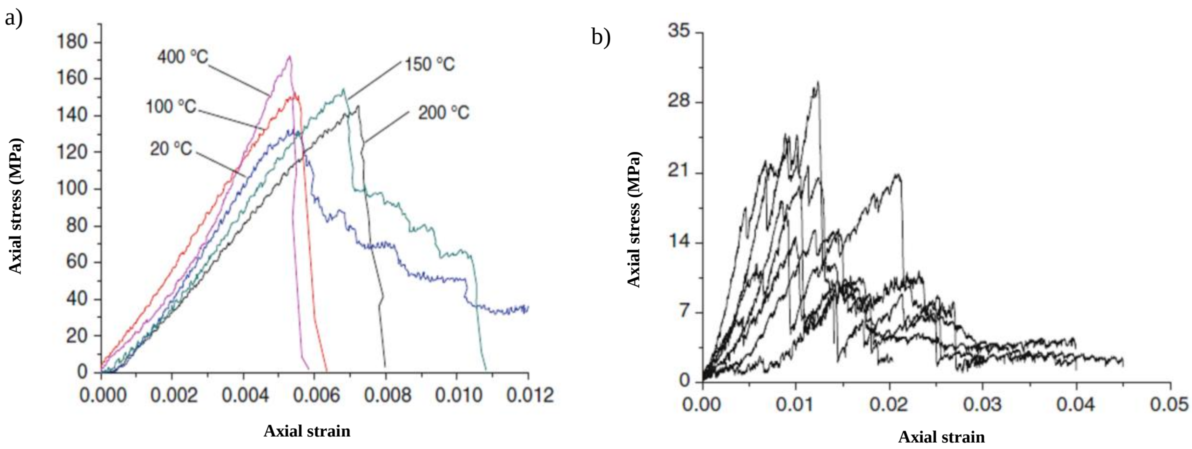

Figure 3. Stress-strain curves of sandstone samples: a – for temperatures in the range of 20-400°C, b – the temperature of 1200°C

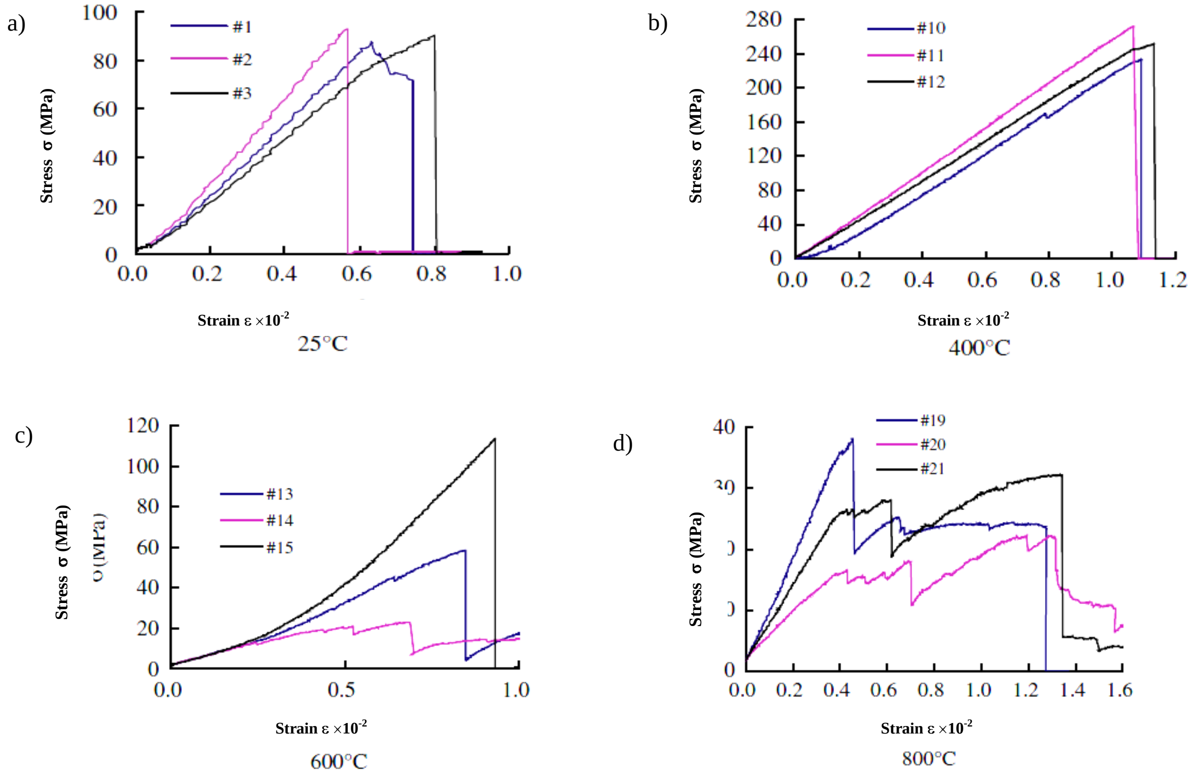

Figure 4. Stress-strain characteristics of mudstones: a – 25°C, b – 400°C, c – 600°C, d – 800°C (Zhang et al. 2013)

Mao et al. (2009) found similar changes in limestone tested by means of a uniaxial compression from room temperature to 600°C. Samples heated at higher temperatures and compressed uniaxially deformed in a plastic way. Zhang received similar results with his team (2009) in the studies of limestone and marble heated from room temperature to 800°C. In this case, the plastic deformation in marble appeared only at temperatures above 800°C.

3.2. The Compressive Strength of Rock Heated to a Temperature above 1000°C

Figure 5 shows the changes in the values of uniaxial compression of several types of rocks, subjected to high temperatures.

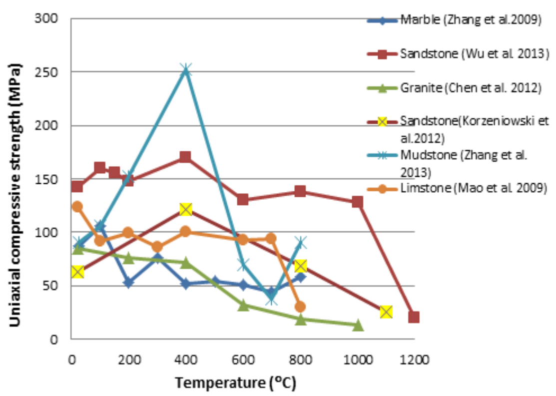

Figure 5. Change of the compressive strength of selected types of rocks subjected to high temperatures

Generally, rock strength decreases with increasing temperature. The magnitude of these changes in the temperature range between 20–1200°C varies depending on the type of rock. In the case of granite, an 80% decrease in strength with an increase in temperature from 20 to 1000°C is noticeable. To a temperature of 400°C compressive strength falls gently. Sudden loss of strength is observed in the temperature range from 400 to 600°C. This is probably related to the phase transitions of quartz at 573°C (Chen et al. 2012).

In studies of the change of strength of the flysch sandstones to the temperature of 800°C an increase was recorded in strength in the range of 25 to 500°C Pinińska (2007). A significant loss of strength, as in the case of granite, was observed at the temperature of about 600°C. It may also be associated with mineral changes of quartz. Research on sandstones, which was conducted by researchers from China, also show an increase in the strength of sandstone heated to 400°C. Heating to a temperature of 600° causes a decrease in the strength of sandstone to a value close to that of the samples obtained during the compression of rocks at room temperature. Heating to 1000°C does not cause major changes in the compressive strength. However, above this temperature range the compressive strength decreases rapidly and reaches 7% of the value achieved with the test sample at room temperature (Wu et al. 2013). In the studies of sandstone samples heated to a temperature of 1100°C, conducted by Korzeniowski and Skrzypkowski (2012), the strength of the samples at 400°C increased almost by 100% and then decreased from 121 to 26 MPa.

When mudstone is heated to a temperature of 400°C, the compressive strength indicates an increase from 90 to 252 MPa (Zhang et al. 2013). The authors attribute this phenomenon to the evaporation of water and the emission of gases contained in the inner structure of mudstone. This contributes to reducing sliding between the particles and results in the increase of the strength of rocks. Zhang with his team in the study on sandstone to a temperature of 800°C also came to similar conclusions, observing the increase in strength at 600°C (Zhang et al. 2009). For temperatures above 400°C, the strength of the mudstone was decreasing with the trend of negative exponential functions to the value of 70 MPa. This is due to the melting and thermal decomposition of minerals, contributing to the establishment and the development of new micro-cracks in the structure of mudstone.

Małkowski in his studies on clay and sandy slate heated to a temperature of 1000°C also recorded an increase in their strength, correlating the phenomenon with loss mass due to inter alia dehydration and decarboxylation (Małkowski, Kamiński, Skrzypkowski 2012).

In limestone heated to 800°C, a considerable loss of strength occurred in samples heated to a temperature of 100°C, decreasing by 26% (Mao et al. 2009). Further heating of limestone to a temperature of 700°C did not result in major changes of strength. Similar observations were made by Zhang and his team (2009). As a result of the thermal expansion of minerals, new micro-cracks that weaken the rock are not formed. It was only after exceeding 700°C that strength rapidly decreased by almost 70% compared to the maximum value characteristics of these rocks.

The compressive strength of marble heated to 800°C shows some variations (Zhang et al. 2009). At 100°C marble reaches its maximum strength. The initial increase in strength is due to the large amount of primary micro-cracks, which as a result of uniaxial compression of the samples heated to a temperature of 100°C, under the influence of the mineral swelling – tighten, thus causing rock reinforcement. At temperatures from 100 to 200°C, strength decreases by about 50% and then increases again at 300°C by half of the obtained value. At a temperature of 400°C a decreasing strength is recorded again. Up to the heating temperature of 800°C compressive strength remains more or less at the same level.

3.3. Change of the Value of the Young's Modulus in a Function of the Temperature of Rock Heating

Elastic properties of isotropic rocks are determined by Young’s modulus and Poisson’s ratio. This is the factor of proportionality between stress and the corresponding elastic strain. Similarly as strength, elasticity of rocks depends mainly on the elasticity of composing minerals, the density, porosity and other factors. Rocks do not show perfect elasticity. The actual stress-strain characteristics are approximated by straight lines so the mechanical processes that occur in rocks as a result of loading are described mathematically. Young’s modulus is determined for the entire height of the sample or at a centre section as the tangent of the angle of inclination to the x-axis of the straight line approximating the post-failure curve in the ascending part of the stress-strain characteristics of compressed rock sample or as a tangent of secant inclination (Bukowska 2012). Changes of the value of Young’s modulus of selected rock subjected to heating at various temperatures are shown in Figure 6.

In the case of granites studied by Chen et al. (2012), to a temperature of 400°C, Young’s modulus is generally not changed significantly. For samples heated at higher temperatures there was a sharp decline in the value of Young’s modulus, reaching a temperature of 1000°C, only 10% of the value obtained at room temperature.

Studies carried out by Ranjith and his team (2007) have shown that sandstones heated to a temperature of 950°C, the value of Young’s modulus increases at 400°C by 34% in relation to the value received at room temperature, then after heating the sample to 950°C there was a reduction in its value by about 74%. The value of Young’s modulus of the sandstone tested by Zhang and his team (2009) showed some fluctuations in temperature below 600°C. Above that temperature, the value of Young’s modulus decreased, indicating a decrease of 35% at 800°C compared to the value obtained at room temperature. A similar result was obtained by Wu with his team (2013). Up to the temperature of 200°C, Young’s modulus decreased by nearly half compared to the value obtained for the samples compressed uniaxially. At a temperature of 400°C, Young's modulus has reached a value close to the one obtained for the samples tested at room temperature, after which this value significantly decreased again to 1200°C with small variations at the temperature of 800°C. Research by Korzeniowski and Skrzypkowski (2012) showed that at 400°C sandstone samples reduced their deformability and there was a 50% increase in the value of Young’s modulus. However, further heating to a temperature of 1100°C caused a decrease in its value to about 20% of the value obtained for the samples compressed uniaxially at room temperature.

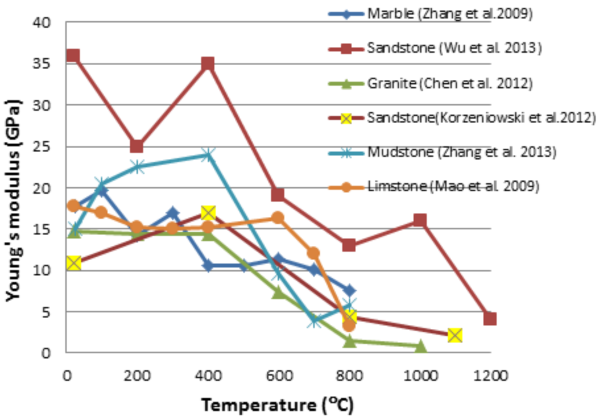

Figure 6. Changes of the value of Young's modulus of selected rocks subjected to high temperatures

In the case of limestone, Young's modulus decreases at a temperature of 200°C compared to tests at room temperature, whereas little changes to the temperature are observed up to 600°C. At temperatures above 600°C elasticity modulus decreases rapidly, losing its value by almost 80% compared to the value of the modulus obtained for samples which were not heated (Zhang et al. 2009; Mao et al. 2009).

Samples of mudstone heated to a temperature of 400°C, similar to sandstones, are characterized by a higher value of Young's modulus by about 60% compared to the value obtained at room temperature (Zhang et al. 2013). The fastest growth of its value took place when the samples were heated to a temperature of 100°C. In the samples heated to a temperature from 400 to 600°C, a decrease of its value occurs. At a temperature of 800°C, the researchers found a 76% decline in the value of Young's modulus with respect to the value obtained after heating the sample to 400°C.

Studies of marble samples, heated to a temperature of from 24 to 400°C show the fluctuation in Young's modulus (Zhang et al. 2009). For samples heated to a temperature above 400°C and uniaxially compressed, Young's modulus for this type of rock decreases and reaches a 58% reduction of its value at 800°C.

The above analysis shows that for all types of studied rocks, similar in compressive strength, the value of Young's modulus value also decreases with increasing temperature. For rocks of similar mineral composition, the influence of temperature on Young's modulus is similar. For rock containing a large amount of silica Young's modulus gradually decreases with increasing temperature.

Zhang et al. (2013) described the main factors affecting the change of rock elasticity. Among them are:

- Thermal evaporation. The volatilization of water contained in the internal structure of rock at a temperature of up to 400°C gives rise to a greater number of pores, the size of which under the influence of axial compression begins to decrease, thus contributing to an increase in the density of rock after reaching a state of stress in the elastic phase. This results in a better resistance of rock to deformation, and therefore causes an increase in strength.
- Thermal cracks. Different thermal expansion of minerals results in an increase of thermal stress, which in the temperature range of 400 to 600°C exceeds the maximum strength. This leads to the creation and development of new micro-cracks in samples which damage the rock structure and reduces the value of Young's modulus.

4. SUMMARY AND CONCLUSIONS

This paper analyses the influence of temperature on the changes in the main geomechanical parameters of selected rocks subjected to compression in a testing machine. They include: compressive strength and Young's modulus. The trends of changes in the values of compressive strength and elasticity of selected rocks were presented using the course of the complete stress-strain characteristics, taking into account its pre- and post-failure specifics.

Scientific literature shows that temperature has a significant effect on the changes of geomechanical properties of rocks. However, the nature of the changes varies for different types of rocks. Depending on various factors such as mineral composition, porosity, density, etc. these changes occur in accordance with different rules. In crystalline and sedimentary rocks the rise of temperature results in temporary rock reinforcement, usually with a temperature of 400°C. At higher temperatures the strength of rocks decreases rapidly. In the case of carbonate sedimentary rocks, strength decreases from the beginning of the heating process. In relation to the study of rocks at room temperature, little change is observed in the later stages of heating at higher temperatures.

Most important processes that cause changes in the strength properties of rocks occurs in the temperature range of 400 to 600°C. As a result of the thermal expansion and decomposition of minerals, dehydration, de-hydroxylation and an increase in thermal stresses, considerable changes in the internal structure of rocks take place. This results in the reduction of the values of geomechanical parameters of rocks, including inter alia the reduction of uniaxial compressive strength and the value decreasing of Young's modulus. The analysis of the stress-strain characteristics indicates brittle behaviour of rocks to a temperature of 400–600°C. Rock samples heated to a higher temperature and then uniaxially compressed, show an increase in the axial critical and total deformation. The model of their destruction changes – brittle destruction is replaced by “ductile” behaviour which results from the plastic deformation curve in the post-failure stage of the destruction of rocks subjected to the load in the testing machine.

Research on the effects of temperature on the properties of rocks are currently a very important research task because of its broad practical application. Data from laboratory studies can be used as input data for the construction of numerical models in a widely understood geoengineering field. The parameterization of the geomechanical processes must, however, be careful, because each rock medium shows a different behaviour under the influence of heat. In view of the above, each model should be developed for each individual rock type.

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