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IMPACT OF HEATING OF CARBONIFEROUS ROCKS ON THEIR MECHANICAL PARAMETERS

1. Introduction

The impact of high temperatures on the rocks is rarely analysed. This results from the fact that among the adopted mining technologies, there is usually no need to determine properties of rocks subjected to high temperatures. The exception is formed by underground coal gasification, where temperature in the gasification tunnel reaches 1200°C and can maintain this level for several days after coal burning beginning [10]. At the contact point of the coal deposit and surrounding rocks, this causes changes to the physical properties of the rocks.

Investments carried out so far in the area of gasification are principally based on the method of open generator channels drilled from the surface [1]. Often, these are only directional holes, and the installation is shaft-free without underground excavations. The gasification installation presently designed in Poland will be run from the existing headings of the active “Wieczorek” mine. It will be therefore, interesting to see how the rocks surrounding the generator will behave, and principally how their mechanical properties will change. It must be noticed that according to Ukrainian studies [4] based on numerical analyses, laboratory and model studies, it was estimated that at the distance of 2 m from the roof of the gasified deposit, rock temperature amounts to approx. 387–432°C, while at the distance of 2 m under the gasified deposit — up to 455–612°C. Due to impact range of high temperatures on the rocks, through to several meters, changes to mechanical properties of the rocks may refer not only to the rock strata adjacent to coal deposit, but also to an approx. 2-metre layer of the roof and direct bed rock.

Dengina points out those cracked and porous layers around the burnt deposit may undergo further stratification, accompanied by propagation of the cracking zone [3]. According to Russian studies, complete changes to rock properties may reach 2/3 height of the roof stratum that has been disturbed. Up to the height of 1/10 of deposit thickness, the rock may be entirely

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burnt. Changes to properties will also refer to all of the rock strata that occur in coal deposits, and due to which some deposits are not exploited using traditional methods.

This article presents the results of strength and deformation tests of carboniferous rocks — mudstones, siltstones and sandstones surrounding the underground georeactor designed in Poland (area of 501 deposit at KWK "Wieczorek" mine). The article presents the values of compression strength and tensile strength of the rocks, modulus of longitudinal elasticity and changes to the above parameters due to rock heating to a temperature of 1000°C. Ignition losses have also been presented, as experienced by the rocks, and the above studies have been confronted to the change of mechanical properties of the rocks due to heating.

2. Rock behaviour in high temperatures

Previous studies on rock behaviour under the impact of high temperatures indicate that this principally depends on their structure and mineral composition [3, 6, 8, 12]. Due to varying thermal expansion of minerals, at the contact between the bond and various minerals, there are cracks and changes to their structure [12]. Under the impact of temperature, strong rock grains expand and increase their contact surfaces, which contributes to the deterioration of rock strength. In the case of carbonate rocks, the result of high temperatures causes, their strength deteriorate from the start of heating, while in the case of crystalline and clastic – particulate rocks (sandstones) characterised with strong quartz grain, in the initial phase of heating they become stronger [12]. At temperatures reaching 1400°C, some minerals can melt, transforming into new minerals, while the entire rock may turn into ash or slag [3]. Soviet studies indicate that at the temperatures above 1100–1150°C, rock volume may increase if they contain very fine fractions, also in sandstones.

Depending on mineral composition and contacts of deposit grains, the process of rock deformation occurs at different temperatures [8]. The most decisive factor affecting rock behaviour at high temperatures is, however, the content of clayey substances [6, 12]. According to the Skochinsky Institute in Moscow, changes to rock properties can be correlated according to their proportion of minerals: quartz–feldspars and clayey minerals [3].

Pinińska's studies indicate that sandstones increase their strength up to the temperature of approx. 400°C, and then their strength decreases, although it is still higher than originaly [8]. Chinese studies confirm this fact and prove that rock strength only decreases in crystalline rocks [12]. In non-crystalline rocks, such as sandstone, such changes are marginal. In turn, where there are clay substance or clayey bond, strength may increase. Studies also performed in China at the Xuzhou Mining-Technology University on samples of marble, limestone and sandstone from mining region in Xuzhou indicate that the only rock for which as increase in strength was recorded with the temperature of up to approx. 600°C, was sandstone, while in other rocks, strength decreases, and the nature of the decrease is more or less linear [12].

Studies on sandstones of various granulation, performed in Moscow, indicated that with thick-grained sandstones and conglomerates, after the temperature exceeding 600–800°C, these begin to lose their strength rather sharply, whereas fine-grained and medium-grained rocks increase their strength [3]. The exception is formed by sandstones with visible detrital substance.

An interesting course of changes to rock strength can be observed in carbonate rocks — e.g. limestones. Studies performed by Mao show that the course of changes up to the temperature of approx. 700°C is sinusoidal and strength reduction will then amount to approx. 25%. After exceeding the temperature of 700°C, there is a sharp decrease in strength to approx. 23% of the original strength [7].

For the assessment of strength, it is also important to consider surrounding pressure [5]. However, it only begins to play a significant role for the temperature above 180°C. It is only then that clear differences to the stress and deformation characteristics occur for shales.

In the case of elasticity modules, a clear effect of reduced rock elasticity occurs up to the temperature of approx. 400–500°C in grainy rocks — andesite, granite, sandstone [12]. In loamy rocks (ceramic shales), the effect of a change to elasticity module due to temperature impact does not occur. Zhang's study indeed indicates that, in sandstones (grainy rocks), there is a slight decrease to Young module, after which stiffness again increases in the temperature range of 400–600°C, and then decreases again [11]. In marbles and limestones, a reduction of modulus of elasticity is exclusively recorded, in particular after exceeding the temperature of 600–700°C. At the same time, the studies reveal that change to limestone stiffness with temperature can be determined using third degree polynomial curve [7].

In this case, above the temperature of approx. 150°C, the increase in surrounding pressure causes a reduction of deformations present, and as a result the increase in elasticity module, is experienced even doubling the value [5]. It is interesting that for carbonaceous shales, above the temperature of 600°C, the effect of increased stiffness vanishes, whereas the range of temperatures of up to 200°C does not cause changes to stress and deformation characteristics.

3. Methodology

The study involved samples of mudstones, siltstones, sandy mudstones as well as sandstones, taken from the ventilation drift at level 400 to deposit 510 at KWK "Wieczorek". The area is in the direct vicinity of the designed geo-reactor. Cubic samples of 50 mm side and cuboid samples with the base of 50×50 mm and height of 100 mm were analysed at the Faculty of Mining and Geoengineering of the University of Science and Technology at the Department of Geomechanics, Civil Engineering and Geotechnics. Particular series of rock samples corresponded to relevant numbers, according to Table 1.

In order to determine the impact of temperature on the strength of and deformation properties of the rocks analysed and to assess the ignition losses (loss in a sample weight), the samples were kilned. Sample heating was performed in muffle kiln SM 2000 with a microchip regulator (Fig. 1a).

In order to determine kilning losses when heating at the temperatures of 20, 100, 200, 300, 400, 500, 600, 700, 800, 900 and 1000°C, they were weighed using laboratory scales WPT 2 (Fig. 1b). The kilning procedure comprised the time of reaching the predefined temperature,

TABLE 1
Numbering of the analysed rock formations

Series number	Rock
1	siltstone
3	sanded mudstone
4	sandstone
4.4	siltstone
7	mudstone
9	sandstone
10	mudstone

which amounted to approx. 20 min and heating time of 10 min. Changes to the above time at particular temperature ranges were caused by inertia of the system. Additionally, at a temperature of 1000°C, samples were furnace for 24 hours. Kilning involved both shaped and non-shaped samples. The analysis involved ovenproof bowls in which the samples were placed. At any given time, there were from 2 to 4 samples in the furnace, for the relevant type of the rock.

a) b) c)

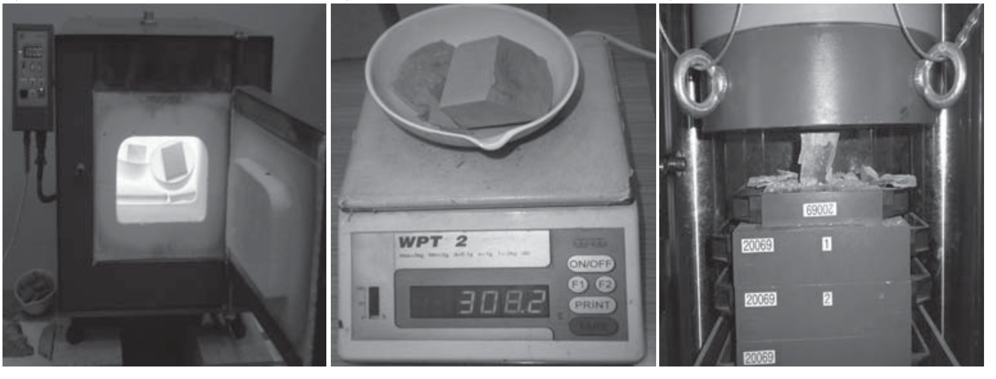

Fig. 1. Laboratory tests
a) sample kilning at muffle kiln SM 2000 with microchip regulator,
b) weighing of sample of mudstone series 12 on laboratory scales WPT 2,
c) sample pressing after kilning at strength machine DB 3000/100

After the kilning process, a strength test was performed in machine type DB 3000/100 (Fig. 1c). Uniaxial compression and tensile strength was determined acc. to the guidelines of standards, respectively, PN-G 04303:1997 and PN-G 04302:1997. For setting the Young modulus, samples with aspect ratio two were prepared, with the base in the form of a square with a side length of 50 mm. Rock samples for deformation test were cut from rocks so that the bedding plane was perpendicular to the stress administered. The Young modulus analysed can, therefore, be referred to as the modulus of longitudinal elasticity. It was defined in the range suggested by ISRM 20–80% of breakage stress. In the case of samples of sanded mudstone, siltstone and sandstone, after the kilning process, the largest possible cuboids were cut, which were then subjected to structural and mechanical tests. In the case of mudstone samples, as a result of kilning, they became stratified and partially decomposed, preventing the performance of strength test.

Due to very similar behaviour of sandy mudstone and siltstone when heating, the analysis of results gave reason to assume that it is the same as with lithological type of rocks.

4. Ignition losses

Heating of carboniferous rocks from the area of designed geo-reactor indicated that the degree of structural changes resulting from the impact of high temperature is varied. Due to the impact of temperature of approx. 520–560°C, mudstone samples became scorched and cracked in various directions (Fig. 2a). Samples of sandy mudstones and siltstones changed colour and cracked locally where the concentration of clayey parts was the highest (Fig. 2b and 2c). Sandstones did not change their form, and few minerals changed colour to red or brown (Fig. 2d). Test results conform to the observations of sandy claystones and sandstones performed by Tian [9]. The sandstones he studied, apart from one sample, did not change form, while sandy claystones cracked densely along the bedding planes.

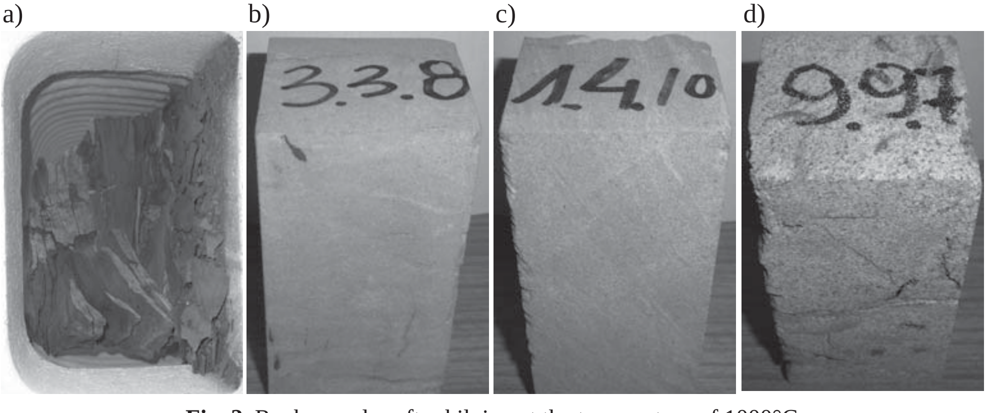

Fig. 2. Rock samples after kilning at the temperature of 1000°C
a) mudstone (in kiln chamber), b) sandy mudstone, c) siltstone, d) sandstone

The performed analysis of ignition losses up to 1000°C revealed that the smallest loss of weight was recorded in sandstones (series No. 4 and 9), where Δm = 2.3–3.7% (Fig. 3). Sandy mudstones and siltstones (series No. 1, 3 and 4.4) recorded similar weight loss, totalling on average 5.65–6.25%, whereas mudstones — 8.78–9.56%. Measurements of weight loss in mudstones are very similar to the ones obtained by Delft University [5], which reached 12.5%.

Attention must also be drawn to temperature thresholds, where significant change to rock weight begins. In the case of mudstones, this is temperature of approx. 200°C. For series No. 10 excess of 1% in weight loss occurred as early as approx. 260°C. To achieve the same, sandy clays need a temperature of approx. 440–480°C, whereas sandstones — approx. 530–620°C.

Temperatures of approx. 150–180°C is where a slow weight loss process begins, and has an almost linear course for all rocks up to the temperature of 500°C (Fig. 3). Next, in the range of 500–700°C, the dynamics of the phenomenon clearly increases, most visible for clayey rocks, while in the final phase it adopts the shape asymptotic to the final value. The weight loss process visibly slows down at the temperature of approx. 700–800°C. Therefore, it can be claimed that the greatest structural changes to all analysed carboniferous rocks occur in the range of 500–700°C.

The samples tested were in an air-dry state (water content ca. 0.3%), so all the changes in the structure and weight were therefore caused by burning and oxidation,

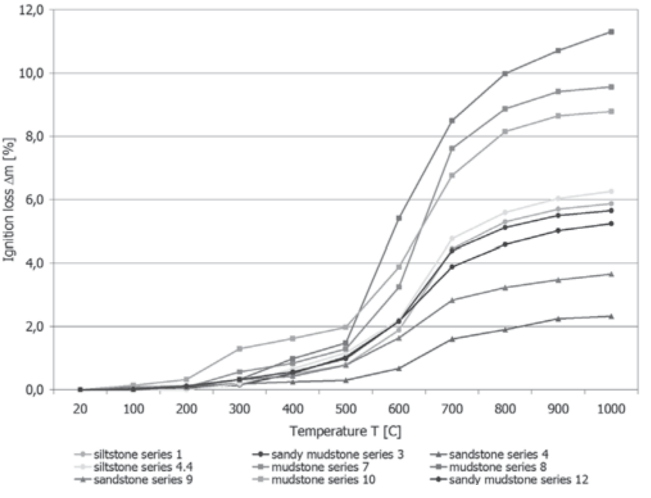

Fig. 3. Weight loss in samples due to impact of high temperature

5. Compression and tensile strength

Compression strength of siltstones, sandy mudstones and sandstone in a natural and burned state has been presented in Figure 4. The number of 180 samples in a natural state and 43 after heating were tested altogether. In natural state, the strength amounts to 52–68 MPa for sandy-mudstones, and 47–50 MPa for sandstones. Values obtained for shales are, therefore, closer to the average values for seam 400 group strata, and values for sandstones — for seam 500 group strata [2]. On the basis of the tests performed, one can state that after heating, for siltstones (series 1, 3 and 4.4), their compression strength increases. The exception is formed by series 1.2, the result of which differs from the general trend. This was caused by the occurrence of coal laminae, due to which rock strength decreased. It must be stressed that an increase in strength for siltstones is clearly greater (on average by approx. 64%) than in the case of sandy mudstones (approx. 15% — Fig. 5). It can even exceed 128% of original value (series 1.3). Mudstones series were marked in blue colour in Fig. 10, as sandstones series in orange.

In the case of sandstones, there is a general decrease in compression strength, amounting on average to 18%. The strength may, however, slightly increase (approx. 6%) or decrease even by 55% (series 9.9). Macroscopic observations indicate that this is caused by the share of clayey particles in the mineral composition of such rocks.

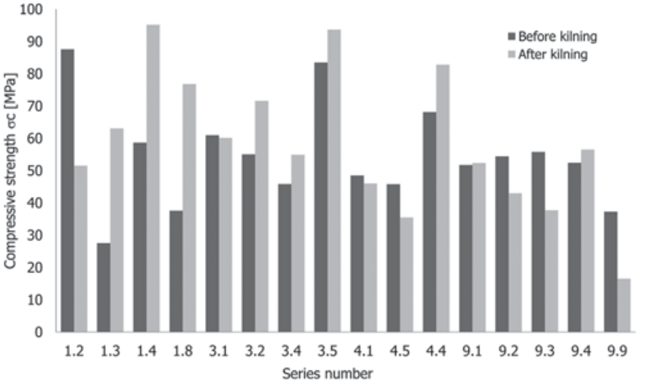

Fig. 4. Average compression strength values before and after kilning

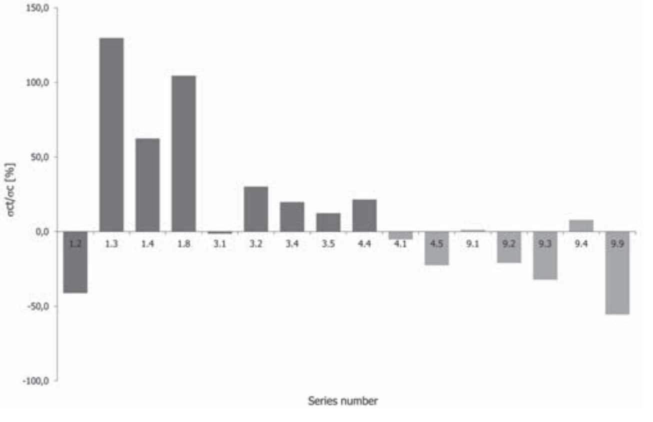

Fig. 5. Change to compressive strength of the rocks affected by heating to the temperature of 1000°C

The comparison of the value of compressive strength change of kilned samples with their weight loss is also interesting (Fig. 6). The diagram shows that together with weight loss, the strength of the rock increases, and the nature of such changes is linear. In the case of sandy mudstones and siltstones, one can speak of a much better adjustment of the correlation function to the results obtained (R^2 = 70%). For sandstones, this tendency is visible, although the correlation factor is low. It can also be observed that for sandstones that record small ignition loss due to heating, the increase in strength is slow. In turn, sandy mudstones record very quick increase in compressive strength with the increased losses during kilning. Increase in weight loss from 5.5% to 6.5% results in 150% increase in strength.

Negative values of changes to strength in the diagram (Fig. 6) indicate decrease in strength, while positive values — its increase.

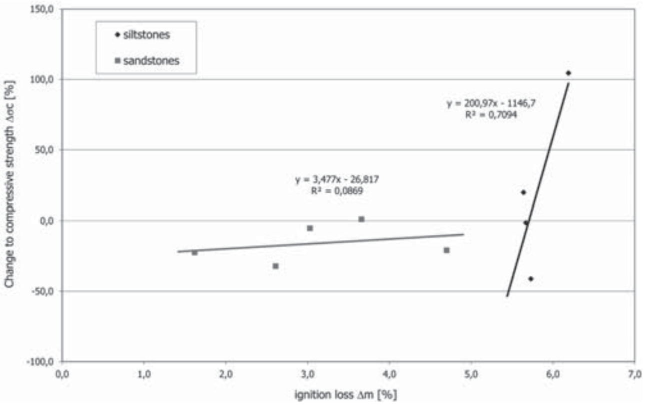

Fig. 6. Dependence of change to compressive strength after kilning and weight loss

Figure 7 presents changes to tensile strength of rocks subjected to high temperatures. Similarly as in the case of compression, also during tensile strength test, samples of sandy mudstones indicated an increase in strength. In turn, samples of siltstone and sandstone recorded a reduction in strength. For analysed series 3.3 and 3.5, there was a change to Rr on average by +39%. Tensile strength of samples of siltstone decreased by 27% (blue colour), and of sandstone — by 52% (orange colour — Fig. 8). The study indicates that the differences in tensile strength are not so high as in the case of compression strength. It must also be added that after heating, from 2 to 4 samples were analysed in each series, therefore the above results are of a rather informative nature and must be completed.

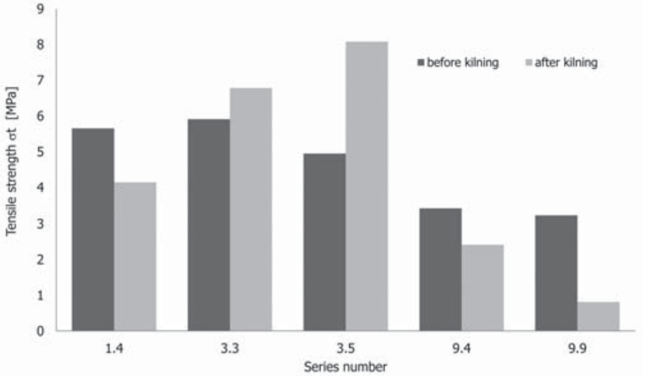

Fig. 7. Average tensile strength values before and after kilning

6. Modulus of longitudinal elasticity (Young modulus)

The analysis of changes to the modulus of longitudinal elasticity was performed on a series of nine rocks. Test results indicate that before heating, the least deformable is sandstone, for which average Young modulus amounts to 8.5 GPa, and the most deformable — sandy

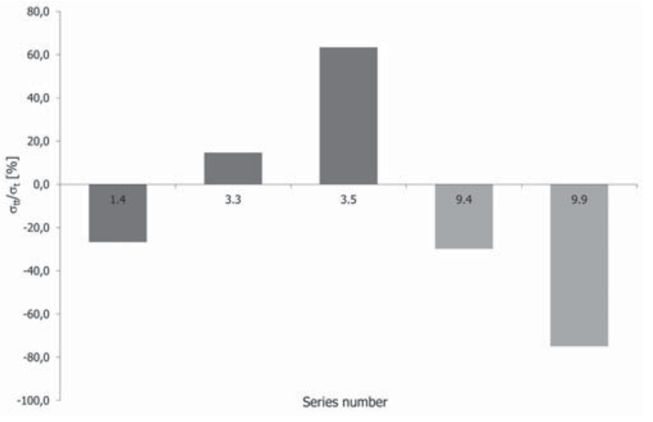

Fig. 8. Change to tensile strength of the rocks affected by heating to the temperature of 1000°C

mudstone: 5.7 GPa (Fig. 9). It must also be stressed that particular samples in a particular batch revealed significant variations, similarly as in the case of strength tests. This testifies to the high non-homogeneity of carboniferous rocks and confirms macroscopic observations of samples for which cracking or stratification was often visible. After the heating process, it was determined that for all series the values of the Young module there was decrease (Fig. 9): for sandy mudstones up to 4.6 GPa, siltstones — up to 2.8 GPa and sandstone — 2.5 GPa. The smallest changes to stiffness were recorded for siltstones (50%), the greatest — for sandy mudstones (75%), whereas sandstone by approx. 63%, within the range of 50–75% (Fig. 10). In the case of sandstone, the change of deformation properties was decided upon by its structure. Very fine-grained sandstones in series 9 reduced their stiffness to a greater extent than sandstones with slightly more coarse fractions (series 4). Test results for sandstones reveal tendencies similar to that of the Chinese studies [11], where up to the temperature of 800°C the rocks lost their stiffness by approx. 32%.

The exception in the study was formed by a series of rocks No. 3.4 (siltstone — Fig. 10). Kilned samples reduced their deformability, and the Young module increased by 25%. Mudstones were marked in a blue colour in figure 10, and sandstones in orange.

Dependence of change to the Young modulus of the rocks after kilning and their weight loss is similar to the previously performed for compression strength (Fig. 11). Also in this case, one can talk of a linear trend, although correlation between both parameters is not high. After kilning sandstones record a smaller weight loss and an accompanying slow decrease in elasticity. Sandy mudstones lose 6–7% weight due to kilning and at the same time their Young modulus decreases very quickly.

Such behaviour of shale samples may be related to the behaviour of sedimentary rocks observed by Mao, which after exceeding a temperature of approx. 600°C begin to get softer, losing the properties of a brittle material and as a result their structure, becoming more plastic, reveals a much greater deformability [7].

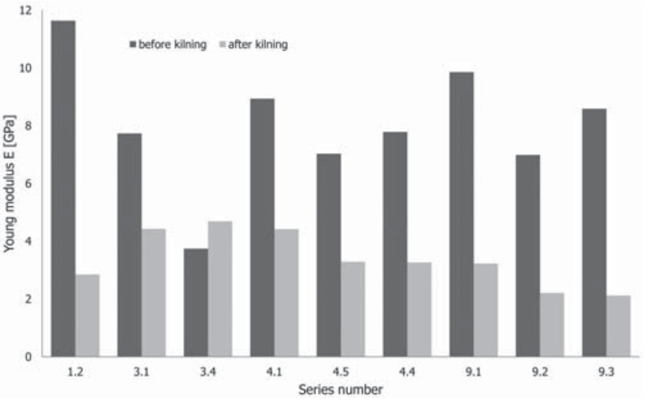

Fig. 9. Average value of Young module before and after kilning process

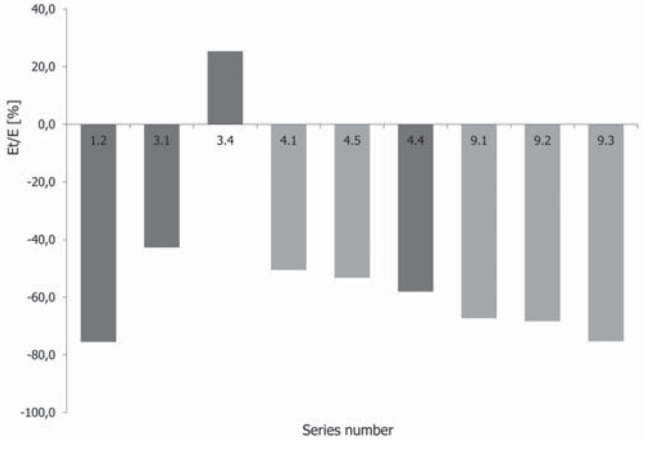

Fig. 10. Change to Young modulus of the rocks affected by heating to the temperature of 1000°C

7. Summary

Studies of changes to the mechanical properties of carboniferous rocks due to high temperatures had not been performed in Poland before. This was due to lack of demand for any such studies. Due to an attempt to implement the technology of underground gasification of hard coal, it is now necessary to investigate the changes to the mechanical parameters of rocks after kilning, rocks of the same tape as those, that would surround the designed georeactor. The studies performed by the authors only refer to carboniferous rocks occurring around coal deposits — mudstones, siltstones (sandy mudstones) and sandstones.

The assessment of the mechanical properties of such rocks involved uniaxial compressive strength, tensile strength and modulus of longitudinal elasticity. The assessment of mudstone properties is prevented by the fact of their very intensive cracking and scorching, made

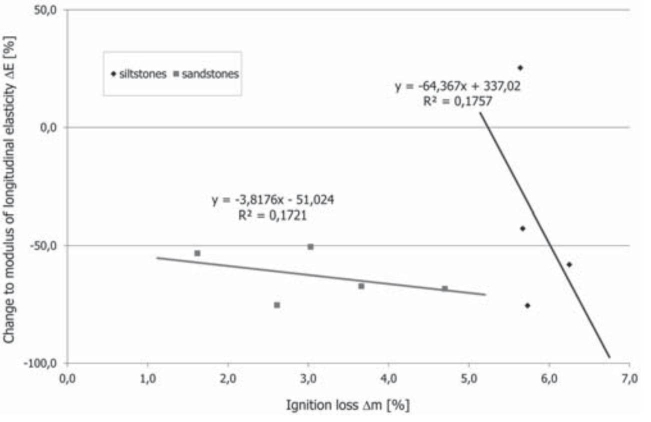

Fig. 11. Dependence of change to elasticity in elongation module after kilning and weight loss

cutting samples for strength and deformation tests impossible. Differences in rock responses to temperature of 1000°C have been documented with measurements of weight losses during heating also recorded. Mudstones become scorched, and their weight loss reaches 10%, siltstones lose approx. 6% weight, whereas sandstones — approx. 3%.

Laboratory tests performed on strength and deformation properties of rocks subjected to the temperature of 1000°C indicate that:

1) Compressive strength of mudstones increases. Coal laminae result in weakening of rocks and decrease in their strength. Increase in strength for siltstones is clearly greater (on average by approx. 64%) than in the case of sandy mudstones (approx. 15%), and may even exceed 128% of original value. In the case of sandstones, there is a general decrease in compressive strength, amounting on average to 18%. This strength may, however, also increase slightly.
2) Tensile strength of sanded mudstone increases (+39%), while samples of siltstone and sandstone recorded reduced strength by, 27% and 52% respectively. The study indicates that differences in tensile strength are not as high as observed in the case of compressive strength.
3) Values of the modulus of longitudinal elasticity after the kilning process decrease for all rock strata. The smallest changes to elasticity were recorded in siltstones (50%) and the greatest — for sanded mudstones (75%), whereas sandstone by approx. 63%, within the range of 50–75%.

The comparison of the value of compressive strength change of kilned samples compared with their weight loss indicates that the nature of such changes is linear. In the case of sandy mudstones, a very good correlation of both values can be observed. For sandstones that record small weight loss due to heating, increase in strength is slow. For siltstones, increase in weight loss from 5.5% to 6.5% results in a very quick 150% increase in strength.

Dependence of change of modulus of longitudinal elasticity after kilning and weight loss is also similar to linear, although correlation between both parameters is not high. Together with slow weight loss in sandstones, there is a slow decrease in elastic properties. The increase in weight loss from 1.6% to 4.8% results in a 15% reduction in deformability. Siltstones lose 6–7% weight due to heating and at the same time their Young modulus decreases very quickly.

As revealed by the study, such high changes to the values of the mechanical parameters of the rocks will decisively change the stresses and deformation in the rock mass. This is very important from the point of view of future designing and modelling of the gasification process for the selected coal deposit.

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