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THE CHANGE OF STRUCTURAL AND THERMAL PROPERTIES OF ROCKS EXPOSED TO HIGH TEMPERATURES IN THE VICINITY OF DESIGNED GEO-REACTOR**ZMIANY WŁAŚCIWOŚCI STRUKTURALNYCH I CIEPLNYCH SKAŁ PODDANYCH WYSOKIM TEMPERATUROM W REJONIE PROJEKTOWANEGO GEOREAKTORA**

Among the main directions of works on energy acquisition, there is the development and application of the technology of underground gasification of coal deposits (UCG). During the process of deposit burning and oxidation, there is also impact of temperatures exceeding 1000°C on rocks surrounding the deposit. As a result of subjecting carboniferous rocks to high temperatures for a prolonged period of time, their structure will change, which in turn will result in the change of their physical properties. Due to the project of underground coal gasification, as performed in Poland, laboratory tests are currently under way to a broad extent, including physical properties of carboniferous rocks subjected to high temperatures. The article presents results of laboratory tests of rocks surrounding the designed geo-reactor: changes to bulk density, specific density and porosity due to high temperature, and confronts the above results with the results of tests of thermal conductivity, specific heat and heat diffusivity (temperature conductivity) of the rocks. The mineralogical investigations were presented too.

Keywords: structural rocks parameters, high temperature, thermal rocks parameters, rocks' kilning

Jednym z głównych kierunków prac nad pozyskiwaniem energii jest opracowanie i zastosowanie technologii podziemnej gazyfikacji pokładów węgla. W czasie procesu spalania i utleniania pokładu dochodzi również do oddziaływania temperatur przekraczających 1000°C na skały otaczające pokład. W wyniku poddania skał karbońskich wysokim temperaturom przez dłuższy okres czasu będzie dochodzić do zmian ich struktury, co z kolei spowoduje zmiany ich właściwości fizycznych.

Ze względu na realizowany w Polsce projekt podziemnego zgazowania węgla prowadzone są obecnie badania laboratoryjne w szerokim zakresie, m.in. właściwości fizycznych skał karbońskich poddanych wysokim temperaturom. W artykule przedstawiono wyniki badań laboratoryjnych skał otaczających projektowany georeaktor: zmian gęstości objętościowej, gęstości właściwej i porowatości na skutek wysokiej temperatury oraz skonfrontowano powyższe wyniki z wynikami badań przewodności cieplnej, pojemności cieplnej i dyfuzyjności cieplnej (przewodzenia temperatury) skał.

Na podstawie opisu mineralogicznego skał przed wygrzaniem stwierdzono, że są to okruchowe skały osadowe z frakcją psamityczną. Szkielet ziarnowy jest zbudowany niemal wyłącznie z ziaren kwarcu,

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a podrzędnie w skałach występują muskowit, biotyt, skalenie i minerały ciężkie. Zawartość procentowa minerałów i spoiwa zmienia się w szerokim zakresie: ziaren mineralnych od 10,3% do 90,0%, a spoiwa od 10,0% do 89,7%. Po przepaleniu skał do temperatury 1000÷1200°C zmniejsza się w nich zawartość matrix, a wzrasta zawartość kwarcu. Pojawiają się także nowe minerały, takie jak hematyt i minerały rudne. Po ogrzaniu nie stwierdzono cementu węglanowego, opali, tlenowodoroków żelaza, kalcytu, hornblendy i porów. Proporcja pomiędzy ziarnami a spoiwem ulega zupełnej zmianie i ziarna stanowią 31-99% objętości, a spoiwo – 1-69%.

Wpływ wysokiej temperatury na zmianę struktury i tekstury skał określano obserwując zachowanie się skał w trakcie ich wygrzewania. W pierwszej kolejności zaobserwowano zdecydowanie różny charakter reagowania poszczególnych typów skał na wysoką temperaturę, a w swoich fazach podobny do obserwacji poczynionych przez Mao (Mao et al. 2008). Łupki ilaste wypalały się całkowicie, zmieniały swój kolor na brązowy, a także rozwarstwiały i pękały na drobne kawałki. Łupki piaszczyste generalnie nie zmieniały swojej postaci, lecz często pękały wzdłuż powierzchni uwarstwienia. Laminy materiałów ilastych ulegały przepaleniu i kolor zmieniał się na brązowy lub brunatno-czerwony. Piaszkowce całkowicie zachowywały swój kształt, natomiast niektóre minerały zmieniały swój kolor na czerwony lub brązowy.

Wykonane badania pokazują, że wszystkie badane skały po wyprażeniu zwiększają swoją gęstość objętościową i zmniejszają swoją gęstość właściwą. Największe zmiany wykazują skały ilowcowe, które mogą zwiększyć swoją gęstość objętościową ρ_o o ponad 20%, podczas gdy największy ubytek gęstości właściwej wykazują łupki ilaste i piaszczyste, których zmiana ρ_v wahała się od 0,88% do 5,93%, natomiast piaszkowce zmniejszają swoją gęstość średnio o ok. 1,5%. Choć wydaje się logiczne, że wraz z wypalaniem się skał powinna wzrastać ich porowatość i jednocześnie zmieniać się gęstość objętościowa, badania nie wykazują ścisłej zależności pomiędzy oboma parametrami.

Analiza granicznych wartości współczynnika przewodzenia ciepła skał karbońskich w temperaturach 20°C i 1000°C pokazuje, że wartości współczynnika λ po wygrzaniu skały ma tendencję odwrotnie proporcjonalną do wartości pierwotnej. Dla współczynnika przewodności cieplnej równego ok. 1 W/m·K w temperaturze pokojowej, po wygrzaniu skał do 1000°C jego wartości gwałtownie rosną do nawet 14 W/m·K. Wraz z większą początkową zdolnością do przewodzenia ciepła, wyprażenie skał w wysokiej temperaturze zaczyna przynosić skutek odwrotny w stosunku do jego przewodności cieplnej. Tendencja spadku przewodnictwa cieplnego dla skał osadowych jest zgodna z obserwacjami niemieckimi łupków i piaszkowców, gdzie stwierdzono, że współczynnik λ dla temperatury pokojowej wynosi ok. 3,0-3,3 W/m·K, natomiast po ogrzaniu do temperatury 800°C jego wartość spada do ok. 1,4 W/m·K (Clauser & Huenges, 1995).

Zauważalny jest także wyraźny logarytmiczny charakter zmian zdolności skał do przewodzenia ciepła przed i po wygrzewaniu ich w wysokich temperaturach. Współczynnik determinacji jest dla przebadanych próbek równy 0,70, co wobec niestabilności procesów termicznych w skałach i ich ścisłej zależności od składu mineralogicznego należy uznać za wyjątkowo wysoki.

Wykonana analiza pokazuje, że nie można wykazać żadnej korelacji pomiędzy właściwościami termicznymi skał a ich gęstością objętościową. Przy tej samej gęstości ρ_o współczynnik przewodzenia ciepła dla skał po wyprażeniu może przyjmować wartości w szerokim zakresie od 1 W/m·K do 15 W/m·K, jak również wiele zbliżonych wartości współczynnika λ dla tej samej gęstości objętościowej przed wyprażeniem. Podobnie rzecz się ma z pojemnością cieplną skał oraz z jej dyfuzyjnością ciepła, która także dla tej samej gęstości objętościowej może przyjmować kilkukrotnie różne wartości.

Przeprowadzone badania właściwości strukturalnych oraz cieplnych skał karbońskich z rejonu Górnego Śląska, gdzie projektowana jest podziemna gazyfikacja węgla, pokazuje, że wraz z temperaturą zmieniają się one w bardzo szerokim zakresie.

Badane skały łupka ilastego, łupka piaszczystego i piaszkowca po wyprażeniu zwiększają swoją gęstość objętościową i zmniejszają swoją gęstość właściwą. Największe zmiany wykazują skały ilowcowe, które mogą zwiększyć swoją gęstość objętościową nawet o ponad 20%. Średnie zmiany gęstości dla łupków ilastych wynoszą 9,76%, łupków piaszczystych – 8,19%, a piaszkowców – 5,73%. W przypadku gęstości właściwej ρ_v , następuje jej zmniejszenie pod wpływem wysokiej temperatury, w przypadku łupków ilastych i piaszczystych nawet do 6%.

Wartości współczynnika przewodzenia ciepła λ skał karbońskich w temperaturach 20°C i 1000°C pokazują wzajemną autokorelację w funkcji logarytmicznej. Oznacza to, że dla wysokich wartości współczynnika λ skał przed wygrzaniem, jego wartość spada po wygrzaniu i na odwrót.

Wykonana analiza pokazuje, że nie można wykazać zależności pomiędzy właściwościami termicznymi skał a ich gęstością objętościową, natomiast w pewnym stopniu można skorelować badane parametry termiczne z gęstością właściwą skał. Poddanie skał bardzo wysokim temperaturom mocno zaburza wza-

jemne relacje pomiędzy ich właściwościami strukturalnymi i termicznymi. Właściwości termiczne skał są zależne od zakresu temperatur, w jakich są wyznaczane i ulegają zmianie wraz ze zmianą ich składu mineralnego. Zmiana struktury skały nie przekłada się jednak wprost na jej zdolności do przewodzenia i akumulacji ciepła.

Słowa kluczowe: parametry strukturalne skał, wysoka temperatura, termiczne właściwości skał, wygrzewanie skał.

1. Introduction

The underground gasification process is related to the supply of very high temperature to the rock mass. According to previous experiments, temperature in the gasification tunnel reaches 1200°C and can maintain this level for several days after coal burning begins (Yang et al., 2009). In the roof and bed rock of coal deposit, the temperature will also impact on the surrounding rocks, causing changes to their properties. According to Ukrainian studies (Falsztyński et al., 2007), based on numerical analyses, laboratory tests and model studies, it was determined that in the distance of 2 m from the roof of the gasified deposit rock temperature amounts to approx. 387-432°C, and in the distance of 2 m under the gasified deposit – up to 455-612°C. At the same time, it is envisaged that disturbing the rock continuity together with their fracturing may reach the level of 6 m over the burnt deposit, with the fissure width of up to 50 mm. Due to such a large range of high temperature impact on the rock mass, it is justified to analyse changes to the rock structure and to determine their thermal parameters in various temperature ranges.

This article presents results of laboratory tests of rocks surrounding the geo-reactor designed in Poland: changes to bulk density, specific density, and porosity due to high temperature. The above results were confronted with the results of tests of thermal conductivity of the rocks, their specific thermal capacity and capacity to conduct temperature. The study involved claystones, siltstones and sandstones. All rocks under study were heated for this purpose to the temperature of 1000°C or 1200°C, depending on the distance of the stratum from the designed geo-reactor.

2. Methodology

In order to determine the impact of temperature on the change of sample mass, representative for the process of underground coal gasification, laboratory tests were performed at the Faculty of Mining and Geoenvironment, Department of Geomechanics, Civil Engineering and Geotechnics of the AGH University of Science and Technology. The samples were furnace in muffle kiln SM 2000 with a microchip regulator (Fig. 1). Next, the following was determined for them:

- bulk density after cooling from the temperature of 1000°C,
- specific density after cooling from the temperature of 1000°C,
- porosity after cooling from the temperature of 1000°C.

Bulk density of the dry material, specific density and total porosity were marked according to the guidelines of the Polish standard based on Eurocode PN-EN 1936:2001. The study of bulk density was performed on cubic samples with the side length of approx. 50 mm, cut from irregular blocks. For calculation of total porosity, it was necessary to perform additional measurement of bulk density, carried out with hydrostatic method (as more precise), and specific density with



Fig. 1. Muffle kiln SM 2000 with a microchip regulator together with rock samples

picnometric method, where the rocks were fragmented to the fraction of below 0.063 mm. For porosity marking, rock samples were dried to the solid mass at the temperature of $70\pm 5^\circ\text{C}$.

The parameters described above were determined both for “raw” samples in the natural state (air-dry), and after their burning at the temperature of 1000°C . The study involved three layers of claystone, four layers of siltstone and two layers of sandstone.

For all seven rock layers, also measurements of thermal property changes were performed. This article presents the values of: thermal conductivity factor λ , specific thermal capacity c_p and thermal diffusivity κ in extreme temperature of 20°C and 1000°C . Measurements of thermal capacity were made at the STA 449 F3 Jupiter apparatus by Netzsch, allowing for simultaneous thermal analysis in reference to one sample, using two research techniques: Thermogravimetrics and Differential Scanning Calorimetrics (TG-DSC) and Thermogravimetrics and Differential Thermal Analysis (TG-DTA). The model material for the tests made was sapphire. Thermal diffusivity tests were carried out in the equipment LFA 427 Netzsch in the dynamic argon atmosphere at the flow velocity of 150 ml/min within the range of from 30 to 1000°C . Setting of c_p and κ gave the grounds for defining the thermal conductivity factor λ .

3. The mineralogical content and division of rocks

The investigated rock beds, surrounding the designed geo-reactor, are marked with numbers from 1 to 12. There are bed series 1, 3, 4, 4.4, 7, 8, 9, 10 and 12 in the closest vicinity of the seam which is planned to be gasified. Their detailed mineral content of rock beds is presented in table 1. The conducted research shown that these are solid clastic sedimentary rocks composed with psammitic fraction (Małkowski et al., 2011). The grain structure is built with quartz, usually poor rounded and poor sorted (rarely fair). The second rate minerals are biotite, muskovite, feldspare and opaque and heavy minerals. Exceptionally one can find the carbonate cement, opal,

iron hydroxides, calcite, anhydrite binder and hornblende. The heavy minerals are represented by zircons, garnets and apatites. The rocks' binder is matrix, often pigmented. The percentage amount of minerals and matrix vary in a wide range. The content of grains in analyzed samples changes from 10.3% to 90.0% and matrix from 10.0% to 89.7%. The amount of quartz in every sample is the highest, varied from 24.5% to 61.1%. After Pettijohn's petrographic classification from 1972 (Pettijohn et al., 1987) plotted projection points show, that in natural state rock beds can be classified to mudstones, which with the increasing amount of quartz and decreasing amount of matrix switch into lithic (sublithic) wackes. The number of 27 samples were analysed in the natural state.

The mineral content of analysed rock beds after heating the samples in the temperature of 1000°C is shown in table 2. One can observe that the amount of matrix drops down, but the amount of quartz grows up. The hematite and ore minerals arise after heating. The case of rock series no 7 is very interesting, because 64% of the volume is filled with hematite. The proportion between grains and matrix has changed and it amounts now 31-99% of grains to 1-69% of matrix. After heating the samples in high temperature there are no carbonate cement, iron hydroxides, opal, calcite, anhydrite binder, hornblende and pores in them. After Pettijohn classification triangle it's clear that high temperature causes mudstone alteration into wacke and wacke into quartz arenite. The exceptional case is series no 12, which transform from lithic wacke into mudstone. The number of 25 samples were analysed after kilning.

TABLE 1

The content of minerals in rock series – natural state

Minerals	Series 1	Series 3	Series 4	Series 4.4	Series 7	Series 8	Series 9	Series 10	Series 12
Quartz	41.94	57.04	61.11	44.00	24.47	18.12	50.17	24.35	32.77
Matrix	35.14	22.36	19.97	28.71	65.17	54.67	16.64	63.33	45.22
Biotite	4.67	6.79	1.06	4.77	4.76	8.15	5.71	4.67	9.92
Feldspar	1.87	2.19	5.02	2.33	0.31	1.35	10.5	0.50	1.67
Ore minerals	0.00	0.00	0.69	5.26	3.11	0.00	0.00	0.00	0.00
Lithoclasts	2.33	2.08	5.57	0.65	0.00	5.16	5.86	0.00	0.50
Muscovite	4.59	4.47	0.00	1.13	0.00	0.00	1.33	2.67	3.50
Opaque minerals	1.67	0.87	0.00	0.80	2.18	0.00	0.00	1.50	6.42
Chlorite	2.93	0.95	0.75	0.00	0.00	4.19	1.87	0.00	0.00
Oxide-hydroxide Fe	2.08	0.00	0.00	0.00	0.00	2.50	2.45	0.00	0.00
Heavy minerals	1.87	1.25	0.41	0.00	0.00	5.91	4.87	0.00	0.00
Carbonate cement	0.07	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.00
Opal	0.53	0.81	1.10	0.00	0.00	0.00	0.49	0.00	0.00
Anhydrite binder	0.33	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hematite	0.00	0.93	0.00	0.00	0.00	0.00	0.00	3.67	0.00
Calcite	0.00	0.00	2.49	0.00	0.00	0.00	0.00	0.00	0.00
Hornblende	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0.00
Pores	0.00	0.00	1.67	0.00	0.00	0.00	0.00	0.00	0.00
Pettijohn classification	Lithic wacke	Sub-lithic wacke	Sub-lithic wacke	Lithic wacke	Mud-stone	Mud-stone	Sub-lithic wacke	Mud-stone	Lithic wacke

TABLE 2

The content of minerals in rock series – after heating

Minerals	Series 1	Series 3	Series 4	Series 7	Series 8	Series 9	Series 10	Series 12
Quartz	57.92	51.29	68.66	15.67	31.95	53.61	23.67	17.76
Matrix	20.98	28.71	13.16	1.00	46.52	16.35	63.33	69.16
Biotite	4.83	4.77	3.83	0.00	4.33	3.53	4.67	5.63
Feldspar	0.52	3.11	6.84	0.00	1.34	7.07	0.50	0.00
Ore minerals	4.92	5.26	0.00	0.00	9.51	2.21	0.00	0.00
Lithoclasts	0.97	0.65	0.00	0.00	1.17	5.45	0.00	0.00
Muscovite	1.67	1.13	0.00	0.00	0.00	0.00	2.67	2.99
Opaque minerals	1.33	0.80	1.84	19.33	0.00	0.00	1.50	0.91
Chlorite	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Oxide-hydroxide Fe	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Heavy minerals	0.00	0.00	0.00	0.00	0.18	0.88	0.00	0.00
Carbonate cement	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Opal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Anhydrite binder	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hematite	6.85	0.00	5.67	64.00	4.80	10.90	3.67	3.57
Calcite	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hornblende	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pores	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pettijohn classification	Sublithic wacke	Sublithic wacke	Sublithic arenite	Quartz arenite	Sublithic wacke	Sublithic wacke	Mudstone	Mudstone

In general, all the carboniferous rocks concerned are typical for Silesian Upper Basin and can be divided into three main groups: claystones, siltstones and sandstones. The high variety of minerals is caused by the sedimentary origin of rocks. With regard of high amount of quartz in claystones it was assumed that sandy claystones in the further analysis of their physical properties will be treated as siltstones. The selected rock beds have been classified as follows (Małkowski et al., 2011):

- claystones: series 7, 8, 10 and 12;
- siltstones: series 1, 3, and 4.4;
- sandstones: series 4 and 9.

The average mineral contents of above type rocks are presented in figure 2.

4. Changes to structural parameters

The impact of high temperature on the change of rock structure and texture was determined by observing rock behaviour during their kilning, and then by performing measurements of the parameters specified above on the rock samples after cooling.

First of all, a clearly different nature of reacting to high temperature was observed for particular types of rocks (Fig. 3-5), while in its phases similar to the observations made by Mao (Mao et al., 2008). Claystones were burnt completely changing colour to brown (Fig. 3), and also underwent stratification and cracked into fine pieces. This is due to their clay mineral content.

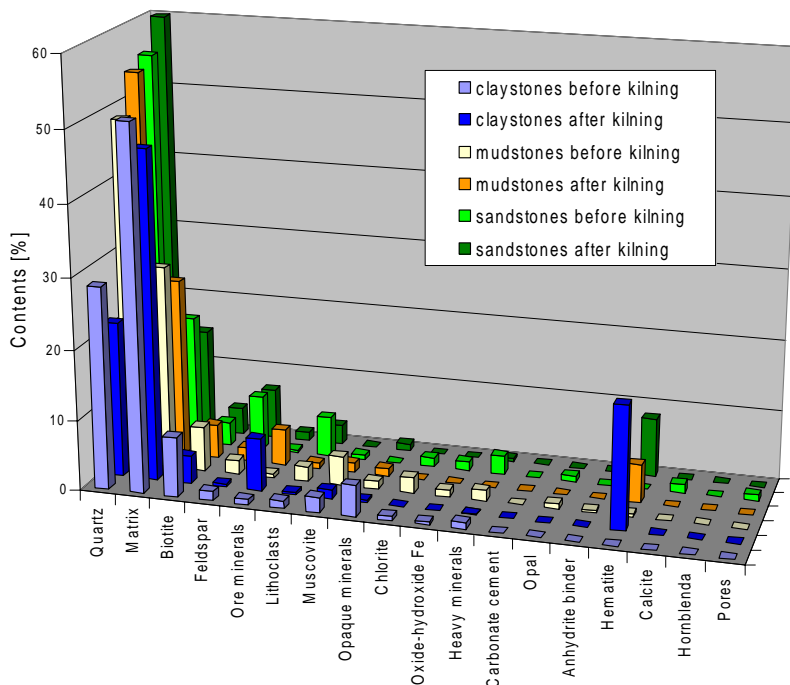


Fig. 2. The content of minerals in analyzed rock layers – before and after kilning

Siltstones generally did not change their appearance, but often cracked along the bed surface (Fig. 4). Laminas of clay materials were overburnt and changed colour to brownish-red.

Sandstones completely preserved their shape (Fig. 5), while some minerals changed their colour to red or brown.



Fig. 3. Claystone after kilning



Fig. 4. Mudstone after kilning



Fig. 5. Sandstone after kilning

The lack of reaction for the high temperature for siltstones and sandstones is caused by the small amount of matrix, below 30%.

Due to the above observations, it is worth drawing attention to Evans' studies, who claimed that rock behaviour in high temperature may be affected by the nature of pore liquids that may then cause rock dilution and strong increase in their porosity (Evans, 2011). Similarly high internal tensions in rocks caused by water pressure in pores may contribute to their fracturing while kilning, and increase in thermal stresses. In this context, one must consider siltstone rocks, the minerals of which easily bind to water.

Studies of structural physical properties, made on 26 samples, show that after kilning all analysed rocks increase their bulk density (Fig. 6) and decrease their specific density (Fig. 7). The greatest changes are recorded for siltstones which may increase their bulk density ρ_o by over 20% (series 8.7), with the average value amounting to 9.76%. Among the rocks in this group, there are also the greatest changes to the structural parameters. Siltstones change their bulk density on average by 8.19%, while sandstones – by 5.73%. In one case in series 4.5, sandstones practically did not change ρ_o .

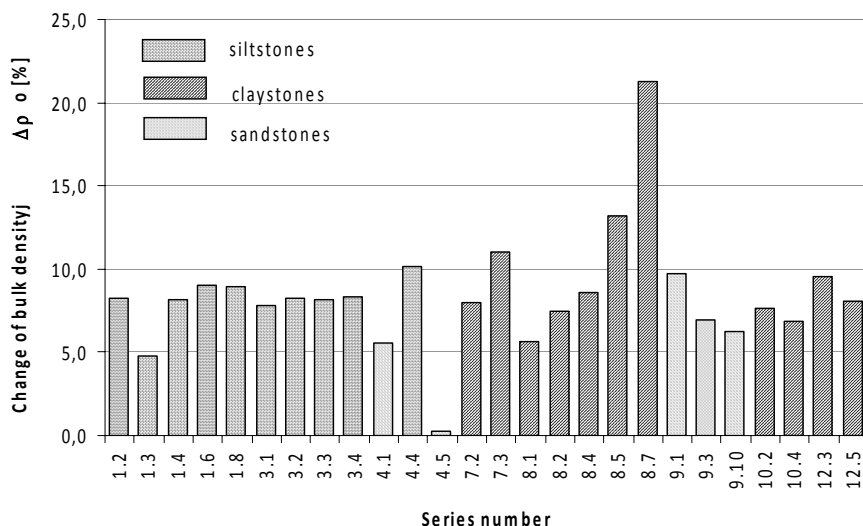


Fig. 6. Change to bulk density due to heating to the temperature of 1000°C

In the case of specific density ρ_s , also rock response to high temperature was in a rather broad range (Fig. 7), although percentage changes were approx. 3 times smaller than in the case of bulk density. The greatest loss to density is shown by claystones and siltstones, where the ρ_s change ranged from 0.88% to 5.93%, whereas sandstones reduce their density on average by approx. 1.5%. Average changes to specific density of claystones amount to 3.74%, while siltstones – 2.79%. In the case of sandstone series no. 9.1, there was an increase in density ρ_s by 0.68% (Fig. 7).

The above analysis confirms macroscopic observation of rock behaviour after their removal from the kiln at the temperature of 1000°C, where sandstones did not change their appearance, whereas claystones (shales), depending on their mineral composition, partly burnt and cracked.

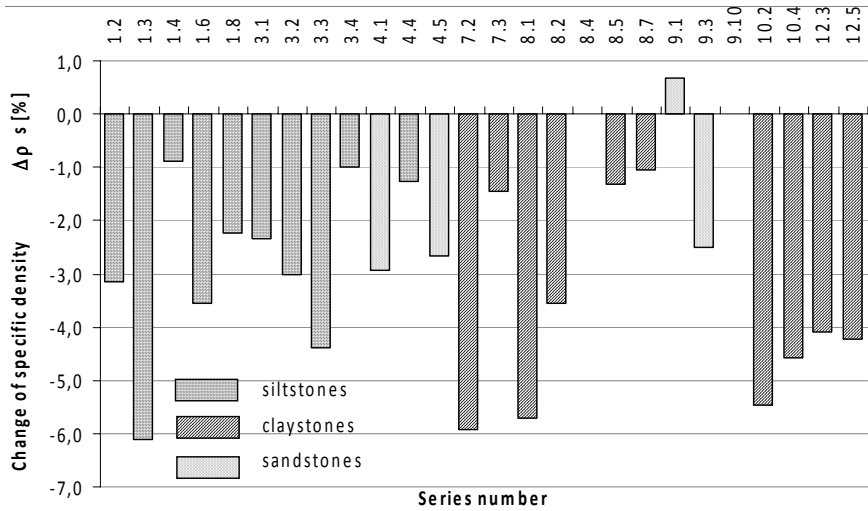


Fig. 7. Change to specific density due to heating to the temperature of 1000°C

Although it seems logical that, together with rock burning, their porosity should increase and at the same time bulk density should change, the tests do not indicate strict dependence between the two parameters (Fig. 8 and 9). In holistic analysis, namely for all samples, the correlation is satisfactory (72.2% – Fig. 7), whereas in the independent rock analysis in the natural states (rhombs) and heated (squares – Fig. 9) – it is not. Determination coefficient R^2 equal to 0.60 for samples in the natural state is acceptable, while equal to 0.15 for heated samples, is clearly low.

The above comparison is even worse in the analysis of changes to porosity and specific density – Fig. 10 and 11. In this case, considering all 26 analysed samples, correlation of the specific density value and porosity forms logarithmic function with determination factor of approx. 23%

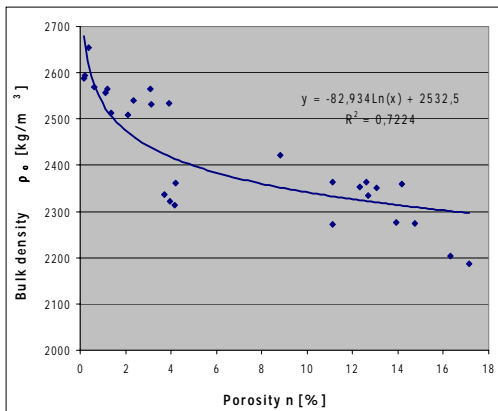


Fig. 8. Dependence of bulk density and porosity

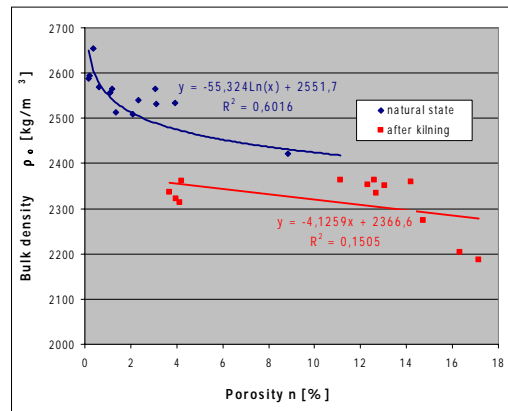


Fig. 9. Dependence of bulk density and porosity considering samples in natural state and heated

(Fig. 10), thus very low. Independent parting of the samples analysed in the natural state and subjected to high temperature shows a completely different lack of dependencies between specific density of the rocks and their porosity (Fig. 11). It can be, however, stated that rock burning in a certain way orders their structure, as correlation, although marginal begins to appear then.

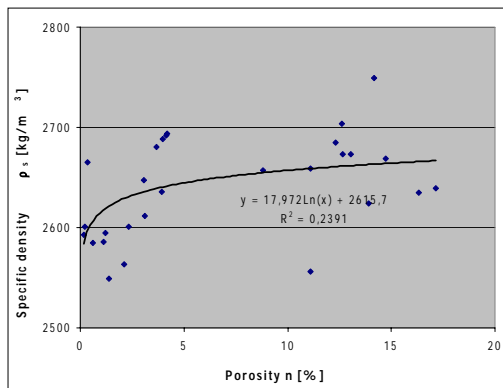


Fig. 10. Dependence of specific density and porosity

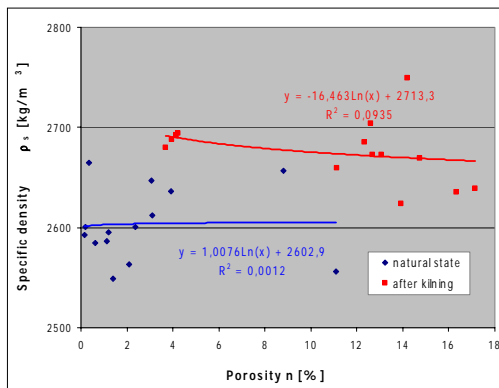


Fig. 11. Dependence of specific density and porosity considering samples in natural state and heated

During the analyses performed, no relations were found between the type of the rock and both structural parameters.

In this case, it must be noticed that natural rock moisture practically did not matter when setting the parameters analysed. All the samples in the natural state were analysed in air-dry state, so their moisture amounted to approx. 0.1-0.3%.

5. Changes to thermal parameters of the rocks

The analysis of limit values of the thermal conductivity of carboniferous rocks at the temperatures of 20°C and 1000°C shows that the values of factor λ after rock kilning have the reversely proportionate tendency to the original value. For the thermal conductivity factor equal to approx. 1 W/m·K at room temperature, after rock heating to 1000°C, its values rapidly increase even to 14 W/m·K (Fig. 12). Together with the greater initial thermal conductivity, rock kilning at high temperature begins to bring the effect reverse to its thermal conductivity. With the initial value λ equal to 3 W/m·K or more, after kilning, the factor usually does not exceed the value of 2 W/m·K. The tendency of decrease in thermal conductivity for sedimentary rocks is in line with German observations of shales and sandstones, where it was determined that factor λ for room temperature amounts to approx. 3.0-3.3 W/m·K, while after heating to the temperature of 800°C its value decreases to approx. 1.4 W/m·K (Clauser & Huenges, 1995).

What is also noticeable is the clear logarithmic nature of the changes of rock capacity to conduct heat before and after kilning them at high temperatures. Coefficient of determination for the samples analysed equals to 0.70 (Fig. 12), which due to instability of thermal processes in the

rocks and their strict dependence on mineralogical composition must be considered unusually high. The authors are aware of the fact that according to the presented trend, the value of λ factor cannot be negative, yet for the case analysed this is related to too few number of the samples analysed. Decisively, however, logarithmic function is the most favourable for the description of changes to the thermal conductivity factor together with rock kilning, yet it requires better calibration.

When analysing the change to specific heat of carboniferous rocks due to heating, one may also notice very high increase in the c_p . Its value for the rocks studied at the temperature of 20°C amounts to approx. 0.5-1.5 kJ/kg·K, while after kilning even –13 kJ/kg·K (Fig. 13). Although increase in heat capacity of the rocks is most noticeable at low c_p values in the natural state, in this case it will be hard to look for correlation between the heat accumulation capacity of the rock analysed before and after subjecting it to high temperature.

The obtained results of thermal parameters tests for carboniferous rocks deposited within the area of the designed geo-reactor in 501 seam in KWK “Wieczorek” for particular rocks – claystones, siltstones and sandstones, were listed in table 3. In this table, they were compared with the results of tests for the rocks of Upper Silesian Coal Basin, performed in the 1960s, 1970s and 1980s by Chmura (Chmura 1970, Chmura & Chudek 1992). When analysing the results obtained, it can be stated that the range of thermal conductivity factor values and specific heat capacity obtained by the authors is much broader than according to the tests made 40 years earlier. In turn, rock capacity to conduct temperature (κ factor) is almost twice higher. State-of-the-art measurement apparatus and other methodology thus allows for effective verification of previous experiments in the area of thermal properties of the rocks. Generally, however, it must be stated that the obtained values are similar to the previous ones, and the sedimentation nature of the rocks contributes to high variability of all physical properties of such rocks.

TABLE 3

Thermal properties of carboniferous rocks in the area of geo-reactor and their comparison to thermal properties of the Upper Silesian Coal Basin rocks

Type of rock	Thermal conductivity λ [W/m·K]		Specific heat c_p [kJ/kg·K]		Thermal diffusivity κ [mm ² /s]	
	Malkowski/ Niedbalski	Chmura/ Chudek	Malkowski/ Niedbalski	Chmura/ Chudek	Malkowski/ Niedbalski	Chmura/ Chudek
Claystone	0.86-4.28	1.28-2.99	0.48-1.42	0.92-1.21	0.73-1.51	0.51-1.13
Siltstone	2.85-4.85	1.41-3.43	0.88-1.38	0.87-1.23	1.12-1.95	0.60-1.34
Sandstone	3.71-5.63	1.94-4.42	1.06-1.36	0.82-1.12	1.79-1.91	1.08-1.49

For all analysed samples of claystone, siltstone and sandstone, a common analysis was also carried out of dependencies of thermal parameters on rock density (Fig. 14-19). Thermal properties were made dependent on bulk density and specific density, and rock state was considered before and after kilning.

The analysis made shows that one cannot show any correlation between thermal properties of the rocks and their bulk density (Fig. 14-16). With the same density ρ_o the thermal conductivity factor for rocks after kilning may adopt values in the broad range of from 1 W/m·K to 15 W/m·K (Fig. 14), as well as many values similar to factor λ for the same bulk density before kilning. It is similar in the case of heat capacity of the rocks (Fig. 15) and its thermal diffusivity (Fig. 16), which may also adopt several different values for the same bulk density.

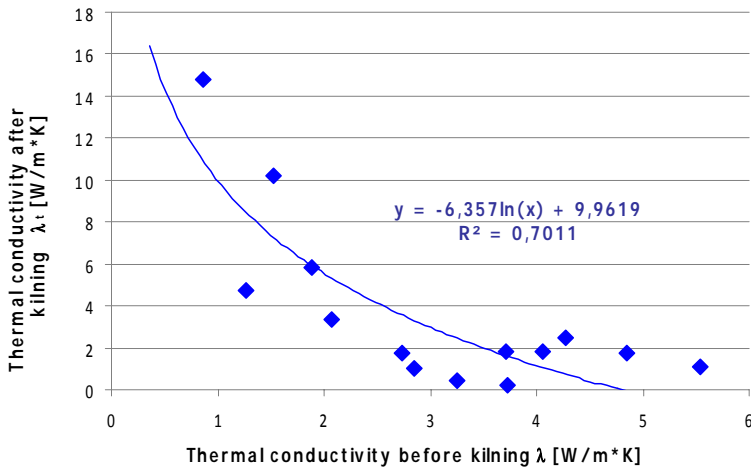


Fig. 12. Dependence between thermal conductivity factor λ before and after kilning λ_t of the same rock

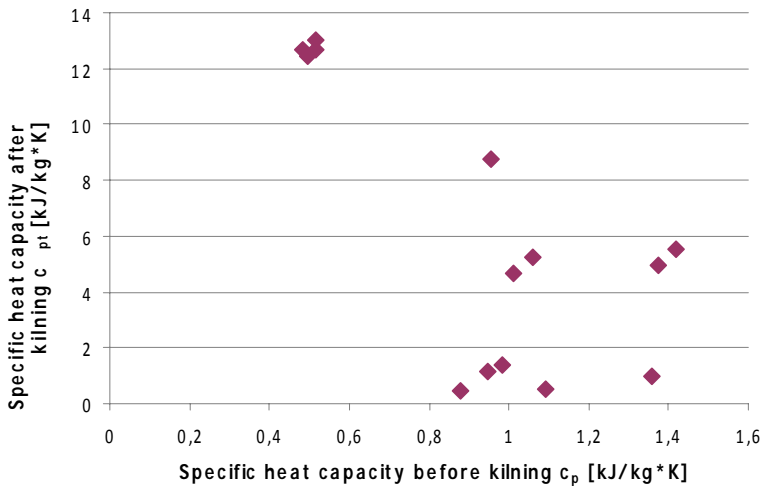


Fig. 13. Dependence between specific heat capacity c_p before and after kilning c_{pt} for the same rock

It is much better to correlate the thermal parameters analysed with specific density of the rocks, but the best adjusted function is the logarithmic dependence. The analyses showed that one can talk about increase in thermal conductivity and thermal capacity together with increased density ρ_s (Fig. 17 and 18). The capacity is, however, very well visible principally for rocks in the natural state (points marked with rhomb). For both thermal parameters, their relation with specific density was determined at the level of 0.58 and 0.61. For rocks furnaced (burnt), the effect of increased capacity to accumulate and transport heat together with increased density vanishes, as the correlation coefficient R^2 decreases to approx. 0.1. Therefore, structural changes occurring

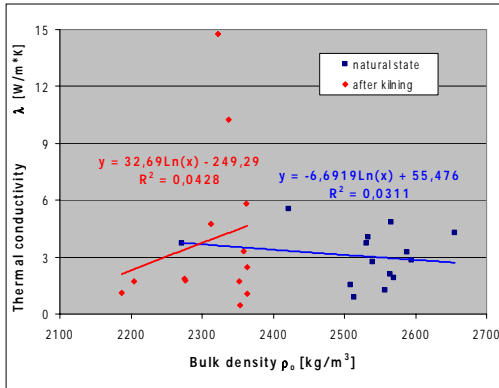


Fig. 14. Dependency between thermal conductivity and bulk density of samples in the natural and after kilning

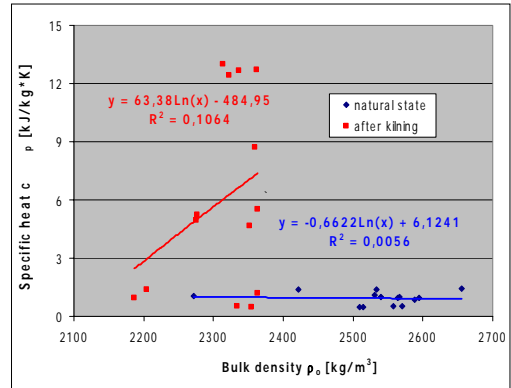


Fig. 15. Dependency between specific heat capacity and their bulk density in the natural and after kilning

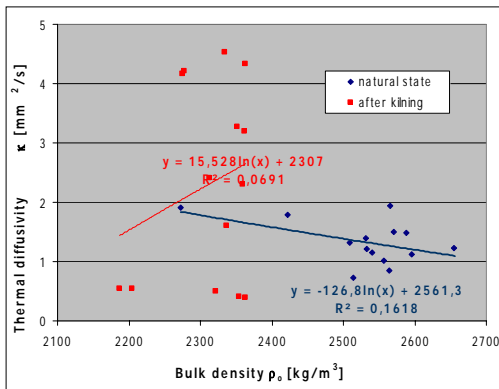


Fig. 16. Dependency between diffusivity factor and bulk density of samples in the natural state and after kilning

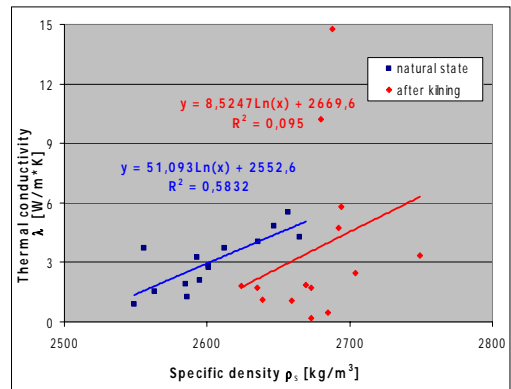


Fig. 17. Dependency between thermal conductivity factor and specific density of samples in the natural state and after kilning

inside the rocks at very high temperatures distort heat flow. A very important factor changing this flow is their cracking and several change of their permeability (Zhi-jun et al., 2009). What is also significant is the lack of high homogeneity and isotropy of sedimentation rocks, as described in the study by Khandelwal (2011).

The analysis performed also showed that the heat diffusivity factor does not depend on specific density (Fig. 19). The pairs of points obtained are hard to describe with any function.

Therefore, it seems that making the thermal conductivity factor in sedimentation rocks dependent e.g. on density and porosity, as done by Khandelwal (2011), is not appropriate and in expert considerations this group of rocks should be neglected.

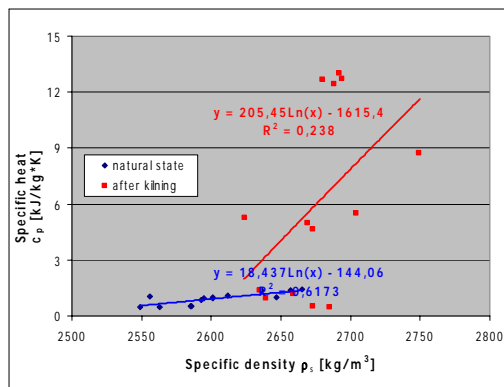


Fig. 18. Dependency between specific capacity of samples and their specific density in the natural state and after kilning

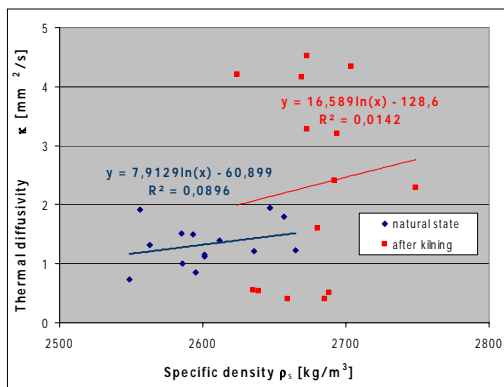


Fig. 19. Dependency between diffusivity factor and specific density of samples in the natural state and after kilning

Because Jougnot and Revil in their study (2010) suggested dependence between thermal conductivity of claystones and their quartz share, such an analysis was also performed for seven cases. The thermal conductivity factor was referred to quartz content before rock kilning (c_{Qz}) and to quartz content after rock kilning (c_{Qz1}). The analysis performed shows that for samples in natural state, increase in quartz content does not result in increased thermal conductivity of the rocks, as suggested by the authors of the article. On the basis of the results obtained, it can be noticed that λ factor is practically constant, while according to correlation analysis it even slightly decreases (Fig. 20), but coefficient of determination is close to zero. What is interesting, in turn, is the fact that after rock heating to the temperature of 1000°C, thermal conductivity of the rocks λ_t decreases together with quartz content, with the rather high correlation as for this type of physical parameters, amounting to 0.54 (Fig. 21). It can be, therefore, stated that the change of specific density of sedimentary rocks due to heating is also related to the change of quartz content, which can decrease or increase, yet it results in decreased thermal conductivity of such a rock mass. In both cases the most suitable function to describe the relation considered is linear one.

Similar observations were made in 2007 by Pinińska, who studies various-grained sandstones. For fine-grained sandstones, she also obtained slight increase in thermal conductivity together with increased quartz content; nevertheless, according to Pinińska, the values of λ factor did not exceed 2.4 W/m·K.

The mineral form of quartz and its phase transition was not investigated.

6. Conclusion

The studies on thermal properties of rocks are rather rare. They are most frequent in the areas of nuclear power plant constructions. Underground coal gasification is another reason for which thermal physical properties of rocks must be analysed in the surrounding of the designed georeactor. The performed studies on structural and thermal properties of carboniferous rocks in the Upper Silesia region, where UCG is planned, show that these change to a very broad extent.

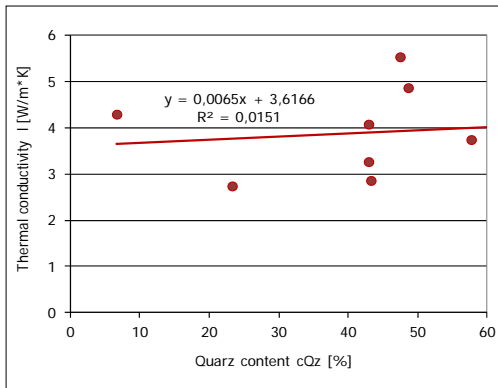


Fig. 20. Dependence of thermal conductivity factor on quartz content in the rocks before kilning

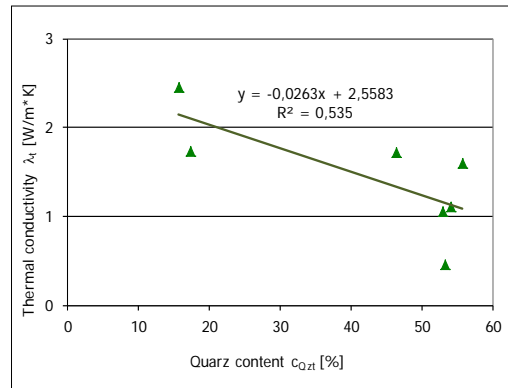


Fig. 21. Dependence of thermal conductivity factor on quartz content in the rocks after kilning

After kilning, the analysed claystones, siltstones and sandstones increase their bulk density and decrease their specific density. The greatest changes are recorded for claystones, which can increase their bulk density even by over 20%. Average changes to density for claystones amount to 9.76%, for siltstones – 8.19, and for sandstones – 5.73%. In the case of specific density ρ_s , it decreases due to high temperature, while in the case of claystones and siltstones even up to 6%. Claystones collapse sometimes entirely after kilning. The mineralogical research allows to claim that high amount of matrix (over 50%) and small amount of quartz is conducive to such a behavior.

As a result of rock kilning, there is clear increase to their total porosity up to approx. 4% in the case of sandstones, and up to 11-18% in the case of claystones and siltstones. The study performed, however, does not point to a dependence between the change to porosity and the change of rock density.

The analysis of thermal conductivity factor at the temperatures of 20°C and 1000°C shows that auto-correlation occurs, with the logarithmic function. For low values of thermal conductivity factor equal to approx. 1 W/m·K at the temperature of 20°C, after rock kilning to 1000°C its values increase to 14 W/m·K, whereas with initial value equal to approx. 3.0-3.5 W/m·K, after heating λ amounts to approx. 1-2 W/m·K. It was also stated that due to rock heating, very high increase to their specific heat capacity c_p occurs. Its value for rocks analysed at the temperature of 20°C amounts to approx. 0.5-1.5 kJ/kg·K, whereas after kilning – even 13 kJ/kg·K. In the case of this parameter, however, auto-correlation does not occur.

The analysis performed shows that one cannot show dependence between thermal properties of rocks and their bulk density, while to some extent one may correlate thermal parameters analysed with specific density of rocks. The dependence is, however, very well visible principally for rocks in the natural state, where coefficient of determination $R^2 = 0.6$. For rocks subjected to the temperature of 1000°C, the effect of increased capacity to accumulate and transport heat together with increased density vanishes, as the correlation factor decreases to approx. 0.1. Usually the best correlation function is logarithmic one.

Also, an analysis of the impact of quartz content on thermal conductivity was performed, as suggested by Jougot and Revil (2010). It was, however, determined that for samples in the natural state, increase quartz content does not cause increase to thermal conductivity, which

confirms observations by Pinińska (2007) performed on sandstones. It was, however, stated that after rock kilning to the temperature of 1000°C their thermal conductivity decreases together with quartz content.

To conclude, it can be stated that subjection of the rocks to very high temperatures strongly distorts mutual relations between their physical properties. This also refers to thermal properties of the rocks that are also strictly dependent on the temperature in which they are set. The change of rock structure does not, however, directly translate to its conductivity capacity and heat accumulation.

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