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Deformation properties of sedimentary rocks in the process of underground coal gasification

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ABSTRACT

The article presents results of research into changes in deformation properties of rocks, under influence of temperature, during the process of underground coal gasification. Samples of carboniferous sedimentary rocks (claystones and sandstones), collected in different areas of Upper Silesian Coal Basin (GZW), were heated at the temperature of between 100 and 1000–1200 °C, and then subjected to uniaxial compression tests to obtain a full stress-strain curves of the samples and determine values of residual strain and Poisson's ratio. To compare the obtained values of deformation parameters of rocks, tested in dry-air state and after heating in a given range of temperature, normalised values of residual strain and Poisson's ratio were determined. Based on them, coefficient of influence of temperature on tested deformation parameters was determined. The obtained values of the coefficient can be applied in mining practice to forecast deformability of gangue during underground coal gasification, when in the direct surrounding of a georeactor there are claystones or sandstones. The obtained results were analysed based on classification of uniaxial compression strength of GZW gangue, which formed the basis for dividing claystones and sandstones into very low, low, medium and high uniaxial compression strength rocks. Based on the conducted tests it was concluded that the influence of uniaxial compression strength on the value of residual strain, unlike the influence of grain size of sandstones, is unambiguous within the range of changes in the parameter. Among claystones changes in the value of Poisson's ratio depending on their initial strength were observed. Sandstones of different grain size either increased or decreased the value of Poisson's ratio in comparison with the value determined at room temperature in dry-air conditions.

1. Introduction

Underground gasification is one of the promising methods of exploiting hard coal deposits especially where using traditional mining methods is impossible or uneconomic. Benefits of implementing the technology seem to be promising, however, there are still difficult safety issues to solve, before it can be commonly used. One of the issues is influence of high temperature of 1000–1200 °C, on the rocks in the

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immediate roof of a coal seam. Due to thermal transformation of the surrounding rocks and changes in their geomechanical properties, a mine working may lose its stability. It, in turn, leads to changes in stress and strain in the rock mass, which may result in displacing the surface, contaminating underground waters and even threatening the whole process (Białecka, 2008; Burton, Friedmann, & Upadhye, 2007; Younger, 2011). As the interest in underground gasification technology is growing and there have already been attempts to implement it, as well as other technologies where temperature affects the rock mass, researchers more and more often analyse changes in geomechanical properties of rocks caused by high temperature (Chen, Ni, Shao, & Azzam, 2012; Keshavarz, Pellet, & Loret, 2010; Korzeniowski & Skrzypkowski, 2012; Luo & Wang, 2011; Małkowski, Kamiński, & Skrzypkowski, 2012; Mao, Zhang, Li, & Liu, 2009; Pinińska, 2007; Zhang, Mao, Liu, Guo, & Ma, 2013; Zhang, Mao, & Lu, 2009). Among the tested parameters, literature often mentions influence of temperature on the value of uniaxial compression strength, Young's modulus, stress-strain curve, critical strain and Poisson's ratio. Influence of temperature on the last of the parameters is not so often tested due to difficulties in conducting the test to determine its value and then in interpreting the obtained results. Nevertheless, due to the geomechanical aspect of the process, determining changes in deformation parameters (critical strain and Poisson's ratio) under influence of temperature, is very important. Research into changes in parameters obtained from the post-critical part of stress-strain curve, including values of residual strain, is also very important. There has been no research conducted into the issue so far. Due to insufficient knowledge of changes in deformation parameters under influence of high temperature, the article focuses on changes in the value of residual axial strain and transverse strain expressed with Poisson's ratio.

Among the tested parameters which determine changes in deformation properties of rocks under influence of temperature, the most often referred to ones are changes in the value of critical strain. The changes are determined with pre-critical part of stress-strain curve, obtained during uniaxial compression tests.

Zhang et al. (2013) determined changes in the value of critical strain for samples of mudstones at the temperature of up to 800 °C. Based on the obtained results, they observed an increase in the value of the tested parameter which followed an increase in the temperature. The biggest changes were observed for the range of temperature of 100–400 °C. In the range of temperature, changes were nearly linear, and the change in the value of critical strain reached 70% in comparison with the initial value, which was determined for samples in dry-air state. At the temperature of 600 °C there was a decrease in the value of critical strain, nevertheless, at the temperature of 800 °C its highest value was recorded. Luo and Wang (2011) also conducted research into changes in critical strain for mudstone samples. In their research they heated the samples to 750 °C. Like Zhang et al. (2013), they observed an increase in the value of critical strain. Up to the temperature of 400 °C it fluctuated a lot (decrease, increase or no significant change). Another research conducted by Zhang et al. (2009) on samples of sandstone, limestone and marble, heated up to the temperature of 800 °C, showed differences in behaviour of changes in the value of deformation following increases in temperature, depending on the type of rocks. Values of critical strain for samples of sandstone were higher in comparison with the ones recorded for limestone and marble. The lowest values were observed for the samples of marble. Nevertheless, in all of the three cases, for the temperature of over 600 °C, an increase in the tested parameter was observed, while at the temperature of 800 °C all the types of rocks reached the maximum value of critical strain. Chen et al. (2012), researching changes in critical strain for samples of granite, heated to the temperature of 1000 °C, did not observe any significant changes in its value up to the temperature of 400 °C. At higher temperatures, the value of deformation increased steadily, reaching the highest value after heating the samples at maximum temperature.

The hitherto research into changes in the value of critical strain under influence of temperature shows that, in general, there is an increase in the value following an increase in temperature, although reaching the maximum value, obtained after heating a sample to the highest temperature does not have to be smooth (Fig. 1). Zhang et al. (2013) attribute the phenomenon to mineral changes such as dehydration, recrystallisation or phase transitions, occurring under influence of high temperature, which lead to fluctuations in the value of critical strain. In turn, softening the structure of rocks at the temperature of over 500–600 °C leads to the rocks becoming less brittle and more plastic, which results in an increase in its deformability (Luo & Wang, 2011; Mao et al., 2009; Ranjith, Viete, Chen, Samintha, & Perera, 2012).

Research works into changes in the value of transverse strain, expressed with the value of Poisson's ratio, under influence of temperature are rare (Brotóns, Tomás, Ivorra, & Alarcón, 2013; Korzeniowski & Skrzypkowski, 2012; Wu, Wang, Swift, & Chen, 2013), in comparison with research into changes in critical strain. Due to insufficient data and major differences in the obtained results, drawing constructive conclusions, concerning influence of temperature on the value of Poisson's ratio, poses a significant problem and requires further studies of the issue.

2. Methodology

Samples of sedimentary rocks (rock core, 30 mm in diameter and 60 mm in high) represented claystones and sandstones of different grain size. The rocks included main lithologic types occurring in direct vicinity of coal seams deposited in Upper Silesian Coal Basin. The samples were collected in mine workings and bore holes, in all the currently mined coal-bearing stratigraphic groups of GZW carboniferous. In total, 31 series of rocks: 8 series of claystones, 4 series of coarse-grained sandstones, 10 series of medium-grained sandstones and 9 series of fine-grained sandstones, were collected.

The samples prior to the tests were heated at the temperature between 100 and 1000 °C for 8 h and 1200 °C for 24 h. In each of the series of rocks, samples were selected for tests in dry-air state, at room temperature, without prior heating. Within the series, for each of the temperature ranges (from room temperature to 1000 °C) up to 6 samples were tested.

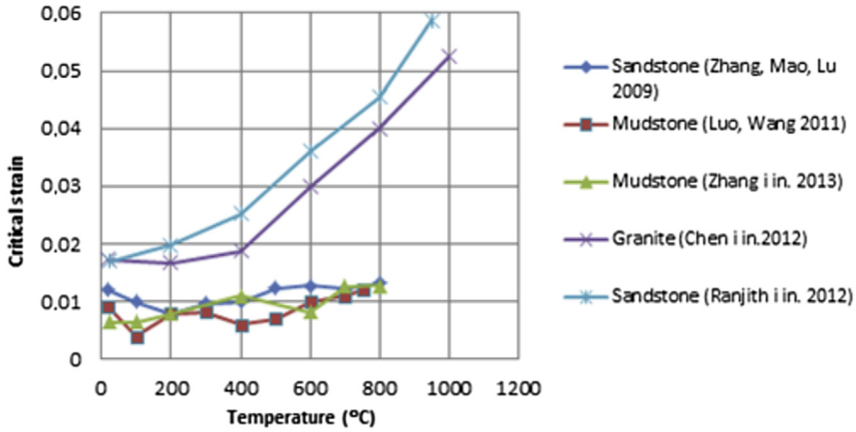


Fig. 1 – Changes in critical strain for different rocks under influence of temperature (own elaboration based on literature review).

Heating at the temperature of up to 1000 °C was conducted in a resistance furnace, at GIG's Laboratory of Information Technologies and Modelling. As it was impossible to heat rocks at the temperature of 1200 °C in a resistance furnace for 24 h, chamber high-temperature furnace Nabertherm HT 16/16 with controller P310 and a gas supply system, was used. To obtain similar results of heating rocks, in both furnaces the heating rate was set at 16 °C/min.

After heating a sample and then cooling it to the room temperature, strength tests in testing machine MTS-810 NEW were conducted, following the current research procedures based on Polish Standards and ISRM guidelines (Ulusey & Hudson, 2007).

Value of residual axial strain ε_r, was determined as a quotient of value of absolute strain on the verge of residual strength sample to sample height before loading (Fig. 2). Transverse strain, expressed with Poisson's ratio ν, was also determined during a uniaxial compression test. The parameter was determined based on measurements of relative transverse strain of a sample and relative axial strain in the range of 30–50% of maximum stress.

3. Results and discussion

To determine influence of temperature on changes in deformation properties under influence of temperature, prior to interpreting the obtained results, standardised values of the tested parameters were determined, related to the values obtained for samples in dry-air state. Results of laboratory tests of deformation parameters for selected rocks, which formed the basis of determining standardised value of residual strain and Poisson's ratio, were also applied to determine the value of temperature influence on the deformation parameters coefficient. Its forecasting values for claystones and sandstones GZW, were classified based on uniaxial compression strength obtained for samples in dry-air state (Bukowska, 2012). Thus gangue of very low, low, medium and high strength was tested (Table 1).

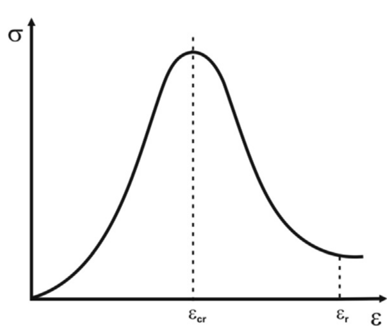


Fig. 2 – Idealised stress-strain curve and geomechanical parameters (ε_{cr} – critical strain; ε_r – residual strain).

3.1. *Coefficient of temperature influence on value of residual axial strain for claystones*

Ranges of residual strain values for very low, low, medium and high uniaxial compression strength claystones, determined in dry-air state at room temperature, are presented in Table 2.

Table 1 – Assessment of uniaxial compression strength of gangue in Upper Silesian Coal Basin (Bukowska, 2012).

Sandstones, mudstones, claystones	
Uniaxial compression strength, MPa	Assessment of uniaxial compression strength
<20.0	Very low
20.0–40.0	Low
40.1–60.0	Medium
>60.0	High

Table 2 – Average values of residual strain for claystones in dry-air state, room temperature.

Rock	Assessment of uniaxial compression strength	Residual strain (‰)
Claystones	High	8.76–12.25
	Medium	11.53–7.99
	Low	10.46–20.03
	Very low	23.11

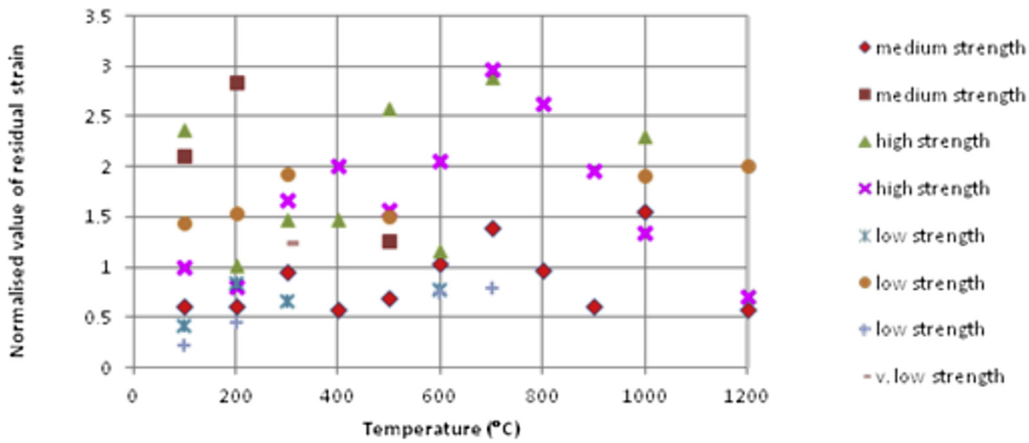


Fig. 3 – Normalised value of residual strain of tested carboniferous claystones of different dry-air strength under influence of temperature of between 100 and 1200 °C.

Points showing standardised value of residual strain for claystones, of different values of dry-air strength, are presented in Fig. 3. Location of the points in the coordinate system of temperature and standardised value of deformation, shows that in certain ranges of temperature deformation increased or decreased in comparison with values of residual axial strain, determined at room temperature.

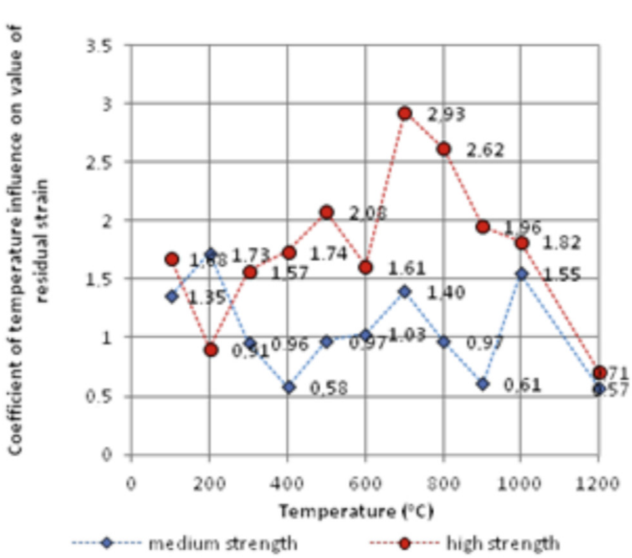
Figs. 4 and 5 present values of coefficient of temperature influence on the value of residual strain for high and medium uniaxial compression strength claystones and low and very low strength claystones. As observations show, for low and very low strength claystones, a different tendency in changes in the value of residual strain is to be expected than for high and medium strength claystones. It particularly concerns values of residual strain for samples heated at high temperature of 1000 and 1200 °C, when the values of increase in residual strain can be very high of between approximately 90 and over 100%.

Examples of stress-strain curves for high and low dry-air compression strength claystones after treatment of selected temperatures are shown in Fig. 6a–b.

3.2. *Coefficient of temperature influence on value of residual axial strain for sandstones*

Average values of residual strain determined based on the laboratory tests of carboniferous sandstones at room temperature are presented in Table 3.

Samples of sandstones showed an increase in values of residual strain when compared with the values determined in dry-air state for the temperature of approximately 700–800 °C, above which the value of residual strain decreased, stabilised or tended to rise up to the temperature of 1200 °C (Fig. 7).



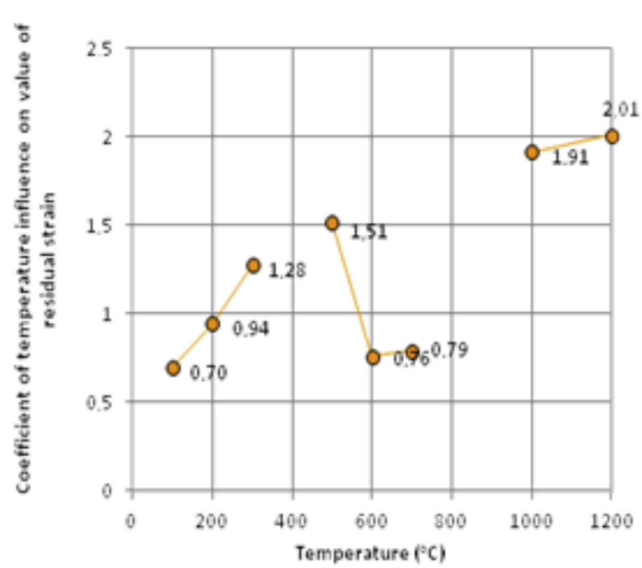
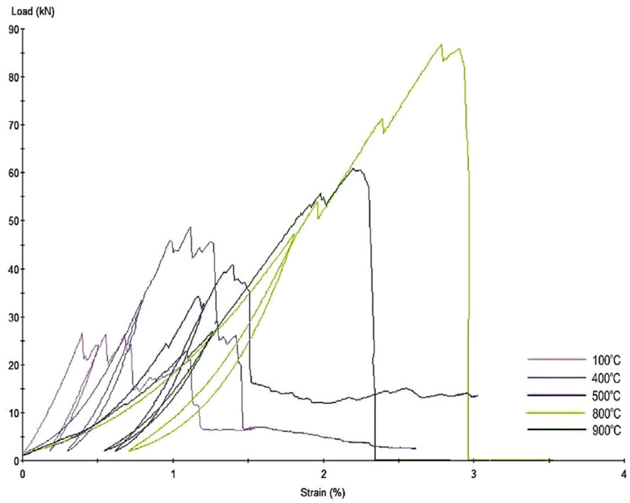
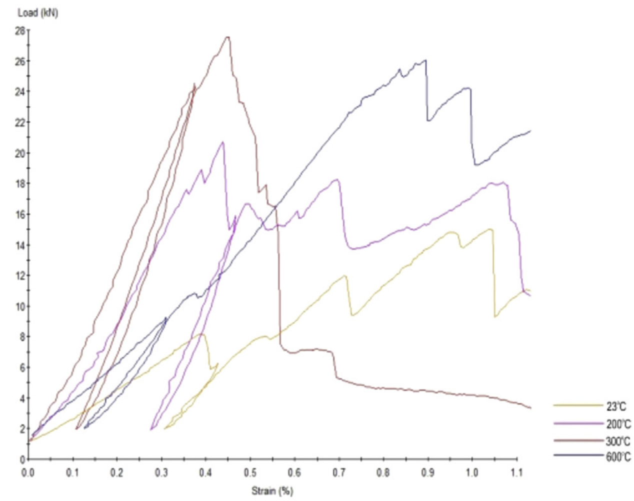


Fig. 4 – Forecast influence of temperature on value of residual strain for high and medium dry-air compression strength claystones.

Fig. 5 – Forecast influence of temperature on value of residual strain for low and very low dry-air compression strength claystones.



a.



b.

Fig. 6 – a) load-deformation characteristics of high dry-air compression strength claystone after treatment selected temperatures. b) load-deformation characteristics of low dry-air compression strength claystone after treatment selected temperatures.

Table 3 – Average value of residual strain of sandstones in dry-air state, room temperature.		
Grain size of sandstone	Assessment of uniaxial compression strength	Residual strain (‰)
Coarse-grained	Very low	8.26–13.14
	Low and medium	15.86–17.58
Medium-grained	Very low and low	8.45–10.11
	Medium	9.38–17.36
	High	8.18–12.52
Fine-grained	Medium	10.64–16.85
	High	8.18–12.82

Values of temperature influence on values of residual strain coefficient for tested sandstones were determined for different grain size classes (Fig. 8a, b, c) and for sandstones of the same strength class, regardless of the grain size (Fig. 9a, b, c).

Examples of stress-strain curves obtained for different types of sandstone after treatment selected temperatures are shown in Fig. 10a–f.

Research into changes in values of residual strain under influence of temperature is a novel issue. No such research has been conducted so far, thus, it is difficult to discuss the obtained results and the research itself requires continuation.

3.3. *Coefficient of temperature influence on value of transverse strain for claystones*

In rock mechanics transverse strain observed when load is exerted on rocks is defined with dimensionless Poisson's

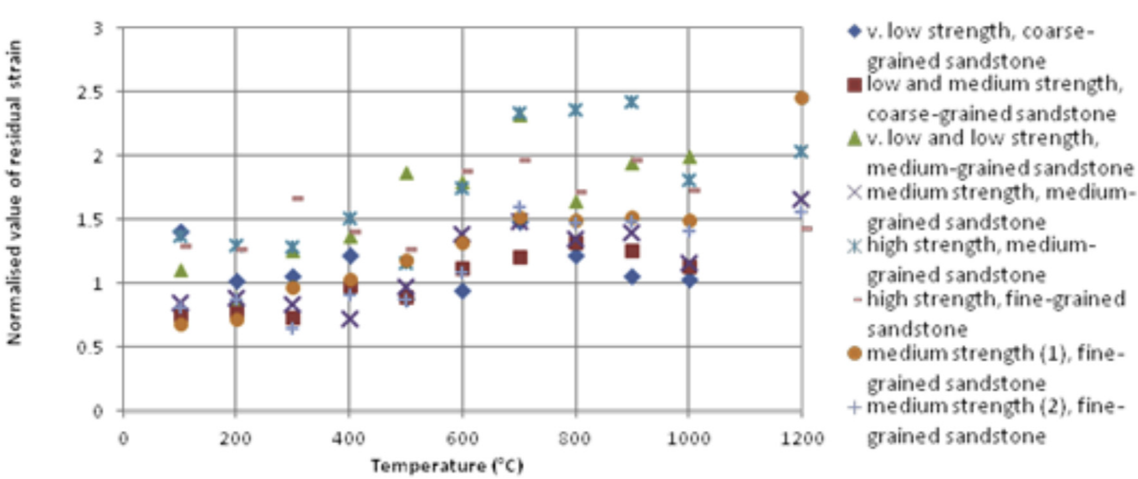


Fig. 7 – Normalised value of residual strain of tested carboniferous sandstones of different dry-air strength under influence of temperature between 100 and 1200 °C.

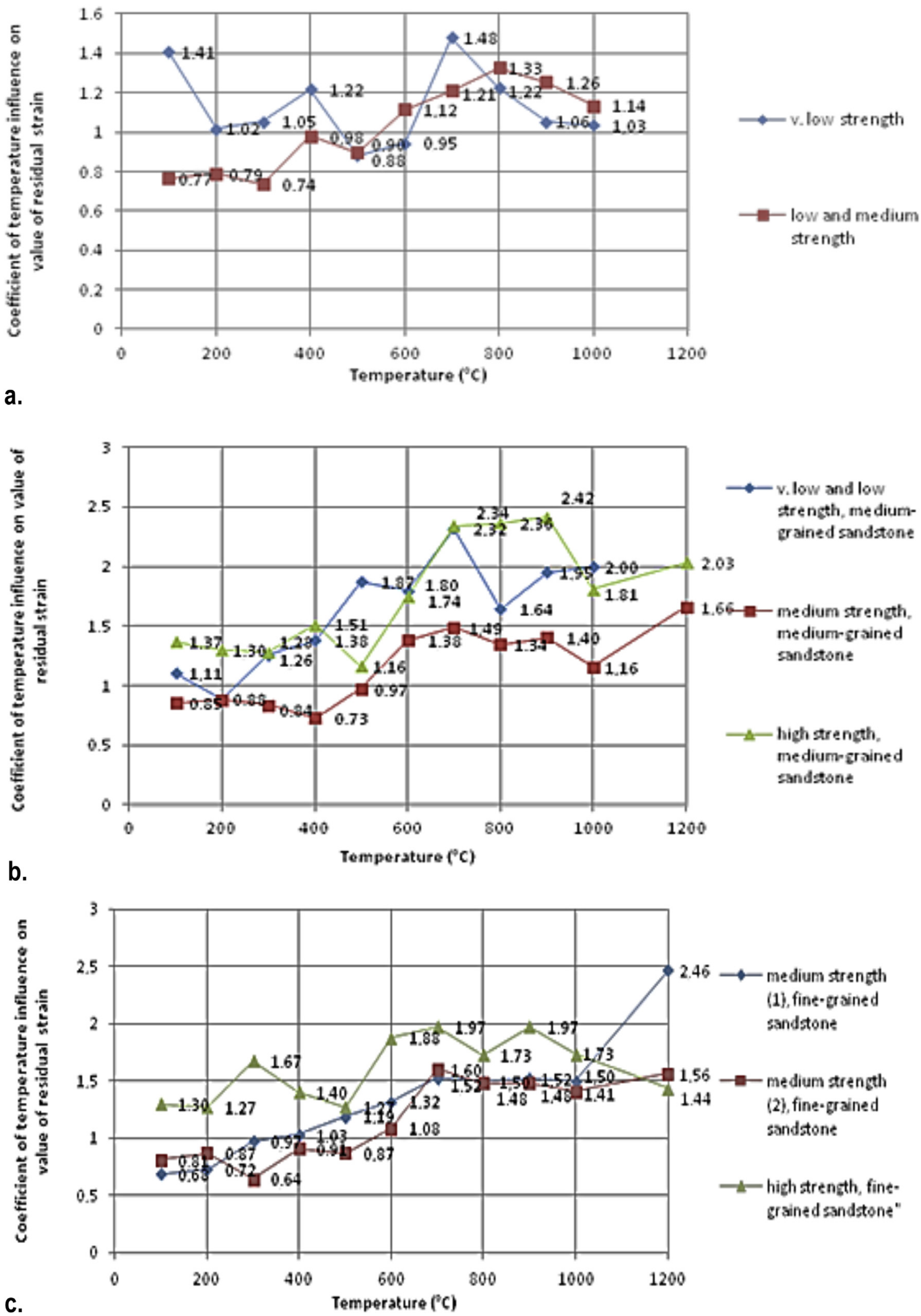


Fig. 8 – a) forecast influence of temperature on value of residual strain for coarse-grained sandstones. b) forecast influence of temperature on value of residual strain for medium-grained sandstones. c) forecast influence of temperature on value of residual strain for fine-grained sandstones.

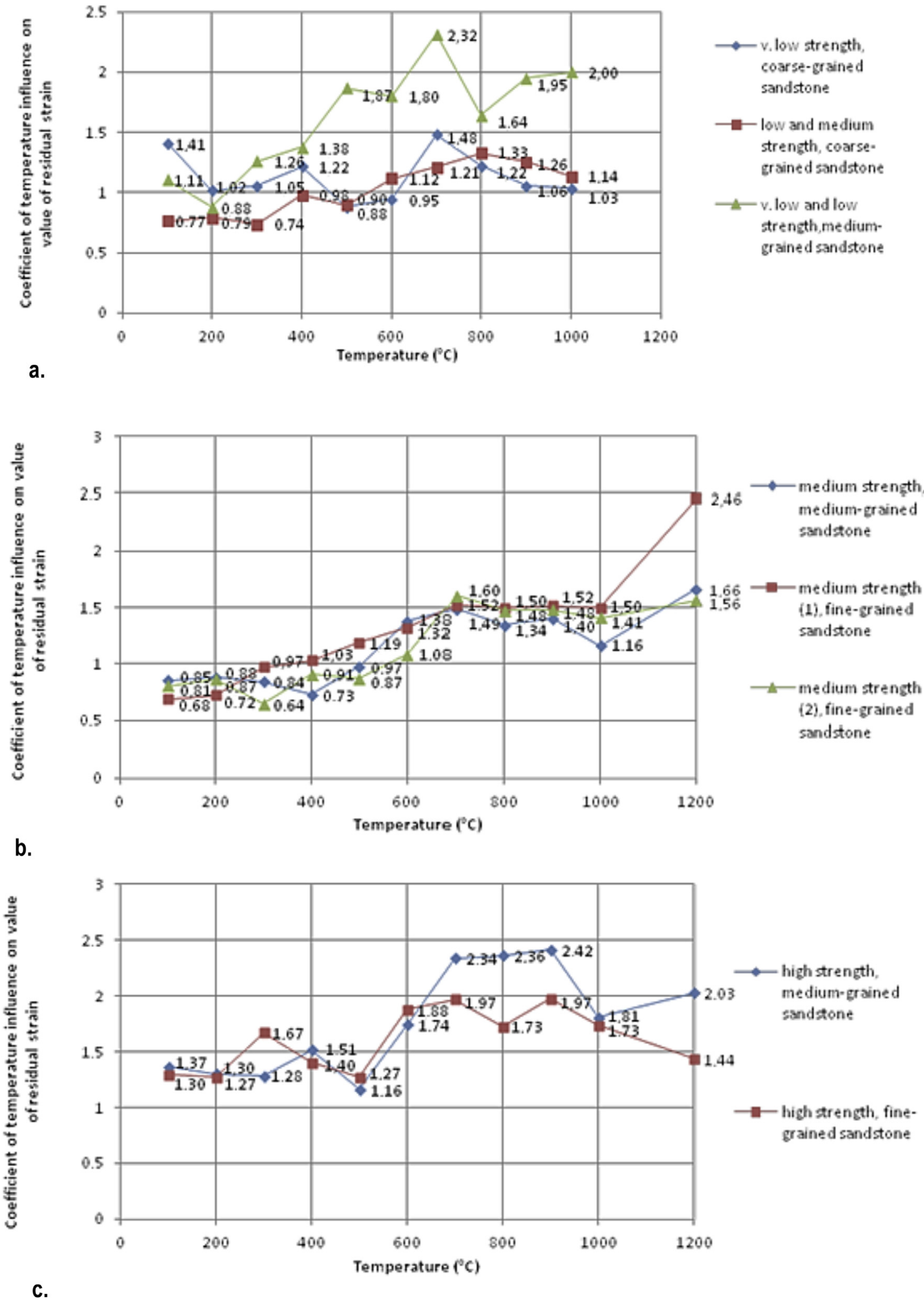


Fig. 9 – a) forecast influence of temperature on value of residual strain for very low, low and medium dry-air strength sandstones. b) forecast influence of temperature on value of residual strain for medium dry-air strength sandstones. c) forecast influence of temperature on value of residual strain for high dry-air strength sandstones.

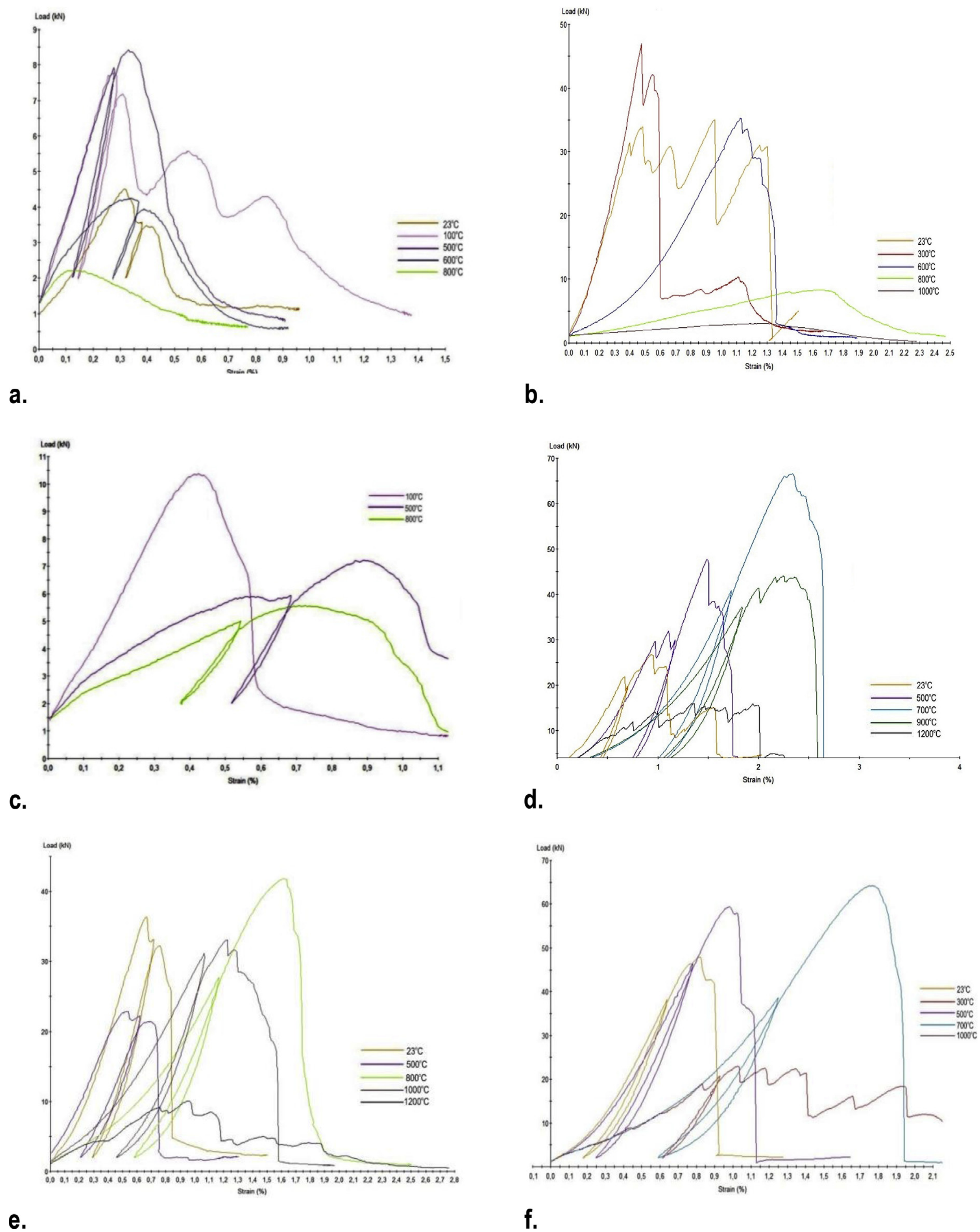


Fig. 10 – a) load-deformation characteristics of coarse-grained sandstone with very low dry-air strength after treatment selected temperatures. b) load-deformation characteristics of coarse-grained sandstone with medium dry-air strength after treatment selected temperatures. c) load-deformation characteristics of medium-grained sandstone with very low dry-air strength after treatment selected temperatures. d) load-deformation characteristics of medium-grained sandstone with medium dry-air strength after treatment selected temperatures. e) load-deformation characteristics of medium-grained sandstone with high dry-air strength after treatment selected temperatures. f) load-deformation characteristics of fine-grained sandstone with high dry-air strength after treatment selected temperatures.

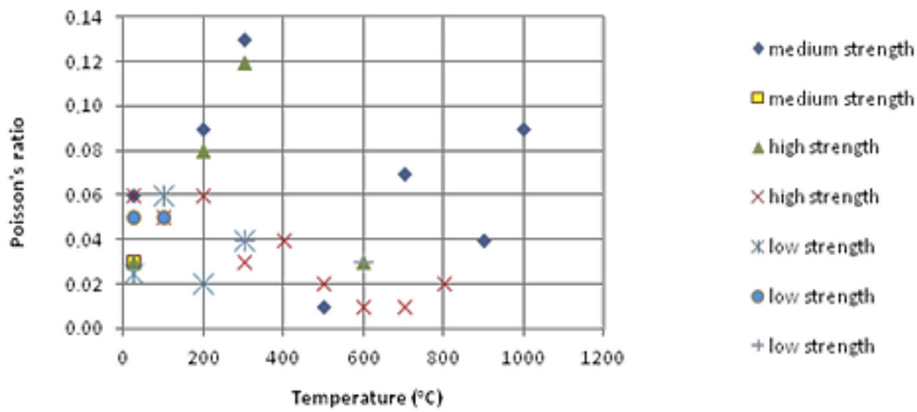


Fig. 11 – Change in value of Poisson's ratio following increase in temperature of heating samples of different dry-air strength carboniferous claystones after heating to temperature of between 100 and 1000 °C.

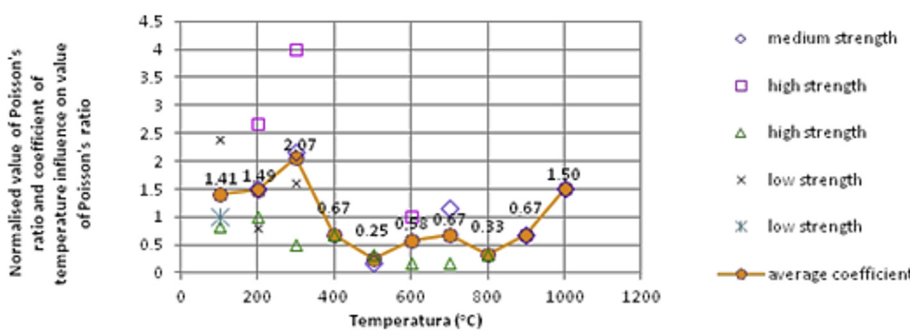


Fig. 12 – Forecast temperature influence on value of Poisson's ratio for tested carboniferous claystones.

Table 4 – Average values Poisson's ratio for sandstones in dry-air state, room temperature.

Grain size of sandstone	Assessment of uniaxial compression strength	Poisson's ratio
Coarse-grained	Very low	0.13
	Low and medium	0.03–0.12
Medium-grained	Very low and low	0.16–0.25
	Medium	0.02–0.04
	High	0.10
Fine-grained	Medium	0.04–0.10
	High	0.09–0.24

ratio, with maximum values of up to 0.50. Given types of GZW carboniferous rocks, including claystones, differed in transverse deformation determined at room temperature in dry-air state, which for the type of rocks was 0.03–0.06. Fig. 11 presents values of Poisson's ratio for tested claystones of different uniaxial compression strength, at the temperature of heating samples of up to 1000 °C. Petrographic structure of claystones and resulting from it properties e.g. values of geomechanical parameters, make testing the rocks very problematic, and testing the discussed parameter particularly problematic. That is why Poisson's ratio is presented and discussed for the whole group of claystone samples.

Based on values of Poisson's ratio, determined as an average value for a given temperature, forecasting values of average coefficient of temperature influence on transverse strain for tested rocks (Fig. 12) were devised. Relatively few results were obtained in tests of claystones, hence, in the future the data base shall be expanded. However, bearing in mind that the average value of coefficient (of 1.50) was determined based on tests of one type of claystone, the conducted tests suggest it is possible that an increase in temperature of heating claystones decreases value of Poisson's ratio. For high strength sandy claystones, coefficient of temperature influence on Poisson's ratio throughout the temperature range reached values below the one determined in dry-air state, at room temperature.

3.4. *Coefficient of temperature influence on value of transverse strain for sandstones*

Values of Poisson's ratio determined in dry-air state at room temperature, which were used in determining standardised value of Poisson's ratio, are presented in Table 4.

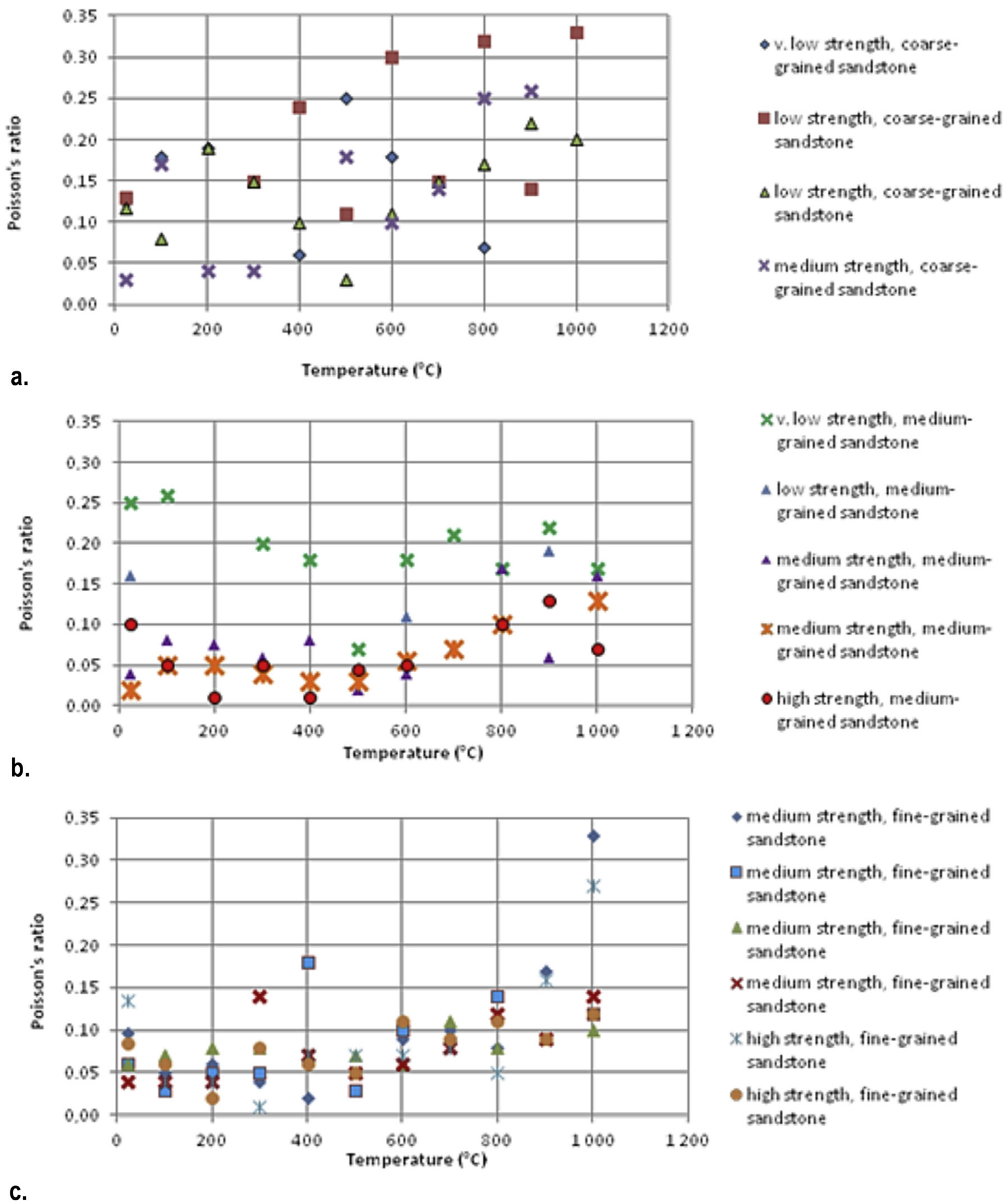


Fig. 13 – a) change in value of Poisson's ratio following temperature of heating for coarse-grained carboniferous sandstone samples of different dry-air uniaxial compression strength. b) change in value of Poisson's ratio following temperature of heating for medium-grained carboniferous sandstone samples of different dry-air uniaxial compression strength. c) change in value of Poisson's ratio following temperature of heating for fine-grained carboniferous sandstone samples of different dry-air uniaxial compression strength.

Values of Poisson's ratio for sandstone samples heated up to the temperature of 1000 °C are presented in Fig. 13a–c, separately for sandstones of given grain size classes. Analysing laboratory data showed an increase in the value of Poisson's ratio for most of the tested series of rocks following an increase in temperature of heating the sandstone samples.

For given series of tested sandstones, values of standardised Poisson's ratio and coefficient of temperature influence on the value of Poisson's ratio were determined (Fig. 14a–c).

Due to relatively few data and widely scattered test results, the obtained results are hard to interpret. The tests showed

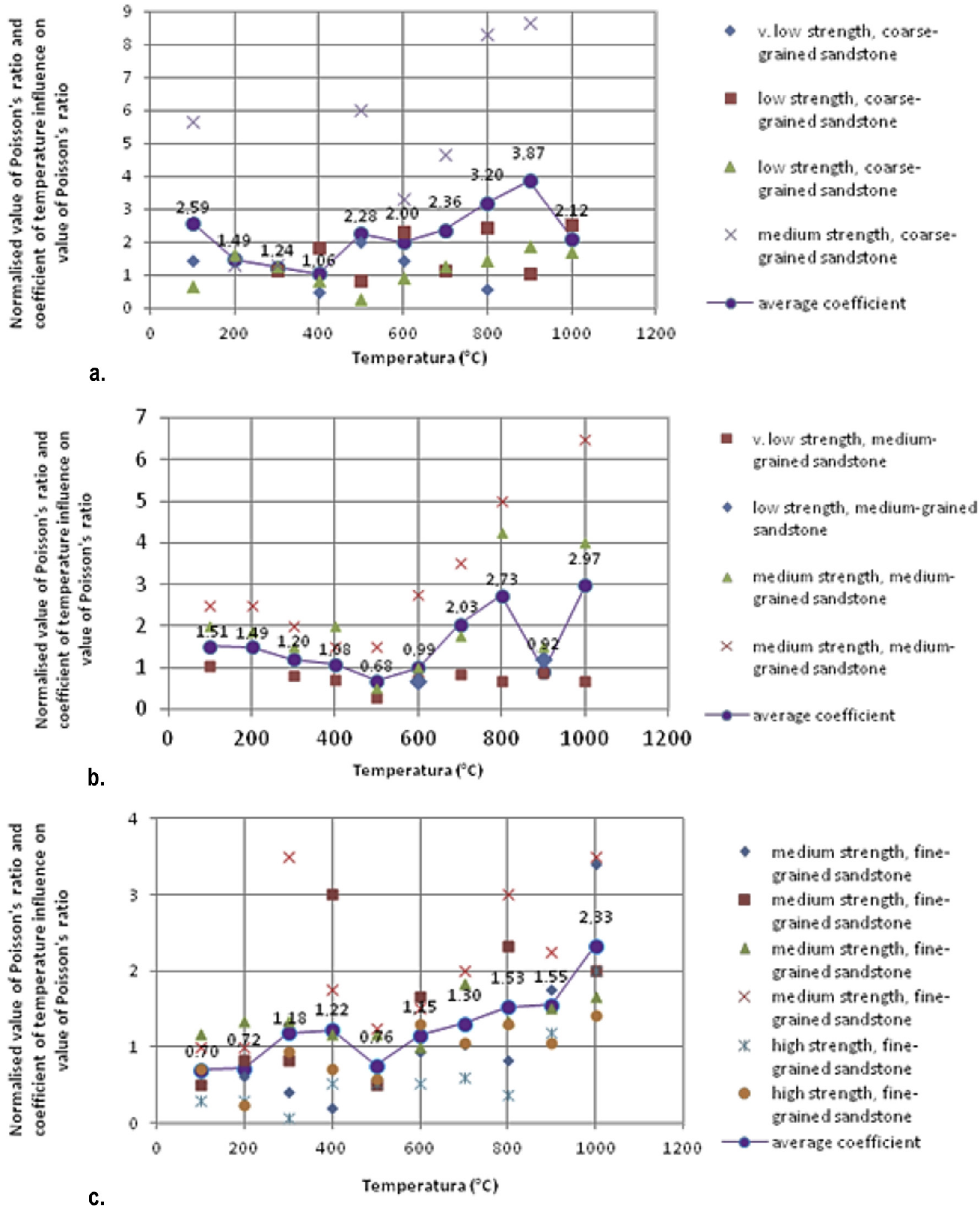


Fig. 14 – a) forecast temperature influence on value of Poisson's ratio for coarse-grained sandstones. b) forecast temperature influence on value of Poisson's ratio for medium-grained sandstones. c) forecast temperature influence on value of Poisson's ratio for fine-grained sandstones.

that grain size of a rock has a bigger influence on changes in the value of Poisson's ratio than the value of dry-air state uniaxial compression strength. In most of the tested samples there was a noticeable increase in the value of transverse strain at high temperature of heating. Korzeniowski and Skrzypkowski (2012) obtained similar results during tests conducted on samples of medium-grained sandstone, where at the temperature of 1100 °C value of transverse strain doubled.

4. Conclusions

Research works into temperature influence on changes in deformation properties of rocks most often concentrate on determining values of critical strain, obtained from the pre-critical part of stress-strain curve. Research into changes in the value of transverse strain, expressed with the value of Poisson's ratio is rare and its results are difficult to interpret. Nevertheless, due to the possibility of implementing the UCG process, research into deformation parameters of rocks after heating and their post-critical deformability is crucial. Nobody has conducted such research so far. Our research covered changes in the value of critical strain and transverse strain of sedimentary carboniferous rocks after they were heated to between 100 and 1000–1200 °C. An innovative approach in analysing the obtained results is based on classification of GZW gangue uniaxial compression strength (Bukowska, 2012), which formed the basis of dividing claystones and sandstones into very low, low, medium and high uniaxial compression strength rocks.

Conclusions of the tests conducted for claystones and carboniferous sandstones, which were heated up to the temperature of 1200 °C, and then compressed in a testing machine, to obtain the values of deformation parameters, are as follows:

- For high and medium strength dry-air state claystones, an increase in residual strain can be expected starting from the lowest temperature of heating the samples up to the value of critical temperature, above which there may be a decrease in its value; reaching the value below the initial one is not possible before reaching the temperature of 1000–1200 °C. Low strength claystones at low temperature of heating decrease residual strain, and at higher temperature the value of initial strain is exceeded and it increases up to the temperature of 1000–1200 °C.
- For high compression strength sandstones an increase in the value of residual strain can be expected throughout the range of temperature of heating, and for medium and low compression strength sandstones no sooner than after reaching a certain critical temperature (200–400 °C).
- Based on conducted tests and analyses, it was concluded that the influence of uniaxial compression strength on the value of residual strain, unlike influence of grain size of sandstones, is unambiguous in range of changes this parameter – an increase or a decrease in the value in comparison with results obtained during tests at room temperature.
- An increase in residual strain, following an increase in the temperature of heating samples of claystones and sandstones, results from, among other factors, a decrease in elasticity of the rocks within the range of temperature during the tests.
- Dry-air state low and medium compression strength claystones, up to the value of threshold temperature, showed an increase in Poisson's ratio above the initial value, and above the temperature there was a decrease below the initial value, unlike high strength claystones, which throughout the range of temperature reached values of the parameter lower than the initial.
- Value of Poisson's ratio for sandstones of different grain size either increased or decreased, in comparison with the value determined in dry-air conditions.
- Due to a small number of measurements, values of transverse strain, the obtained results are not credible and require further research works.

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