THE INFLUENCE OF TEMPERATURE ON THE UNIAXIAL COMPRESSIVE STRENGTH OF ROCKS

Marek Brabec[*,1], Roman Šimáček[1]

[*]marek.brabec.mb@gmail.com
[1]Institute of Geotechnics, Faculty of Civil Engineering, Brno University of Technology, Veveří 331/95, 602 00 Brno, Czech Republic

Abstract
This study focuses on determination of the temperature effect on uniaxial compressive strength of different rock types. For our laboratory tests, we chose local greywacke from the Kobeřice quarry which is situated 10 km south of Prostějov. For comparison, datasets representing other rock types have been gathered from the literature cited. As shown in this study, the rock type structure, composition or the processes that formed the rock can influence how the compressive strength changes across the temperature range. Results of similar analyses can be utilized during the design of underground constructions or for assessment of the fire damage on a rock-based constructions.

Keywords
Rock mechanics, uniaxial compressive strength, greywacke, temperature influence

1 INTRODUCTION

One of the many obstacles that have to be overcome during construction design is elevated temperature. Usually, it is associated with unintentional fires happening in the construction itself or in its vicinity. Thus, the knowledge of the heated rock behaviour can be needed to assess the fire damage. These types of constructions usually include historical buildings with stone as the main building material (e.g. the Notre Dame Cathedral fire in 2019) or some special cases of tunnels with a limited use of concrete lining [1]. In some cases of underground constructions, such as deep geological repositories of nuclear waste or enhanced geothermal systems (EGS), the elevated temperature is a necessary part of the intended use of the designed construction. Rock-based parts of both of the construction types can be exposed to temperatures reaching up to lower hundreds of degrees and therefore have to be designed and protected accordingly [2].

The objective of this small study was to conduct laboratory examinations of the uniaxial compressive strength (UCS) of greywacke and its dependence on temperature. The results were then compared with other studies performed on various rocks. An insight into rock changes during heating was also presented along with a possible explanation for the greywacke strength changes.

2 PRESENT STATE OF RESEARCH

Thermomechanical studies of rock properties have been performed since the 1970s. Emphasis has been placed on uniaxial compressive strength and elasticity modulus studies, with other rock properties studied less frequently. In most studies, the cylindrical rock samples were heated to the target temperature with gradients between 2 and 10 °C/min. After reaching the target temperature, it was held for 1 to 12 hours to ensure uniform heating throughout the body. The studies differ in terms of using different cooling methods, such as a slow air cooling or quick cooling with water simulating firefighting [3].

According to some researches, the process of heating a rock can be divided into three phases [4]. The strength of the rock in the first stage is mostly dependent on the thermal stability of the individual minerals and their expansion. In the second stage, the strength depends on the intergranular contact and the build-up of stress due to the volumetric changes inside the rock mass. The third stage is influenced by the minerals' degeneration and destruction. Based on the rock's behaviour during these stages, the rock types were divided into two groups [5]: crystalline and clastic rocks in the first group and carbonated rocks in the second group. The first group of rocks withstands the first stage of heating without any significant changes, with the second stage usually showing a slight increase in strength. During the third stage, structural defects are formed and the strength decreases until rock

DOI 10.13164/juniorstav.2024.24025

destruction. The carbonate rocks start to slowly degrade at relatively low temperatures owing to their chemical composition.

As for the tested rock types, most of the studies found during our research focused on granites (e.g. [1], [2], [6], [7], [8], [9] or [10]). Several studies focused on testing limestone (e.g. [3], [11], [12] or [13]), sandstone (e.g. [8], [12], [14] or [15]) or marble (e.g. [8], [12] or [13]). The least tested rock types include diabase [1], schist [1] and mudstone [16] with only one study performed. Greywacke has never been tested according to our research.

3 METHODOLOGY

For the purpose of the study, two types of greywacke from the Kobeřice quarry (49°22'02.9"N, 17°06'19.2"E) were used. Blocks made from fine grained greywacke were sampled directly from the quarry. The bodies were machined using a diamond core drill bit with a 46 mm diameter and a circular saw with a diamond cutting disc. A second set of samples was made of four coarser greywacke samples with a diameter of 38 mm from the depository of our institute. All of the samples had a length-to-diameter ratio of 2.0. The fine greywacke bodies were divided into four groups and heated to 200, 300 and 400 °C with one set unheated. The coarser samples were heated to 400, 800 and 1200 °C respectively, with one also left unheated. A simple heating curve was utilised with a temperature gradient of 10 °C/min until the desired temperature was reached. Then it was held for 60 minutes after which the samples were air cooled slowly. Then the dimensions for cross section area calculation were measured using a calliper with multiple measurements for each dimension. The uniaxial compressive tests were carried out using a loading rate of 800 and 1500 N/s based on the body diameter.

Individual datasets were then collected from the literature cited and from our laboratory tests. As for the interpretation of the results, an unheated mean uniaxial compressive strength was determined for each dataset. All of the strength values were then divided by the mean values, split based on the rock type and plotted against the temperature. The data were then fitted using multiple order polynomials for easier interpretation.

4 RESULTS

The coarser greywacke sample set clearly illustrates the drastic structural and visual changes caused by the high temperatures (see Fig. 1). Heating to 800 °C causes only slight changes in the rock structure, with slight sample volume increase. The main rock degeneration happens in temperatures of around 1200 °C when the rock starts to melt, the body centre becomes porous and causes significant volume increase with surface tensile cracks.

Fig. 1 The coarser greywacke samples after heating.

The results of the greywacke laboratory tests are summarized in Tab. 1. An outlying strength value had to be excluded from the fine greywacke heated to 200 °C dataset. The unheated sample strength value for coarser greywacke also had to be excluded because of a hidden defect in the sample. Instead, a strength value from previous research performed on the same sampled set of blocks was used as a substitute [17].

Tab. 1 The greywacke uniaxial compressive strength values in MPa, the substituted value is marked with *.

Set	Unheated (20 °C)	200 °C	300 °C	400 °C	800 °C	1200 °C
Fine	*142.1*	*124.8*	*127.3*	*155.5*		
	150.9	*129.2*	*137.1*	*125.1*		
	152.7	*119.6*	*151.3*	*137.1*		
	155.1	*104.6*	*139.7*	*140.4*		
	132.7	-	*107.2*	*137.6*		
Coarser	*191.0**			*197.5*	*165.3*	*17.0*

The greywacke compressive strength values along with the other rock types from cited literature were converted to ratios of heated to unheated values. Plots of the ratio against the temperature were then presented with polynomial fits signifying the UCS trend (see Fig. 2). No polynomial was used for rock types with only one dataset (n = 1), the values were connected with a line instead.

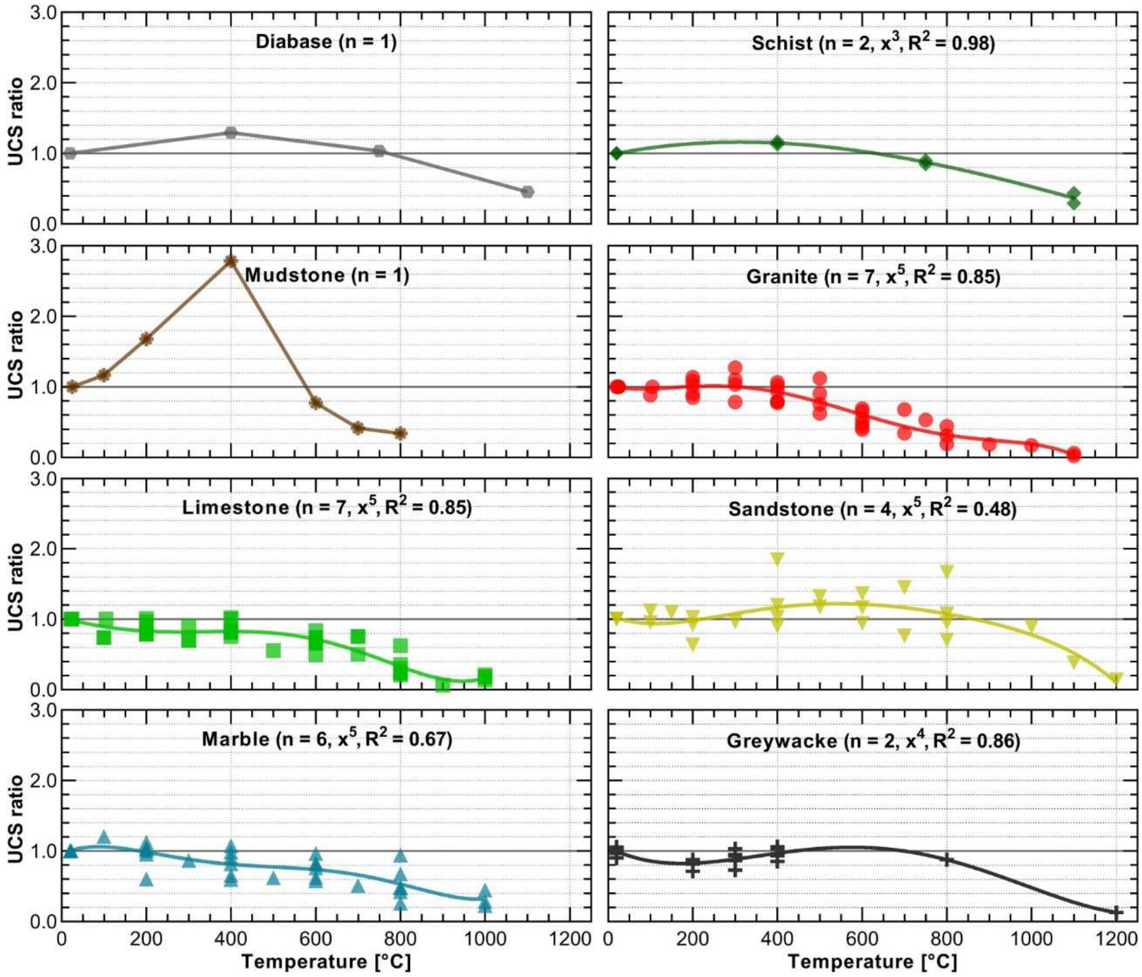

Fig. 2 Graphs of uniaxial compressive strength (UCS) ratio dependence on temperature. Number of individual datasets for each rock type is represented by n. Degree of the used polynomial is marked by x^{degree}. Coefficient of determination is also shown.

5 DISCUSSION

There are significant differences in individual rock types' behaviour when heated. Diabase and schist show an increase in strength at 400 °C followed by a slow degradation. Mudstone follows a similar trend with the increase being more significant to almost three times the unheated strength value. Granite holds relatively well

DOI 10.13164/juniorstav.2024.24025

to temperatures below 400 °C with an almost constant decrease afterwards, caused mostly by an α-β quartz phase transition happening at 573 °C and a formation of microcracks [7]. Limestone and marble start to slowly decompose even in lower temperatures, as stated before. Marble seems to resist decomposition until around 200 °C which could be caused by its metamorphic state. Sandstone holds its strength until 300 °C with a significant increase in strength to 600 °C. Around 800 °C the strength falls back to the unheated value and decreases afterwards. The strengthening of sandstone could be caused by fusion of the individual sand grains as shown in [8].

Greywacke seems to differ from the other presented rock types. The strength shows a slight decrease in the range around 200 to 300 °C. In the range between 400 and 700 °C, the strength again equals the unheated value and afterwards greywacke steadily weakens. Greywacke differs from sandstone with a slight state of metamorphosis. There have been several different geological studies of local greywackes (Vitrinite reflectance [18], Illite crystallinity index [19] and presence of an authigenic monazite [20]) determining the individual formations temperature history. According to them, the Myslejovice formation where we sampled the blocks should have been heated to maximum temperature of 200 to 300 °C in the past. This corresponds to the compressive strength decrease we observed and possibly explains it. Greywacke could have a thermal memory which causes it to be weaker against temperatures it already underwent. The increase in strength after the 400 °C is not as pronounced as in sandstone. However, our dataset does not cover that temperature range in detail. As mentioned before, greywacke heated up to 1200 °C is already significantly decomposed. Development of many pores in the sample core can be observed, resulting in a volume increase and surface cracking.

6 CONCLUSION

The greywacke compressive strength seems to develop differently from the other rock types presented in this paper. In general, greywacke holds relatively well to the temperatures up to almost 800 °C. Unexpectedly, its strength drops in the range of around 200 to 300 °C. This phenomenon is possibly related to the maximum paleotemperature it underwent during its formation.

As for possible future research, higher temperature ranges between 500 to 800 °C and even 800 to 1200 °C could be studied in more detail. According to our data, greywacke does not show a significant increase in strength in higher temperatures as sandstone. However, this could be due to the fact that only a few samples were heated to these temperatures. Another possibility for further research is to determine the effect of different means of cooling on the strength of greywacke.

Acknowledgement

This paper was written with the support of Brno University of Technology – Faculty of Civil Engineering, within grant No. FAST-S-23-8272.

References

[1] MISKOVSKY, Karel and Christine SAIANG. Effect of heat on the mechanical properties of selectedrock types – a laboratory study. In: ZHOU, Yingxin, eds. *Harmonising Rock Engineering and the Environment* [online]. London: CRC Press, 2011, pp. 815–820. [accessed 2 October 2023]. ISBN 978-0-415-80444-8. DOI 10.1201/b11646-149

[2] SHAO, Shishi, Pathegama Gamage RANJITH, Piyal Wasantha Pallewela WASANTHA and Bernard CHEN. Experimental and numerical studies on the mechanical behaviour of Australian Strathbogie granite at high temperatures: An application to geothermal energy. *Geothermics* [online]. March 2015, 54, pp. 96–108. [accessed 2 October 2023]. ISSN 03756505. DOI 10.1016/j.geothermics.2014.11.005

[3] GARRIDO, María Elvira, Ferry Blondo PETNGA, Víctor MARTÍNEZ-IBÁÑEZ, José SERÓN, Carlos HIDALGO-SIGNES and Roberto TOMÁS. Predicting the Uniaxial Compressive Strength of a Limestone Exposed to High Temperatures by Point Load and Leeb Rebound Hardness Testing. *Rock Mechanics and Rock Engineering* [online]. January 2022, **55**(1), pp. 1–17. [accessed 2 October 2023]. ISSN 0723-2632, 1434-453X. DOI 10.1007/s00603-021-02647-0

[4] PINIŃSKA, Joanna. Impact of the elevated temperatures for the geomechanical properties of the rocks. In: *Prace Naukowe Instytutu Geotechniki i Hydrotechniki Politechniki Wrocławskiej. Konferencje*. 2007, **76**, pp. 527–534. ISSN 1230-3100

[5] SYGAŁA, Anna, Mirosława BUKOWSKA and Tomasz JANOSZEK. High Temperature Versus Geomechanical Parameters of Selected Rocks – The Present State of Research. *Journal of Sustainable Mining* [online]. 2013, **12**(4), pp. 45–51. [accessed 2 October 2023]. ISSN 23003960. DOI 10.7424/jsm130407

[6] YANG, Sheng-Qi, Pathegama Gamage RANJITH, Hong-Wen JING, Wen-Ling TIAN and Yang JU. An experimental investigation on thermal damage and failure mechanical behavior of granite after exposure to different high temperature treatments. *Geothermics* [online]. 2017, **65**, pp. 180–197. [accessed 2 October 2023]. ISSN 03756505. DOI 10.1016/j.geothermics.2016.09.008

[7] GAUTAM, Pradeep Kumar, Amit Kumar VERMA, Manish Kumar JHA, Pushpendra SHARMA and Trilok Nath SINGH. Effect of high temperature on physical and mechanical properties of Jalore granite. *Journal of Applied Geophysics* [online]. 2018, **159**, pp. 460–474. [accessed 2 October 2023]. ISSN 09269851. DOI 10.1016/j.jappgeo.2018.07.018

[8] GU, Bin, Zhijun WAN, Yuan ZHANG, Yangsheng MA and Xiaodong Bernard XU. Influence of Real-Time Heating on Mechanical Behaviours of Rocks. *Advances in Civil Engineering* [online]. 2020, pp. 1–10. [accessed 2 October 2023]. ISSN 1687-8086, 1687-8094. DOI 10.1155/2020/8879922

[9] ZHU, Zhennan, Hong TIAN, Gang MEI, Guosheng JIANG, Bin DOU and Peng XIAO. Experimental investigation on mechanical behaviors of Nanan granite after thermal treatment under conventional triaxial compression. *Environmental Earth Sciences* [online]. 2021, **80**(2), 46. [accessed 2 October 2023]. ISSN 1866-6280, 1866-6299. DOI 10.1007/s12665-020-09326-3

[10] TOMÁS, Roberto, Miguel CANO, Luis Pulgarín PULGARÍN, Vicente BROTÓNS, David BENAVENTE, Tiago MIRANDA and Graça VASCONCELOS. Thermal effect of high temperatures on the physical and mechanical properties of a granite used in UNESCO World Heritage sites in north Portugal. *Journal of Building Engineering* [online]. 2021, **43**, 102823. [accessed 2 October 2023]. ISSN 23527102. DOI 10.1016/j.jobe.2021.102823

[11] MAO, Xian-biao, Lian-ying ZHANG, Tian-zhen LI and Hai-shun LIU. Properties of failure mode and thermal damage for limestone at high temperature. *Mining Science and Technology (China)* [online]. 2009, **19**(3), pp. 290–294. [accessed 2 October 2023]. ISSN 16745264. DOI 10.1016/S1674-5264(09)60054-5

[12] ZHANG, LianYing, XianBiao MAO and AiHong LU. Experimental study on the mechanical properties of rocks at high temperature. *Science in China Series E: Technological Sciences* [online]. 2009, **52**(3), pp. 641–646. [accessed 2 October 2023]. ISSN 1006-9321, 1862-281X. DOI 10.1007/s11431-009-0063-y

[13] OZGUVEN, Ahmet and Yılmaz OZCELIK. Effects of high temperature on physico-mechanical properties of Turkish natural building stones. *Engineering Geology* [online]. 2014, **183**, pp. 127–136. [accessed 2 October 2023]. ISSN 00137952. DOI 10.1016/j.enggeo.2014.10.006

[14] KORZENIOWSKI, Waldemar and Krzysztof SKRZYPKOWSKI. Badania zmian wybranych właściwości geomechanicznych skał pod wpływem temperatury do 1100°C w aspekcie potencjalnych możliwości procesu podziemnego zgazowania węgla. *Przegląd Górniczy*. 2012, **68**(5), pp. 44–53. ISSN: 0033-216X

[15] WU, Gang, Y. WANG, G. SWIFT and J. CHEN. Laboratory Investigation of the Effects of Temperature on the Mechanical Properties of Sandstone. *Geotechnical and Geological Engineering* [online]. 2013, **31**(2), pp. 809–816. [accessed 2 October 2023]. ISSN 0960-3182, 1573-1529. DOI 10.1007/s10706-013-9614-x

[16] ZHANG, Lianying, Xianbiao MAO, Ruixue LIU, Xiaoqian GUO and Dan MA. The Mechanical Properties of Mudstone at High Temperatures: an Experimental Study. *Rock Mechanics and Rock Engineering* [online]. 2014, **47**(4), pp. 1479–1484. [accessed 2 October 2023]. ISSN 0723-2632, 1434-453X. DOI 10.1007/s00603-013-0435-2

[17] ZÁVACKÝ, Martin. Correlations of parameters of selected rock types based on laboratory tests [online]. Brno, 2021. [accessed 2 October 2023]. Dissertation. Brno University of Technology, Faculty of Civil Engineering. Available at: http://dspace.vutbr.cz/handle/11012/201664

[18] FRANCU, Eva, F. FRANCU, Jiří KALVODA, Harald S. POELCHAU and Jiří OTAVA. Burial and uplift history of the Palaeozoic Flysch in the Variscan foreland basin (SE Bohemian Massif, Czech Republic). *Stephan Mueller Special Publication Series* [online]. 2002, **1**, pp. 167–179. [accessed 2 October 2023]. ISSN 1868-4564. DOI 10.5194/smsps-1-167-2002

[19] FRANCŮ, Eva, Juraj FRANCŮ and Jiří KALVODA. Illite crystalinity and vitrinite reflectance in Paleozoic siliciclastics in the Bohemian Massif as evidence of thermal history. *Geologica Carpathica* [online]. 1999, **50**(5), pp. 65–71. [accessed 2 October 2023]. ISSN 1335-0552. Available at: https://www.muni.cz/vyzkum/publikace/217611

[20] ČOPJAKOVÁ, Renata, Milan NOVÁK and Eva FRANCŮ. Formation of authigenic monazite-(Ce) to monazite-(Nd) from Upper Carboniferous graywackes of the Drahany Upland: Roles of the chemical composition of host rock and burial temperature. *Lithos* [online]. 2011, **127**(1–2), pp. 373–385. [accessed 2 October 2023]. ISSN 00244937. DOI 10.1016/j.lithos.2011.08.001

DOI 10.13164/juniorstav.2024.24025