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Geotechnical Behavior of Rocks under High Thermal Effect

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ABSTRACT

The effect of under/after high temperature conditions on the thermo-mechanical behaviour of different rocks is extremely important issue for several engineering applications. Changes in the properties of rock after undergoing high temperature may affect stability and even induce engineering disasters. In General, the scope of high temperature ranges from normal temperatures (10-50 ¡C) to high temperatures (1000-1500 ¡C). Temperature is one of the key factors that influence the microstructure, the physical and mechanical properties for variety of rocks as Granite, Sandstone, Limestone, Mudstone, Marble and Diorite. A review study for vast majority of previous experimental investigations was carried out for some mechanical, physical and thermal properties of rocks, including deformation modulus, Poisson's ratio, tensile strength and compressive strength all vary considerably with increasing temperatures. Therefore, the results of experimental studies indicated that, behavior of rocks that exposed to high temperatures is different from those under normal temperature conditions. It has been known that rock strength and deformation modulus generally declined with the elevated temperature, especially beyond a certain temperature. Moreover, new correlations for the uniaxial compressive strength (UCS) with Tensile strength (TS) and for Young's modulus (Es) with uniaxial compressive strength (UCS) due to the elevated temperatures for different types of rocks were presented.

Keywords: *Review study, Experimental investigations, Thermal Effect, Behavior of rocks.*

Introduction

The impact of thermal effect on rocks is a topic of growing importance in geotechnical engineering because of its relevance to several engineering applications such as hot dry rock (HDR), deep geological disposal of nuclear waste, (Granitic rocks such as granite and diorite are a widely acceptable site for nuclear waste disposal and are also main rock types of HDR reservoir) (at temperatures which generally vary from 100 to 300 ◦C and will rise over the storage interval), geothermal energy resource extraction, solar heating of rock monuments and buildings, Fires in tunnels, mines and buildings and underground coal gasification (UCG). (Sellin and Leupin 2013; Verma et al. 2015), (Brown et al. 2012; Gelet et al. 2012), (Burton et al. 2006; Otto and Kempka 2015). The process of underground coal gasification (UCG) is based on in situ, sub-stoichiometric coal combustion for production of a high-calorific synthesis gas, which can be applied for electricity generation. Fig. 1 presents a schematic view of the in-situ coal gasification principle. However, UCG can induce impacts such as high thermal effects on the surrounding rocks of the coal layer. Temperatures above 1,000 °C can be achieved in the UCG reactor and its close vicinity (Otto and Kempka 2015)

The impact of high temperature on the physical and mechanical properties of rocks has been largely investigated using laboratory studies since the 1970s over the last several decades. (Francois, 1980; Bauer et al., 1981; Paquet et al., 1981; Heuze, 1983; Hirth and Tullis, 1989). Exploration of geothermal activities has posed new challenges for geotechnical engineers to counter rock engineering problems at high temperatures. Laboratory testing is an important aspect of rock mechanics, which provides essential input data for the design of engineering structures in the Earth's crust and mantle subjected to tectonic forces. Heuze, 1983; Wang et al., 2002; Dwivedi et al., 2008; Xu et al., 2008)

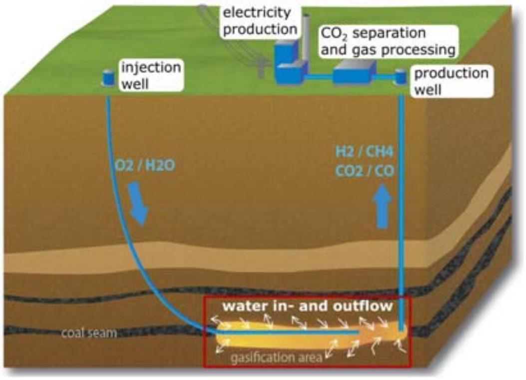
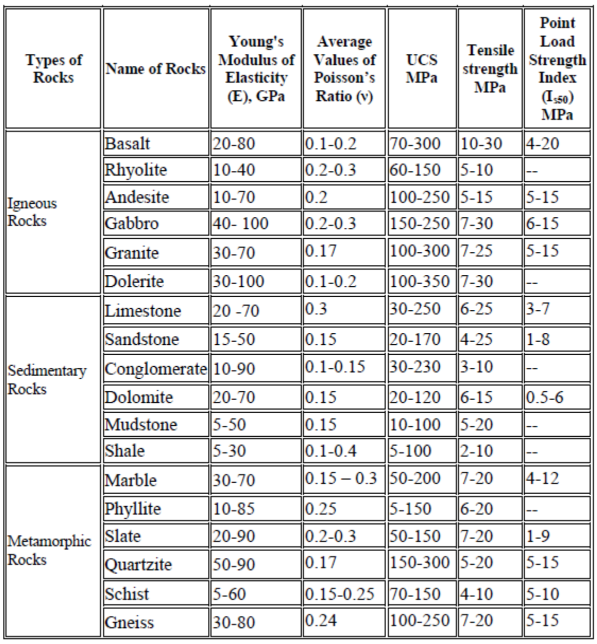


Fig. 1. Principle of in situ coal gasification method (Otto and Kempka 2015)

The most vital scope in rock mechanics is measuring the geotechnical rock properties and behavior such as its strength, mode of deformation, mode of failure, and modulus of elasticity, tensile strength etc. by using the experimental testing methods. Table. 1 illustrates different properties for variety of rocks.
The most common methods of laboratory testing for rock are:-

- Point-load index test.
- Unconfined compressive strength test.
- Brazilian or Indirect tensile strength test.

Table. 1: Modulus of Elasticity, Poisson's ratio, UCS, Tensile strength and Point load strength of some common rocks (Thuro and Schutz, 2001)



Types of Rocks	Name of Rocks	Young's Modulus of Elasticity (E), GPa	Average Values of Poisson's Ratio (ν)	UCS MPa	Tensile strength MPa	Point Load Strength Index (I_{s50}) MPa
Igneous Rocks	Basalt	20-80	0.1-0.2	70-300	10-30	4-20
	Rhyolite	10-40	0.2-0.3	60-150	5-10	--
	Andesite	10-70	0.2	100-250	5-15	5-15
	Gabbro	40- 100	0.2-0.3	150-250	7-30	6-15
	Granite	30-70	0.17	100-300	7-25	5-15
	Dolerite	30-100	0.1-0.2	100-350	7-30	--
Sedimentary Rocks	Limestone	20 -70	0.3	30-250	6-25	3-7
	Sandstone	15-50	0.15	20-170	4-25	1-8
	Conglomerate	10-90	0.1-0.15	30-230	3-10	--
	Dolomite	20-70	0.15	20-120	6-15	0.5-6
	Mudstone	5-50	0.15	10-100	5-20	--
	Shale	5-30	0.1-0.4	5-100	2-10	--
Metamorphic Rocks	Marble	30-70	0.15 – 0.3	50-200	7-20	4-12
	Phyllite	10-85	0.25	5-150	6-20	--
	Slate	20-90	0.2-0.3	50-150	7-20	1-9
	Quartzite	50-90	0.17	150-300	5-20	5-15
	Schist	5-60	0.15-0.25	70-150	4-10	5-10
	Gneiss	30-80	0.24	100-250	7-20	5-15

In the case of a high-temperature impact on rock, an additional factor which influences its strength is the thermal expansion of minerals included in the composition of the rock. The temperature induces micro cracks due to the different natures of the constituent minerals (intergranular). These cracks are due to the different expansion coefficients of the component minerals as shown in Table. 2, causing a differential expansion, generating internal stresses resulting in the creation of cracks in the transition phase between components. When temperature changes occur in a very short time, intergranular cracks occur by another different process than the previous ones: high temperature gradients in the material. These temperature gradients act by amplifying the differential dilation effects by different coefficients of expansion, which causes volumetric increase, and thermal crack opening. (Jansen et al., 1993).

Moreover, chemical changes take place, the result of which is polymorphic transformation, melting and the disappearance of certain minerals in rocks (Dengina, Kazak, Pristash 1993; Pinińska 2007; Małkowski, Skrzypkowski, Bożęcki 2011; Wu et al. 2013).

Table. 2: Linear thermal expansion coefficients for rock minerals (Siegesmund et al. 2011)

	Linear thermal expansion coefficient		
Mineral	Parallel to c-axis $[K^{-1}]$	Perpendicular to c-axis $[K^{-1}]$	Temp. range [°C]
Calcite	25.1×10^{-6}	-5.6×10^{-6}	0-85
Dolomite	25.8×10^{-6}	6.2×10^{-6}	24-700
Quartz	7.7×10^{-6}	13.3×10^{-6}	0-80
Albite	10.5×10^{-6}	5.6×10^{-6}	25-970
Gypsum	54×10^{-6}	$7\text{-}117 \times 10^{-6}$	25-42
Micas	8.7×10^{-6}	17.8×10^{-6}	unknown
Clay	6×10^{-6}	15×10^{-6}	25-350

Based on the characteristics of the axial stress–axial strain and axial stress–lateral strain curves of uniaxial compression tests, Hoek and Bieniawski (1965) found that the crack propagation process of brittle materials consists of three main stages: (1) crack of pre-existing micro-cracks closure followed by an elastic region; (2) crack initiation followed by a stable crack propagation region; (3) crack damage followed by unstable crack propagation until ultimate failure. Brittle to plastic transition in response to increasing temperature has been studied for different types of rocks. Tullis and Yund (1987) studied the Brittle to plastic transition in response to increasing temperature for different types of rocks. Xu et al. (2008) had used different temperatures ranging from room temperature to 1200 ◦C for different granite samples. The results showed that the phase-changing behaviour of brittle–plastic transition appears around 800 ◦C and the mechanical properties of samples did not significantly vary before that. Moreover a mix trend of the maximum unconfined compressive strength of the granite rocks with the elevated temperature was appeared until it reaches 800^0C; the trend significantly decreases after that. The normalized elastic modulus decreases with the elevated temperature as shown in Fig. 2.

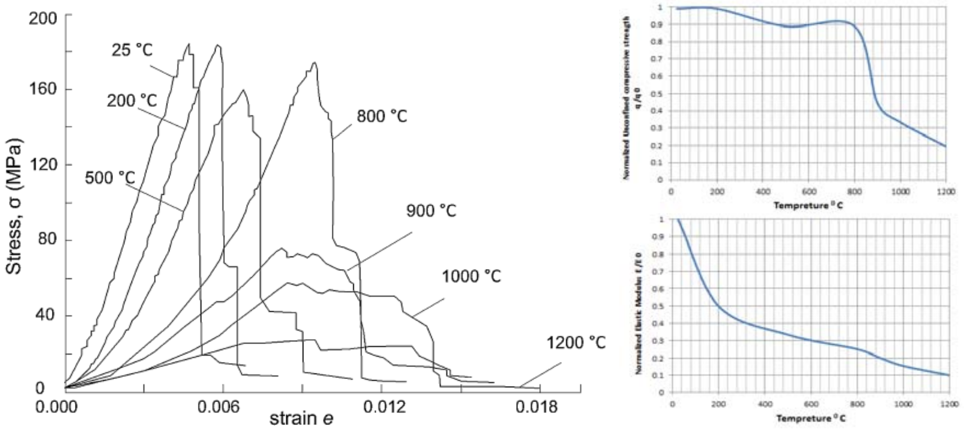


Fig. 2. Stress–strain curves of granite rocks after high temperature (Data from Xu et al., 2008).

(Houpert ,1988) are illustrated the following trends with increases temperature

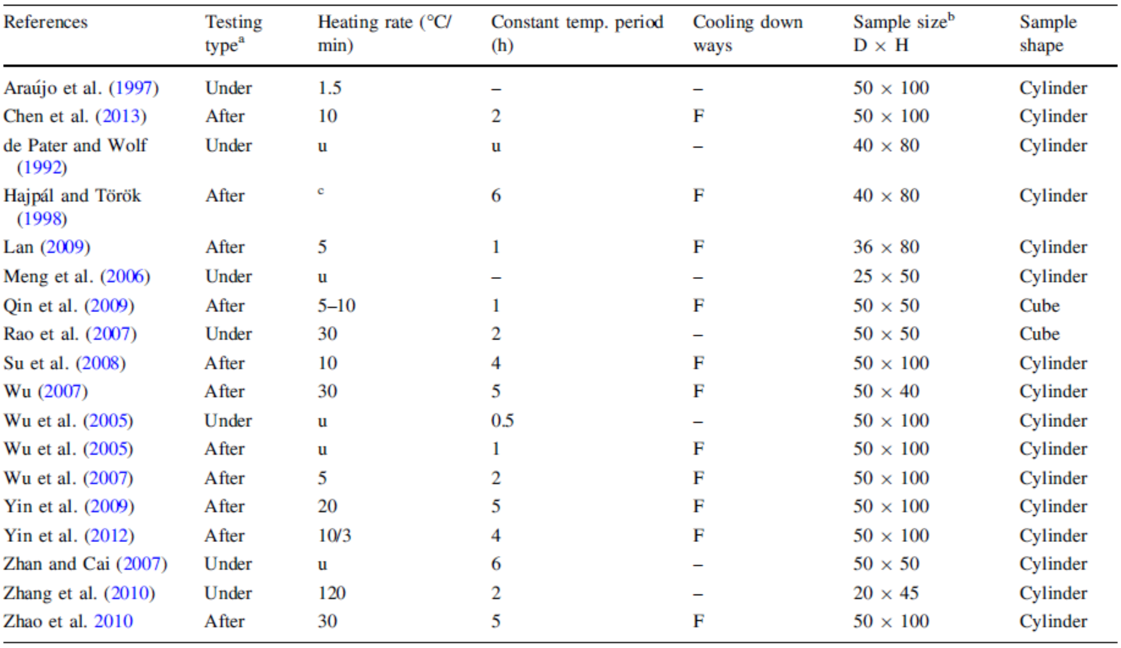
- Porosity increases.
- Rock compressibility increases.
- Sonic velocity decreases as temperature increases.

- Rock deformability increases.
- Rock strength decreases as temperature increases.
- Rock creep increases.

Preparation of Rock Samples exposed to thermal effect

The experimental procedures of ‘‘after/under high-temperature treatment’’ in the reviewed references are basically identical, taking into account heating the samples at a certain rate to prevent occurring heat shock in the rock samples under atmospheric pressure in a furnace until a predetermined temperature is reached. Then, the temperature is maintained for a given period (several hours), followed by cooling down the samples in the furnace chamber or under normal ambient conditions (room temperature cooling). Varieties of Lab. Tests were conducted on rock samples either under or after high-temperature treatment. The detailed testing parameters for each reference reviewed are summarized in Table 3.

Table. 3: Testing parameters of thermal effects



References	Testing type[a]	Heating rate (°C/min)	Constant temp. period (h)	Cooling down ways	Sample size[b] D × H	Sample shape
Araújo et al. (1997)	Under	1.5	–	–	50 × 100	Cylinder
Chen et al. (2013)	After	10	2	F	50 × 100	Cylinder
de Pater and Wolf (1992)	Under	u	u	–	40 × 80	Cylinder
Hajpál and Török (1998)	After	[c]	6	F	40 × 80	Cylinder
Lan (2009)	After	5	1	F	36 × 80	Cylinder
Meng et al. (2006)	Under	u	–	–	25 × 50	Cylinder
Qin et al. (2009)	After	5–10	1	F	50 × 50	Cube
Rao et al. (2007)	Under	30	2	–	50 × 50	Cube
Su et al. (2008)	After	10	4	F	50 × 100	Cylinder
Wu (2007)	After	30	5	F	50 × 40	Cylinder
Wu et al. (2005)	Under	u	0.5	–	50 × 100	Cylinder
Wu et al. (2005)	After	u	1	F	50 × 100	Cylinder
Wu et al. (2007)	After	5	2	F	50 × 100	Cylinder
Yin et al. (2009)	After	20	5	F	50 × 100	Cylinder
Yin et al. (2012)	After	10/3	4	F	50 × 100	Cylinder
Zhan and Cai (2007)	Under	u	6	–	50 × 50	Cylinder
Zhang et al. (2010)	Under	120	2	–	20 × 45	Cylinder
Zhao et al. 2010	After	30	5	F	50 × 100	Cylinder

Samples were cooled down in the furnace chamber ‘F’, or under normal ambient conditions ‘A’
The unit is mm, D is short for diameter and H for height

Variations of Mechanical Properties

Normalized values of bulk density, elastic modulus, passion ratio, compressive strengths and tensile strengths for different rocks at various temperatures were collected from literature.

Bulk Density (⍰$_b$)

Unit weight of rocks declines with raising the thermal effects on rock samples from the room temperature to the high temperature due to volumetric expansion of the constitution minerals and mass loss of rock sample (Otto and Kempka 2015). Fig. 3 shows the variation of normalized bulk density versus temperature up to 1000 °C for different sandstone samples, the decrease of sandstone samples density is slightly little compared with initial room temperature. Only above 1000 °C a significant decrease is noticed.

Uniaxial compressive strength (UCS)

UCS is one of the most important parameters reflecting the basic mechanical properties of rocks. It is extremely essential in the fields such as rock mass classification and development of rock and rock mass failure criteria (Jaeger et al. 2007).

The trend of UCS change is complex due to the variety of minerals compassion in different rock samples at elevated temperatures, although it is more likely to decrease with increasing temperature in almost cases.

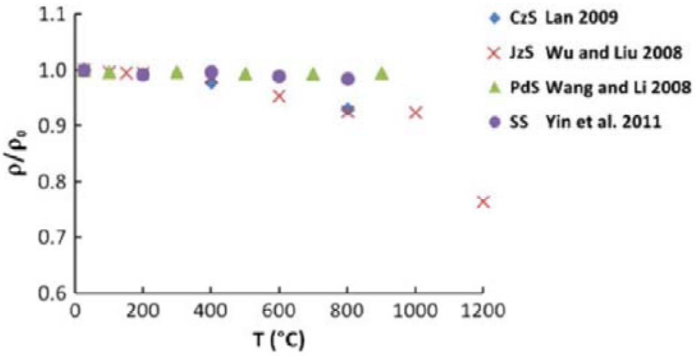


Fig. 3: Variation of normalized bulk density versus temperature for different sandstone samples (Tian et al., 2012)

Numerous experiments in literature have shown that apart from the temperature, acting pressure is also significant in the change of rock strength parameters. Ferrero and Marini (2001) tested 15 samples of two types of marble which were previously heated to temperatures up to 600 °C and later cooled applying a very low gradient of temperature. Koca et al. (2006) studied nine samples of intact marble, under different temperatures observing important descents of the rock strength. These authors also tested five rock samples obtained from building elements previously exposed to fire (subjected to an estimated temperature of 500 °C) using temperatures from room temperature to 300 °C which caused a very high elastic modulus decrease beyond 200 °C. A noteworthy aspect in the work from Koca et al. (2006) is that the uniaxial compressive strength of the material exposed to 500 °C and then cooled to room temperature exhibits very similar uniaxial compressive strength values than the intact material tested at 500 °C.

Rao et al. (2007) tested eight sandstone samples and observed a strong initial increase of resistance to 250 °C, and then a decline to 300°C, however at this temperature, resistance is 138% higher than the initial. Ranjith et al. (2012) tested sandstones until 950 °C obtaining different results than in other works, highlighting the significant increase in strength with temperature, reaching 180% of the initial strength at 600 °C, then lowering until the maximum test temperature is reached, remaining above the initial strength. Sygała et al. (2013) introduce the changes in the values of uniaxial compression of several types of rocks, subjected to high temperatures.

Liu and Xu (2014) discovered the threshold temperature is 400 °C. They found granite UCS changes slightly from room temperature to 400 °C, but dramatically decreases with temperature from 400 °C onward, by means of testing on granite sample after high-temperature treatment.

Shao et al., (2015) studied the Fracturing behaviour of Australian Strathbogie granite test specimens such as the crack propagation at high temperatures up to 800 using electron microscopy scanning (SEM) and unconfined strength test. Specimens were heated at a rate of 5 °C /min with a 1 h holding period before testing. The results of stress–strain and SEM reveal that the failure modes of Strathbogie granite specimens changed from brittle fracturing to quasi-brittle shear fracturing and eventually to ductile failure with increasing temperature. Fig. 4 graphically summarizes the all previously described results. The results show that a mixed trend in the values of the normalized UCS q / qo, where qo is the value of the UCS at the room temperature= 25 °C in all cases with the elevated temperature generally occurs until reaches to 800 °C, after that steeply decreases.

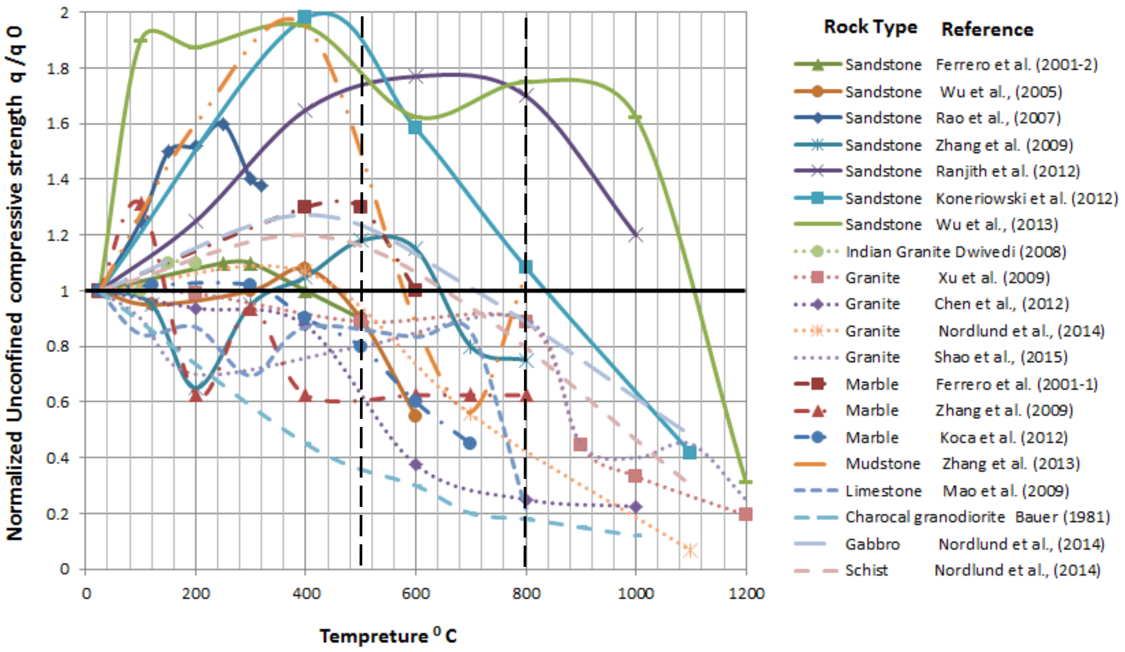


Fig. 4: Variation of normalized UCS for different types of rocks versus temperature
Data from (Brotóns et al., 2013) and (Sygała et al. 2013)

Young's modulus and Poisson's ratio (E_s and ν)

Elastic properties of isotropic rocks are determined by Young's modulus and Poisson's ratio. This is the factor of proportionality between stress and the corresponding elastic strain. Similarly as strength, elasticity of rocks depends mainly on the elasticity of composing minerals, the density, porosity and other factors. Young's modulus is determined for the entire height of the sample or at a center section as the tangent of the angle of inclination to the x-axis of the straight line approximating the post-failure curve in the ascending part of the stress-strain characteristics of compressed rock sample or as a tangent of secant inclination (Bukowska 2012). Changes of the value of Young's modulus of selected rock subjected to heating at various temperatures. In the case of granites studied by Chen et al. (2012), to a temperature of 400°C, Young's modulus is generally not changed significantly. For samples heated at higher temperatures there was a sharp decline in the value of Young's modulus, reaching a temperature of 1000°C, only 10% of the value obtained at room temperature.
Some rocks exhibit a clear decrease in elastic modulus at elevated temperatures, while some rocks firstly experience a slight increase within a certain temperature range (from 25 to 200 °C). But for all rocks, elastic modulus will finally decrease to a much lower level after critical temperatures equals to (600 °C). Fig. 5 graphically summarizes the all previously described results.

(Yang et al. 2017) presented the variation of Poisson's ratio versus temperatures for different granite samples. Poisson's ratio reduces slightly with raising the temperature between 50 °C and 400 °C. He mentioned also that this trend is not yet profound due to limited available experimental data beyond 600 °C and might be different for the variety types of rock. Brotons et al. (2013) introduce Poisson's ratio values for calcarenite stone samples before and after the specimen heating obtained by ultrasonic propagation velocity tests. This parameter decreases inversely proportional to the temperature. Fig. 6 graphically summarizes the all previously described results.

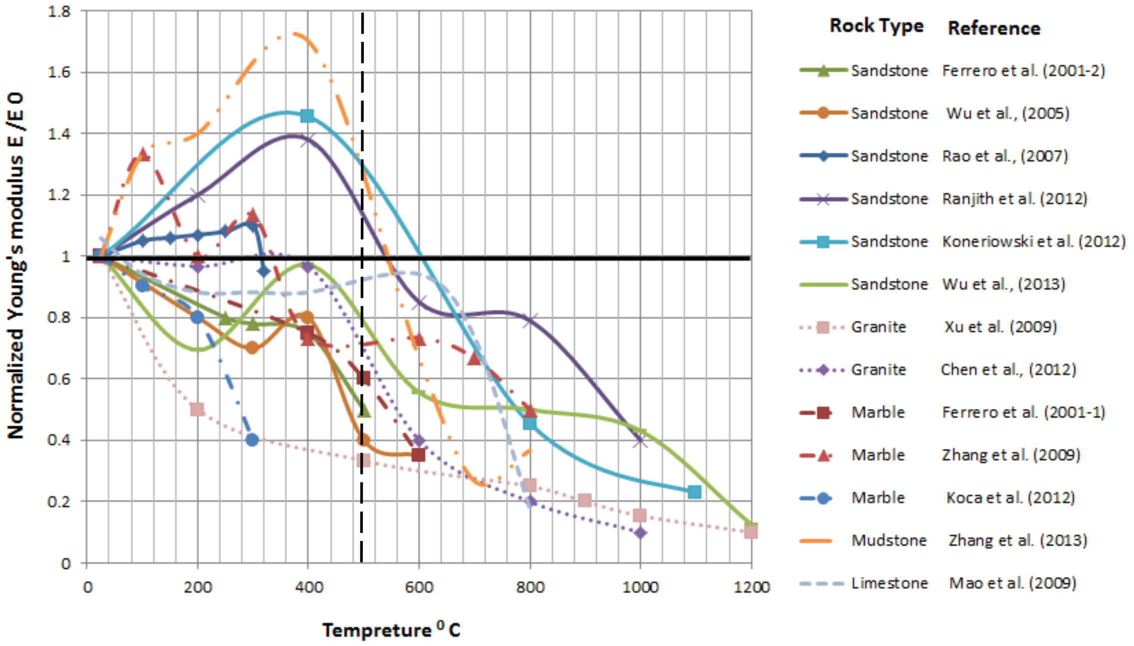


Fig. 5: Variation of normalized Young's modulus for different types of rocks versus temperature
Data from (Brotóns et al., 2013) and (Sygała et al. 2013)

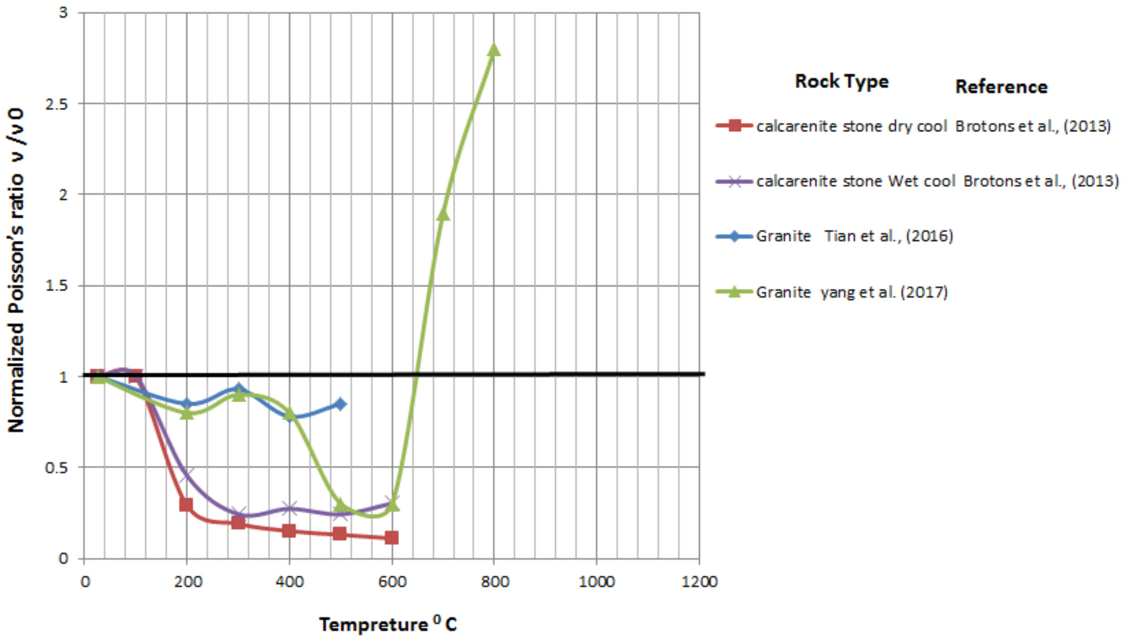


Fig. 6: Variation of normalized Poisson's ratio for different types of rocks versus temperature
Data from (Brotóns et al., 2013) and (Yang et al. 2017)

Tensile strength (TS)

Almost different types of rocks, tensile strength parameter (TS) declines with increasing the temperature, especially after 400°C where the decreasing rate will become much higher. (Dwivedi et al., 2008) presented Variation of normalized tensile strength of granite samples versus different temperature up to 1200 °C. (Roy and Singh, 2016) showed that the decrease of tensile strength of granite is negligible below 250 °C. (Liu et al., 2016) study falls in the context of underground coal fires (UCF). The objective of the research is to experimentally characterize the change in mechanical behavior using tensile strength test of two Australian mudstone rocks when subjected to temperatures up to 1200 °C for 24 hours. Results show that, when the heating temperature increases, the normalized tensile strength significantly decreases. (Tian et al., 2015) presented the values of normalized tensile strengths for different sandstones samples. Similar to the relations of normalized tensile strengths with temperature, the values of normalized tensile strengths can also be increasing, decreasing or remain constant with temperature up to a certain temperature which may be about 500 °C for most sandstones samples. Fig. 7 graphically summarizes the all previously described results.

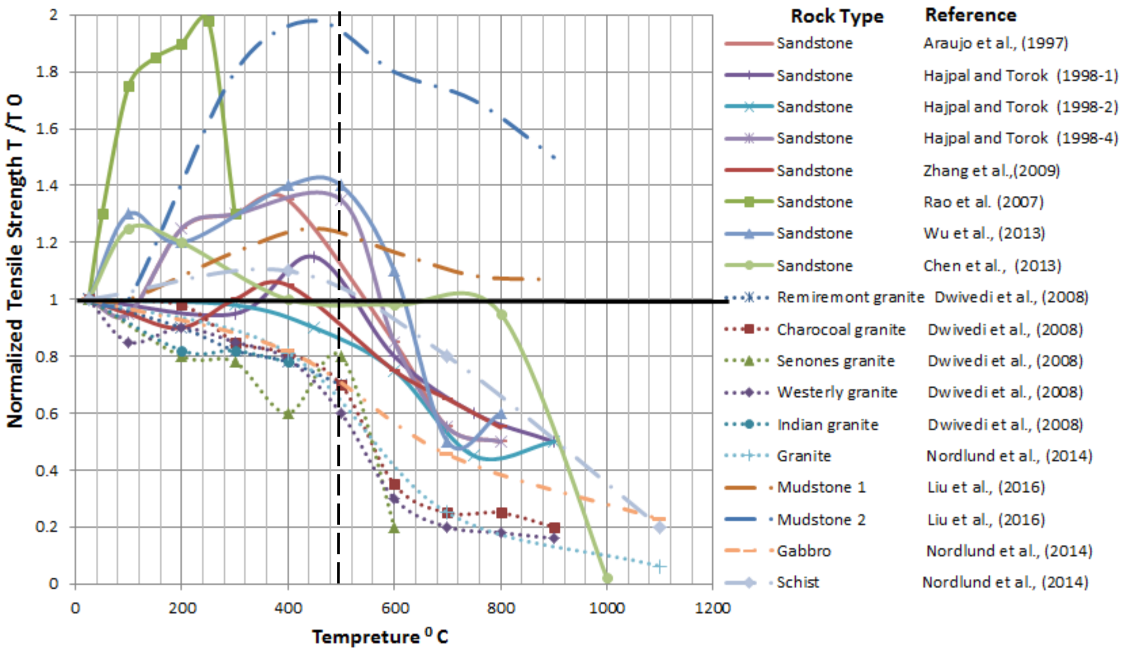


Fig. 7: Variation of normalized tensile strength of rock samples versus different temperature
Data from (Tian et al., 2015), (Dwivedi et al., 2008) and (Liu et al., 2016)

It is generally accepted that elastic modulus and strength of rocks decrease with increasing temperature. Experimental results in the literature have indicated that the nature of changes of the strength properties with increasing temperature is not consistent for all the rocks. Below 500–800 °C, the trend of strength with temperature can be increasing, decreasing or unchanged. Above that, a decreasing trend is always observed due to the variety of minerals compassion, initial micro-cracks for different rocks and experimental conditions Tian et al. (2015).

Rao et al. (2007) reported that increase in the strength and mechanical properties of rocks from 20°C to 400°C due to the free moisture content in rock and the applied heat reduced the moisture content, thereby making the rocks to be stronger.

Relation between the uniaxial compressive strength (UCS) and Tensile strength (TS) with the elevated temperatures for rocks

To develop a new correlation between UCS and TS with the elevated temperatures for different types of rocks, comparisons of vast majority of previous experimental investigations were reviewed. Fig. 8 shows the ratio between the uniaxial compressive strength (UCS) and Tensile strength (TS) for rocks versus different temperature Data from (Tian et al., 2015), (Dwivedi et al., 2008) and (Liu et al., 2016). The results shows that at the room temperature the ranged of the correlation between the uniaxial compressive strength (UCS) and Tensile strength (TS) was between (7 to 15) % for different rocks. This coloration sharply decreases with the elevated temperature, until the temperature reach 1000 °C the correlation finds to be from 9 to 2%.

Relation between the Young’s modulus (Es) and uniaxial compressive strength (UCS) with the elevated temperatures for rocks

The uniaxial compressive strength and static Young’s modulus Es of intact rocks are the most important geotechnical parameters for stability analysis of surface and underground structures. These parameters are obtained by the uniaxial compressive test. Fig. 9 shows the ratio between the Young’s modulus (Es) and uniaxial compressive strength for rocks versus different temperature Data from (Tian et al., 2015), (Dwivedi et al., 2008) and (Liu et al., 2016). The results shows that at the room temperature the ranged of the correlation between the Young’s modulus (Es) and uniaxial compressive strength was between (15 to 35) % for different rocks. This coloration sharply decreases with the elevated temperature, until the temperature reach 1100 °C the correlation finds to be from 13 to 5%.

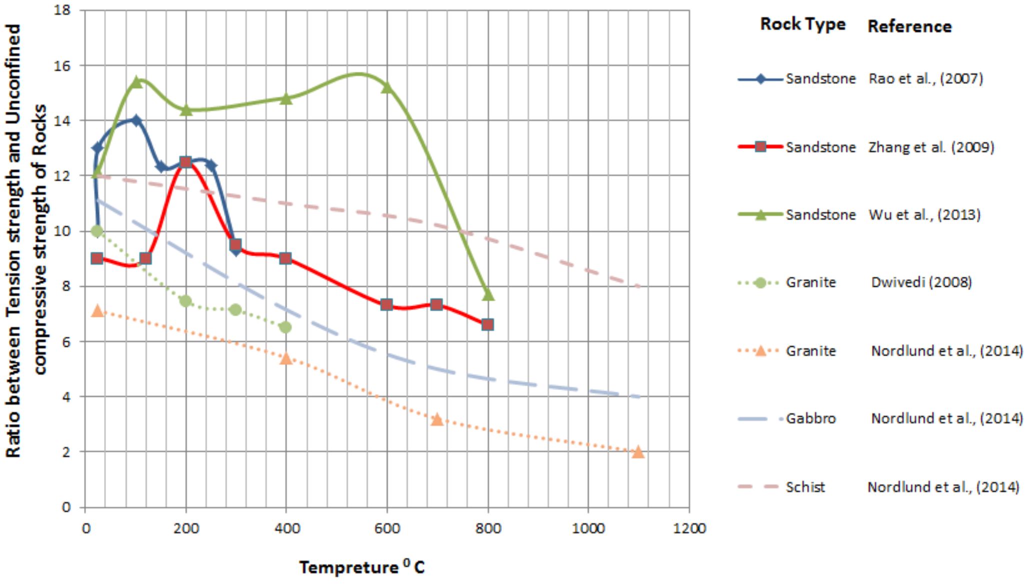


Fig. 8: Ratio between the uniaxial compressive strength (UCS) and Tensile strength (TS) for rocks versus different temperature Data from (Tian et al., 2015), (Dwivedi et al., 2008) and (Liu et al., 2016)

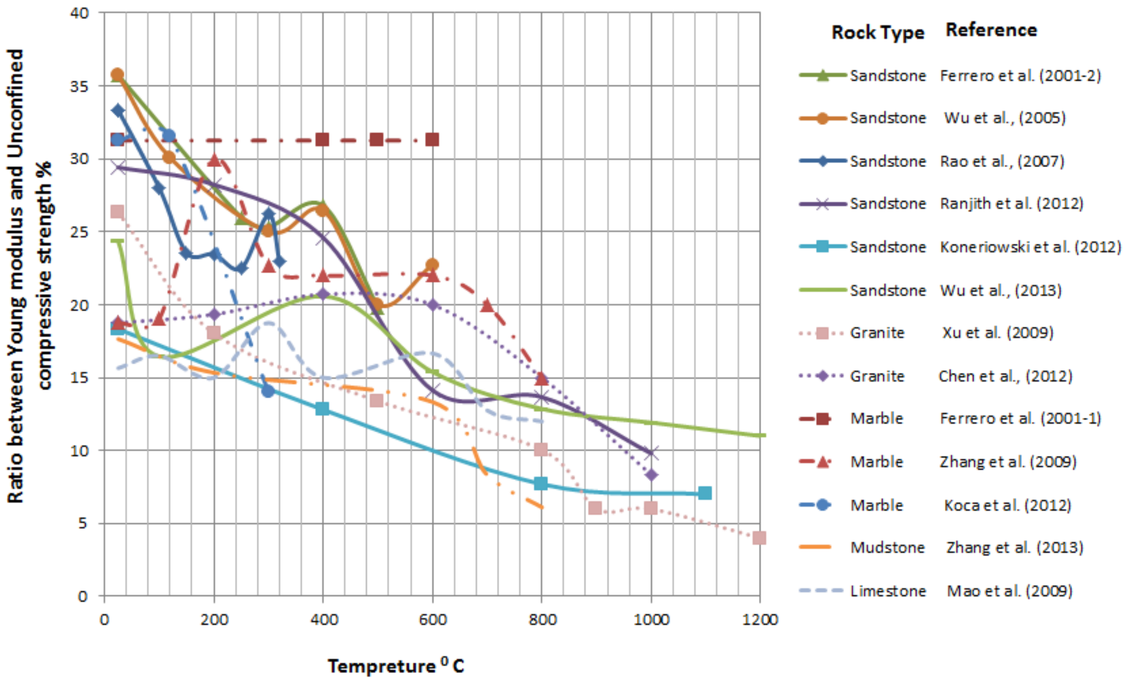


Fig. 9: Ratio between the Young's modulus (Es) and uniaxial compressive strength (UCS) for rocks versus different temperature Data from (Tian et al., 2015), (Dwivedi et al., 2008) and (Liu et al., 2016)

CONCLUSIONS

The presented reviewed data are expected to support analytical calculations and numerical simulations of thermo-mechanical processes for different rocks. Based on the extensive review on mechanical rock properties during and after high-temperature treatment, the following conclusions are drawn:

- The decrease of rocks samples density is slightly little compared with initial room temperature. Only above 1000 °C a significant decrease is noticed.
- The trend of UCS change is complex at the elevated temperatures, although it is more likely to decrease with increasing temperature after (500 °C to 800°C) in almost cases.
- A mixed trend for normalized elastic modulus and normalized tensile strength were obtained up to about 500 °C. Beyond the temperature, normalized elastic modulus and normalized tensile strength decrease with increasing temperature up to 1000 °C.
- Poisson's ratio reduces slightly with raising the temperature between 50 °C and 400 °C.
- The coloration between the uniaxial compressive strength (UCS) and Tensile strength (TS) sharply decreases with the elevated temperature, until the temperature reach 1000 °C the correlation finds to be from 9 to 2%.
- The coloration between the Young's modulus (Es) and uniaxial compressive strength was decreases with the elevated temperature, until the temperature reach 1100 °C the correlation finds to be from 13 to 5%.

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