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TECHNICAL NOTE

Mechanical Properties of Sandstones Exposed to High Temperature

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1 Introduction

Modern rock engineering applications such as deep geological disposal of nuclear waste (Ringwood 1985; Gibb 1999; Hökmark and Claesson 2005; Gibb et al. 2008; Sanchez et al. 2012), geothermal heat (especially of hot dry rock) extraction (Zhao 2000; Ghassemi and Zhou 2011; Feng et al. 2012; Gelet et al. 2012; Cherubini et al. 2013), and underground coal gasification (Burton et al. 2007; Luo et al. 2011; Kempka et al. 2011; Younger 2011; Nakaten et al. 2014) experience high-temperature environments, where rocks generally experience high temperatures up to several hundred degrees Celsius. Consequently, rock behaviors under and after high-temperature conditions are of high interest and still a challenge to scientists and engineers of different disciplines. High temperatures result in thermal stresses and mineral expansion as well as various changes of physical and mineralogical properties within rock bodies (Hajpál and Török 2004; Tian et al. 2012a, 2013), and thus lead to micro-structure changes and micro-cracks development and extension (Den'gina et al. 1994; Dwivedi et al. 2008). These effects change rock mechanical properties such as elastic modulus and compressive strength under and after high-temperature treatment, from a macro point of view, compared to those at normal temperature. Therefore, corresponding high-temperature mechanical properties of rocks are of high relevance for successful implementation of underground rock engineering projects.

Sandstone is a widely distributed sedimentary rock composed mostly of sand-sized minerals or rock grains cemented mainly by siliceous, argillaceous, or calcareous materials. Its mechanical properties depend highly upon the degree of cementation and grain composition which are affected by temperature and burial history. In this manuscript, a comprehensive review of international literature, including Chinese publications not available for the English-speaking scientific community so far, described elastic modulus, compressive and tensile strengths of sandstones under and after high-temperature treatment.

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2 Reviewed Sandstone Samples

The considered sandstones along with their original characteristics and mechanical properties are listed in Table 1. The experimental procedures of "after high-temperature treatment" in the reviewed references are basically identical, taking into account heating the samples at a certain rate under atmospheric pressure in a furnace until a predetermined temperature is reached. Then, the temperature

Table 1 Original characteristics and mechanical properties of the reviewed sandstones

Abbr.	Origin	Main mineral	Cement type	E_0 (GPa)	UCS_0 (MPa)	σ_{t0} (MPa)	References
ChS	China	–	–	–	–	24.0	Zhan and Cai (2007)
CsS	Changsha, China	Quartz	–	20.2	126.4	–	Yin et al. (2012)
CtS	Cottaer, Germany	Quartz	Argillaceous	–	23.1	3.1	Hajpál and Török (1998)
CxS	Chuxiong, China	Quartz	Argillaceous	10.7	66.0	2.2	Rao et al. (2007)
DdS	Donzdorfer, Germany	Quartz	Argillaceous	–	32.9	3.0	Hajpál and Török (1998)
FsS	Felser, Germany	Quartz, feldspar	Calcareous	16.2	75.0	4.0	de Pater and Wolf (1992)
FzS	Fangzhuang, China	Feldspar, quartz	Calcareous	21.0	80.0	2.6	Wu (2007); Su et al. (2008); Yin et al. (2009)
FzS*	Fangzhuang, China	Feldspar, quartz	–	18.5	205.6	–	Qin et al. (2009)
HbS	Hebi, China	Quartz kaolinite, mica	Argillaceous	17.7	138.5	–	Wu et al. (2005)
JzS	Jiaozuo, China	Quartz, feldspar	–	36.4	142.2	–	Wu et al. (2007)
MbS	Maulbronner, Germany	Quartz	Argillaceous	–	43.1	4.5	Hajpál and Török (1998)
PbS	Potiguar Basin, Brazil	–	–	6.0	13.5	–	Araújo et al. (1997)
PdS	Pingdingshan, China	Quartz	–	–	–	2.83	Zhao et al. (2010)
PhS	Pliezhausener, Germany	Quartz	Dolomitic	–	50.0	4.	Hajpál and Török (1998)
QlS	Qinling, China	Quartz, calcite	–	–	60.1	40.0	Chen et al. (2013)
TlS	Talimu, China	–	–	3.3	20.8	–	Meng et al. (2006)
TwS	Taiwan	–	Argillaceous	51.1	88.1	–	Lan (2009)
XzS	Xuzhou, China	–	–	16.7	171.0	–	Zhang et al. (2010)

is maintained for a given period (several hours), followed by cooling down the samples in the furnace chamber or under normal ambient conditions. The detailed testing parameters for each reference reviewed are summarized in Table 2.

3 Variations of Mechanical Properties

Normalized values of elastic moduli (E/E_0), compressive strengths (σ_c/σ_{c0}) and tensile strengths (σ_t/σ_{t0}) for sandstones at various temperatures were collected from literature. The normalized value is equal to the ratio of the value at a specific temperature of thermal treatment to that at normal temperature (about 20 °C).

3.1 Elastic Modulus

Generally, the static elastic modulus (E) is temperature and pressure dependent (Heuze 1983). Values of E/E_0 obtained on sandstones either under or after high-temperature treatment at atmospheric pressure vary with temperature (Fig. 1). At temperatures up to about 500 °C, sandstones show different trends (left of dashed line in Fig. 1), but from that to 1000 °C, E/E_0 decreases nearly linearly with increasing temperature. From 1000 °C onwards, E/E_0 slightly increases for HbS, but dramatically decreases for JzS (Fig. 1). Araújo et al. (1997) observed an approximate 23 % decrease of E as temperature increased from 24 to 150 °C for friable PbS under high-temperature treatment, while Meng et al. (2006) proposed a linear decrease rule of E with temperature from 0 to 150 °C for TlS based on regression analysis of testing data under high temperature.

Due to the variances in mineralogy, initial micro-cracks and experimental conditions, the values of E/E_0 of FzS and FsS do not exhibit a uniform tendency with temperature under confining pressures, but are in the range of 0.6–1.2 (Fig. 2). In addition, increasing pressure tends to retard the decay of E/E_0, when temperature increases (Fig. 2). However, at temperatures from 25 to 70 °C and confining pressures from 0.1 to 60 MPa, Zhou et al. (2005) observed E not changing distinctly with confining pressures, through testing on the dolomitic argillaceous fine sandstones obtained from boreholes of the west route of the South-to-North Water Transfer Project in Western China.

Table 2 Testing parameters of thermal treatment

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

'u' represents the condition is not given in the paper

Samples were cooled down in the furnace chamber 'F', or under normal ambient conditions 'A'

[a] Tests were conducted on rock samples either under or after high-temperature treatment

[b] The unit is mm, D is short for diameter and H for height

[c] The heating procedure took 1 h to reach a predetermined temperature

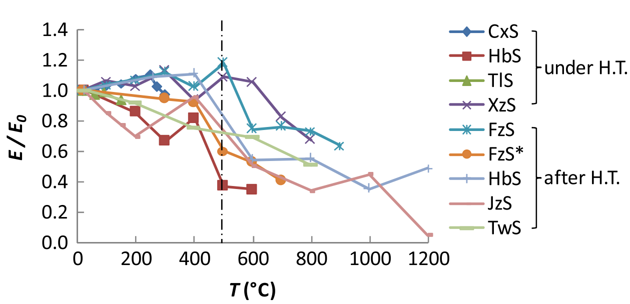

Fig. 1 Normalized static elastic modulus vs. temperature at atmospheric pressure. *HT* high-temperature treatment

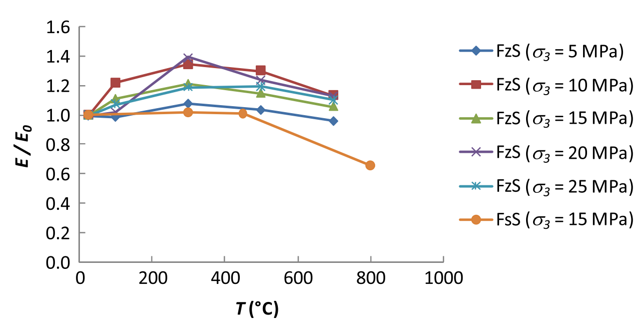

Fig. 2 Normalized static elastic modulus vs. temperature under confining pressures

Additionally, Luo and Qin (2005) found that the normalized dynamic elastic modulus decreases with increasing temperature from 25 to 1200 °C. An about 70.49 % decrease occurred until reaching 1200 °C. In their study, the dynamic elastic modulus is calculated by taking into account density, longitudinal wave velocity and Poisson's ratio.

3.2 Compressive Strength

Figure 3 shows the values of normalized uniaxial compressive strengths (σ_c/σ_{c0}) at atmospheric pressure for different sandstones. The trend of σ_c/σ_{c0} with temperature can be increasing, decreasing or remain constant below a certain temperature T_t (left of dashed lines in Fig. 3), while

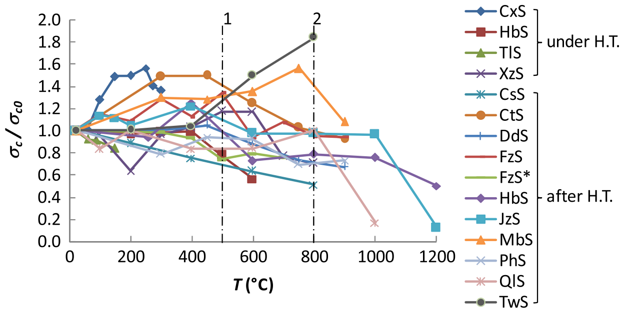

Fig. 3 Normalized uniaxial compressive strength vs. temperature at atmospheric pressure. *HT* high-temperature treatment

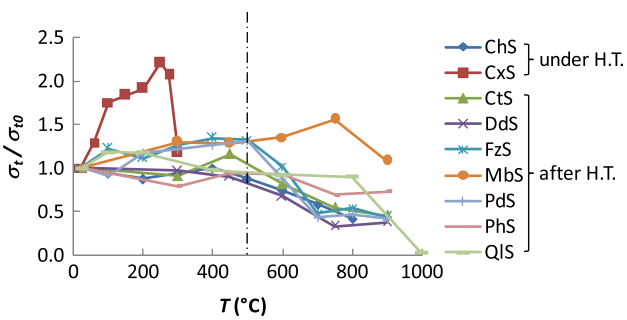

Fig. 4 Normalized tensile strength vs. temperature. *HT* high-temperature treatment

a decreasing trend usually occurs beyond T_t. For most of the sandstones reviewed, the T_t value is about 500 °C. However, it can be around 800 °C for some sandstones such as MlbS and TwS (Fig. 3). Above T_t, σ_c/σ_{c0} decreases with increasing temperature. Furthermore, the trend with temperature is generally decreasing gently up to 800 °C, but steeply from that onwards.

Comprehensive triaxial compression testing results have been published for FzS tested after exposure to high temperatures (Yin et al. 2009). It revealed that the normalized values of ultimate compressive strength decrease with increasing temperature from 500 °C onwards, while increase with increasing confining pressure. Based on triaxial tests under high temperature, Araújo et al. (1997) observed an average reduction of compressive strength by 22 % for friable PbS with temperature increasing from 24 to 80 °C.

3.3 Tensile Strength

The values of normalized tensile strengths (σ_t/σ_{t0}) for sandstones are plotted in Fig. 5. Similar to the relations of σ_c/σ_{c0} with temperature, the values of σ_t/σ_{t0} can also be increasing, decreasing or remain constant with temperature up to a certain temperature which may be about 500 °C for most sandstones (left of dashed line in Fig. 4) or about 200 °C such as C × S. However, from that onwards, σ_t/σ_{t0}

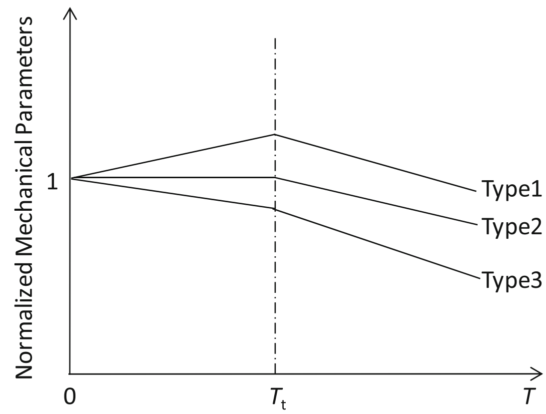

Fig. 5 Types of simplified relations between normalized mechanical parameters and temperature

decreases with increasing temperature except for MbS (right of dashed line in Fig. 4).

4 Discussion

Rock mechanical properties depend on many parameters such as rock properties (presence of micro- and macro-cracks and rock-forming minerals, grain size, cementation, etc.), experimental methods and burial history. The combination of all these parameters determines the relationship between mechanical rock properties and temperature, which have been widely investigated (e.g. Hajpál 2002; Zhan and Cai 2007; Zhu et al. 2007; Qin et al. 2009; Shao et al. 2014; Liu and Xu 2015). Exposure of rocks to high temperature results in mineral expansion, thermal reactions and stresses inside the rock body, and thus probably causes significant changes in rock micro-cracks, micro-structure and mineral bonds, which can be indirectly analyzed by changes in porosity, permeability and compressive wave velocity. Experimental parameters such as heating rate, cooling rate, constant time intervals, and confining pressure also have impacts on temperature-dependent mechanical parameters. During the thermal treatment procedure, fast heating and/or cooling generally cause a thermal shock in a rock and trigger extra thermal damage. Experimental investigations have revealed that a temperature level to which samples are heated should be kept constant for at least 20 min prior to mechanical testing or cooling (Dmitriyev et al. 1969). However, it is yet not known whether a constant period of 1, 2 h or more has an significant effect on the thermal treatment results. Nevertheless, slow heating and/or cooling as well as a sufficiently constant temperature during the exposure period should be maintained in the research on the relations between rock properties and temperature (not fire), which have been applied to most of the tests reviewed except those not giving any details on the procedures.

The experimental relationship between rock mechanical properties and temperature is the end product of these factors including the rock properties and experimental conditions. Taking into account that the impacts of these parameters related to rock exposed to high temperatures are directly related and scientific research does still not provide all relationships required in engineering applications exhibiting high temperature levels, generalized relationship is provided by the present study based on data available in literature.

As shown in Figs. 1, 2, 3 and 4, the nature of the dependence on temperature of elastic modulus, compressive and tensile strengths obtained for the same rock usually coincides. Although the testing approaches in the specific thermal treatment and samples are somewhat different, the relationships between the mechanical parameters (E, σ_c and σ_t) and temperature can be generally categorized into three types as follows:

- Type1: mechanical parameter values increase with increasing temperature below a certain temperature, namely threshold temperature (T_t), and subsequently decrease;
- Type2: mechanical parameter values change by ±10 % or remain constant with increasing temperature below the threshold temperature T_t, and subsequently decrease;
- Type3: mechanical parameter values decrease with increasing temperature, but show different decreasing trends below and above the threshold temperature T_t, and a steeper drop is normally observed above T_t.

Visual illustration of the three types in a linear fashion is plotted in Fig. 5. Actually, non-linear relations are more realistic, e.g., as shown in Fig. 4. However, the linear relations are simple and easy to use, especially in the case that there are no corresponding testing data of thermal treatment.

As discussed above, both rock properties and experimental conditions have an impact on the temperature-dependent relationship of sandstone mechanical properties, while the detailed interaction resulting in that relation is yet not fully known. Hence, it is difficult to predict which type the trend of a sandstone property with temperature will follow without the results of a thermal treatment test. However, the authors suggest that sandstones with clayey or argillaceous cementation after thermal treatment probably behave as that of Type1 sandstone, since strength of rocks containing clay minerals usually increases with temperature as a result of the baking effect occurring below a certain threshold temperature (Wolf et al. 1992; Tian et al. 2012b, 2014). Further research related to the relations between mineral composition (particular quartz and feldspar), cementation as well as original porosity (or permeability) and the three types has to be carried out to extend the scientific knowledge in the area.

Dissociation of mineral structural water usually happens above 400 °C. It triggers mineral structure and composition changes, and introduces micro-crack development. Török and Hajpál (2005) demonstrate that quartz and feldspar components of sandstones do not exhibit significant alterations up to 900 °C, and that micro-cracks at the grain boundaries of these two minerals first develop above 600 °C. The transition temperature of α-quartz to β-quartz at atmospheric pressure is 573 °C, and accompanied by a linear expansion of 0.45 %. This is the main reason why changes in the temperature-dependent trend of the sandstone mechanical properties mainly occur in the temperature range between 400 and 600 °C (Figs. 1, 2, 3, 4), even though rock parameters and experimental conditions differ in the present experimental results from literature. If testing data are not available, the authors suggest defining the turning point of temperature, i.e., threshold temperature, at around 500 °C. According to the literature data reviewed, at the threshold temperature, the normalized elastic modulus, unconfined compressive strength and tensile strength are generally in the range of 0.4–1.2, 0.8–1.5, and 0.8–1.4, respectively.

5 Conclusions

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

- A mixed trend for normalized elastic modulus (E/E_0) and tensile strength (σ_t/σ_{t0}) was obtained up to about 500 °C. Beyond the temperature, E/E_0 decreases with increasing temperature up to 1000 °C.
- A mixed trend of uniaxial compressive strength was also observed up to a threshold temperature, and from that onwards a decreasing trend often occurs. This threshold temperature is about 500 °C for most of the sandstones, but also about 800 °C for others.
- The relations between the mechanical parameters and temperature can be generally categorized into three types Type1, Type2 and Type3. For Type1, mechanical parameters increase with temperature below a threshold temperature T_t, and subsequently decrease. For Type2 and Type3, mechanical parameters change by ±10 % or remain constant and decrease with temperature,

respectively, and subsequently decrease. At T_t, the normalized elastic modulus, unconfined compressive strength and tensile strength of sandstones are usually in the range of 0.4–1.2, 0.8–1.5, and 0.8–1.4, respectively.

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