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TECHNICAL NOTE

Physical Properties of Sandstones After High Temperature Treatment

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1 Introduction

Under the influence of high temperatures below the rock melting point, rock micro-structures change significantly (Dwivedi et al. 2008), new micro-cracks are developed, and pre-existing ones extended/widened (Den'gina et al. 1994). Meanwhile, various physical and mineralogical changes take place in the rock matrix. After cooling down to room temperature, thermal-induced changes are irreversible to some extent. Hence, rock physical properties from a macroscopic point of view are temperature-history dependent as they rely on the maximum temperature experienced. Knowledge on this issue is a key factor for successful implementation of modern geotechnical engineering projects, such as nuclear waste storage (Sundberg et al. 2009), underground coal gasification (Roddy and Younger 2010), geological CO_2 storage (Rutqvist et al. 2002), geothermal heat extraction (Zhao 2000) and stability analysis of constructions in rocks after exposure to fire (Zhan and Cai 2007).

Sandstone is a common sedimentary rock, having broad applications in geotechnical engineering. Therefore, the research on the thermo-physical properties of sandstones is extremely meaningful on a wide range. In this manuscript, an extensive review of international literature, especially of Chinese publications not considered in the English-speaking scientific community so far, covers physical properties such as bulk density, porosity, permeability and compressional wave velocity of sandstones after high temperature treatment. The considered sandstones along with their characteristics are listed in Table 1. The testing procedures of thermal treatment in the references reviewed in this manuscript are identical, taking into account heating the samples at a certain rate and under atmospheric pressure conditions in a furnace until a predetermined temperature is reached. The maximum temperature is maintained for a period (several hours), and then cooled down in the furnace or at ambient conditions. The detailed testing parameters for each reference reviewed are summarized in Table 2.

2 Variations of Physical Properties

Normalized values of bulk density (ρ/ρ_0), porosity (Φ/Φ_0), permeability (k/k_0) and compressional wave velocity (V_p/V_{p0}) for sandstones after high temperature treatment were reviewed here based on an extensive literature study. The normalized value is defined as the ratio of a testing index after a specific temperature treatment to that at room temperature. Hence, it is always equal to one at room temperature.

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Table 1 Characteristics of the reviewed sandstones

Name (abbreviation)	Ref.	Main mineral	Color	Grain size	Cementation type	Density (g/cm^3)	Porosity (%)	Compressional wave velocity (m/s)
Chinese								
Changzhi (CzS)	Lan (2009)	–	Grey	Fine	Argillaceous	2.67	–	–
Fangzhuang (FzS)	Qin et al. (2009)	Feldspar, quartz	Light green	Coarse	–	2.65	–	–
Guhanshan (GS)	Zhao et al. (2009)	–	Grey	Fine	Argillaceous	–	1.25	3,764
Hebi (HS)	Luo and Qin (2005)	Quartz, kaolinite	Greyish black	–	Argillaceous	2.65	–	–
Jiaozuo (JzS)	Wu and Liu (2008)	Feldspar, quartz	Dark grey	–	Carbonaceous	2.65	–	4,055
Pingding-shan (PdS)	Zhao et al. (2010); Wang and Li (2008)	Feldspar, quartz	Grey	Coarse	Calcareous	2.35	–	3,279
Sichuan (ScS)	You and Kang (2009)	Feldspar, quartz	–	Fine	Argillaceous	2.44	5.7	4,784
Sandstone (SS)	Yin et al. (2011)	–	Greyish white	Very fine	Ferruginous	2.68	–	3,227
German								
Maulbronner (Ms)	Hajpál (2002)	Quartz	Reddish grey	Fine	Clayey	–	21.19	–
Pfinztaler (PS)	Hajpál (2002)	Quartz	Reddish	Fine	Ferruginous clayey	–	9.77	–
Postaer (PtS)	Hajpál (2002)	Quartz	Whitish yellow	Coarse	Siliceous-kaolinitic	–	22.79	–
Rohrschacher (RS)	Hajpál (2002)	Quartz	Grey	Fine	Calcareous	–	2.54	–

Table 2 Testing parameters of thermal treatment

Ref.	Heating rate (°C/min)	Constant temp. period (hour)	Cooling down ways	Maximum temp. achieved (°C)
Hajpál (2002)	[a]	1	F	900
Lan (2009)	5	1	F	800
Luo and Qin (2005)	10	1	F	1,200
Qin et al. (2009)	5–10	1	F	700
Wang and Li (2008); Zhao et al. (2010)	30	5	F	900
Wu and Liu (2008)	5	2	F	1,200
Yin et al. (2011)	3.33	4	F	800
You and Kang (2009)	[b]	1	A	600
Zhao et al. (2009)	[b]	2	A	600

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

[a] The heating procedure took 6 h to reach the maximum temperature

[b] The heating rate was fast but unknown

2.1 Mass, Volume and Bulk Density

When the treatment temperature is lower than 200°C, mass loss is generally caused by evaporation of the free water contained in the pore volume. Above 200°C, the main contributors to mass loss of sandstones after high temperature treatment are: (1) clay minerals, which loose absorbed water, hydroxyl and oxygen, and (2) carbonates and organic materials, which are disintegrated into oxides, carbon dioxide and water. You and Kang (2009) determined that mass loss of four tight ScS samples was about 1% after 200°C treatment and remained unchanged after 600°C treatment. Wang and Li (2008) found the average mass loss of PdS being below 1% after 900°C treatment.

In general, rock volume increases due to thermal expansion at high temperatures and is characterised by permanent elongation after cooling down (Somerton 1992). Wu and Liu (2008) found that the volume of JzS was almost unchanged below the treatment at 400°C, slightly increased from that to 800°C, and significantly increased by 3.51 and 24.06% after 1,000°C and 1,200°C treatment, respectively. Lan (2009) also obtained the volume of CzS increased by 3.82% after 800°C treatment.

Therefore, the effect of thermal treatment on bulk density includes two aspects: mass loss and volume variation. The more clay minerals, carbonates and organic materials are contained, the more mass losses occur. The volume of a rock always expands during high temperature treatment. The higher temperature a rock experiences, the larger the volume expansion will be. As shown in Fig. 1, bulk

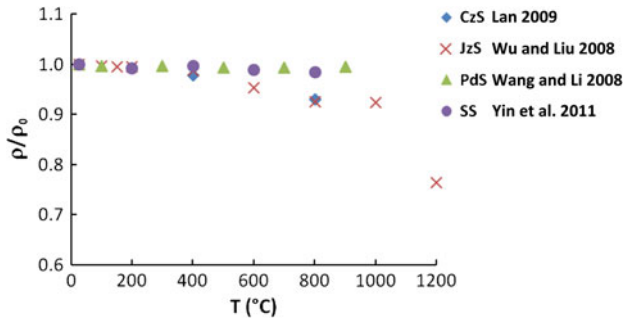

Fig. 1 Normalized bulk density as a function of treatment temperature

densities for the sandstones reviewed are almost unchanged (less than 2%) below 500°C treatment. But from that onwards, notable decreases for argillaceous (CzS) and carbonaceous sandstones (JzS) are observed.

2.2 Porosity

Porosity (Φ) of untreated sandstones varies in a large range from 0.7 to 34% (Fang 1991) due to different arrangement of grains and cementing compositions. After high temperature treatment, changes in porosity are either related to thermal expansion and changes of the micro-crack network, or driven by the structural damage of rocks (Hajpál and Török 2004). Figure 2 plots effective porosity (ScS) and total porosity (the other sandstones except ScS) at atmospheric conditions as functions of temperature. It is found that the general trend of normalized porosity is to increase with the increasing treatment temperature except for PtS (2% decrease at 200°C). The increment is small (<30%) below 300°C, but becomes significant from that onwards especially for rocks (GS, ScS and RS) with small initial porosities. The porosity of RS, not plotted in Fig. 2, increased by a factor of 9 after 900°C treatment. For the porosity variation with temperature, the initial porosity of sandstone plays a more important role, compared to the cementing materials.

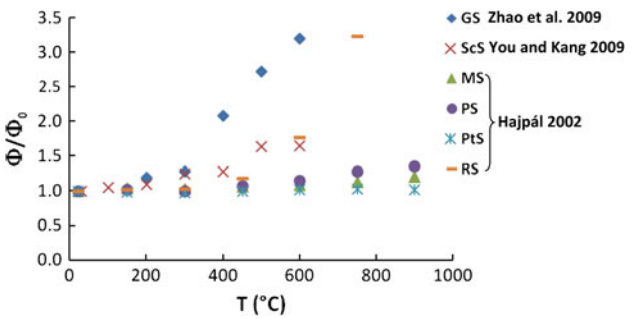

Fig. 2 Normalized porosity as a function of treatment temperature

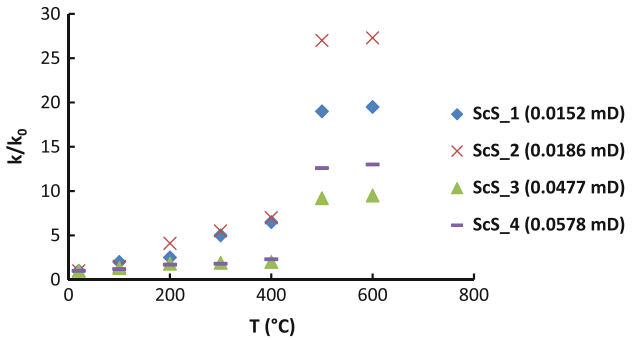

Fig. 3 Normalized permeability versus treatment temperature (data from You and Kang 2009)

2.3 Permeability

Experiments up to treatment temperatures of about 200°C from various authors (Aruna 1976; He and Yang 2005; You and Kang 2009; Dutton and Loucks 2010) show that the trend of permeability with increasing temperature is mixed. Thus the permeability after thermal treatment can increase, remain unchanged or decrease depending on the materials, the composition of the pore fluids and the experimental boundary conditions.

Figure 3 shows the results of four ScS with different initial permeabilities of 0.0152, 0.0186, 0.0477 and 0.0578 mD, respectively. An upward trend is observed, and a sharp increase takes place at the temperatures of 400 to 500°C.

2.4 Compressional Wave Velocity

It is generally accepted that the compressional wave velocities of rocks decrease with increasing temperature both under and after high temperature treatment (Somerton 1992). Normalized compressional wave velocities (V_P/V_{P0}) after different temperature treatment tested on dry samples are plotted in Fig. 4. Below 200°C treatment, V_P/V_{P0} increases very slightly (<1%) for GS and JzS, but decreases in most cases. From 200 to 800°C, a decreasing trend is observed for all the reviewed sandstones. V_P/V_{P0}

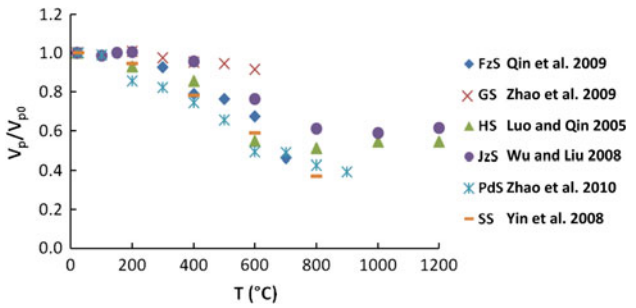

Fig. 4 Normalized compressional wave velocity versus treatment temperature

changes slightly at treatment temperatures above 800°C. You and Kang (2009) also observed the average compressional wave travel time of ScS after 600°C treatment increased by 1.68 times (velocity decrease by 40.5%).

3 Discussion

The original physical properties of sandstones vary in a wide range. After thermal treatment, upward tendencies of normalized porosity and permeability as well as a downward tendency of normalized compressional wave velocity were observed independent of sandstone composition and thermal treatment experienced. Small variations occur below 200°C treatment. In general, the increasing/decreasing rate of a physical index depends not only on the temperature a rock is exposed to, but also on the environmental conditions such as thermal treatment path, heating/cooling rate, temperature history, etc. However, the main mechanism of changes in physical properties of sandstones after thermal treatment is rock structural damage caused by mineral thermal expansion and thermal reactions.

3.1 Mineral Thermal Expansion

A rock is an assemblage of mineral grains. Even though the thermal expansion of rocks is relatively small in magnitude, the expansion behavior has significant effects on the structure of rocks. Differences in thermal-expansion characteristics of minerals can produce great thermal stresses inside the rocks. The maximum stress normally concentrates among the boundaries of mineral grains. If stresses reach or exceed the rock tensile/shear strength limits, new cracks will develop along the boundaries. Meanwhile, thermal stresses can also extend existing cracks resulting in irreversible rock structural damage. In addition, differences in thermal expansion along different crystallographic axes of the same mineral can also cause structural damage upon heating (Somerton 1992).

The volume expansion of quartz and mica is about four times higher than that of feldspars (Siegesmund et al. 2008). Therefore, sandstones mainly composed of quartz and/or feldspar and a certain amount of mica always show a sharp change in the range of 400 and 600°C on each curve of normalized physical indexes as functions of treatment temperature.

3.2 Mineral Thermal Reactions

During the process of thermal treatment, the thermal reactions related to sandstone-forming minerals are listed in Table 3. For clay-minerals, desorption reaction releases absorbed water between layers and in structural channels, while decomposition reaction makes bound water in the form of hydroxyl ions driven off. Thermal decomposition of calcite starting at 700°C follows the equation $CaCO_{3(s)} \rightarrow CaO_{(s)} + CO_{2(g)}$. Therefore, these factors play important roles on sandstone mass losses. The more such minerals a sandstone contains, the more mass loss occurs due to thermal treatment. Moreover, β-quartz will transform into β-quartz at 573°C, and the latter has higher volume compared to the former. Thus, the thermal reactions can also cause structural damage.

Table 3 Thermal reactions for several sandstone-forming minerals

Temp. range (°C)	Mineral	Reaction
25–220	Clay-minerals	Desorption
400–700	Clay-minerals	Decomposition
573	Quartz	α–β transition
700–830	Calcite	Decomposition

Source: Somerton (1992)

3.3 Pressure Effect

All the testing related to the present study was undertaken under atmospheric pressure conditions. However, in geotechnical engineering conditions, overburden pressure has great influence on rock behaviors, especially at great depths. Thus, the changes of physical properties of sandstones under in situ conditions are controlled by both temperature and pressure. In the authors' opinion pressure can suppress the changes caused by high temperature treatment. Therefore, more tests are required to determine the coupled effects of temperature and pressure on the physical properties of sandstones during exposure to high temperatures.

4 Conclusions

The data summarized in this manuscript are based on an extensive review of international literature, especially involving data from Chinese publications. These are expected to support researchers and engineers involved in analytical and numerical modelling of thermo-mechanical processes in sandstones. The following conclusions may be drawn on the basis of the reviewed publications.

The variations of bulk density for all sandstones reviewed are negligible (<1%) below 500°C treatment. However, a downward trend is observed above that treatment temperature for argillaceous and carbonaceous sandstones.

An upward trend of normalized porosity with increasing temperature is observed for all sandstones except PtS at

temperatures below 300°C. This increment is small (<30%) below 300°C treatment, but from that onwards becomes significant for sandstones with small initial porosities.

Normalized permeability always increases with increasing temperature for all the reviewed sandstones. However, mixed trends exist below 200°C treatment.

A downward trend in normalized compressional wave velocity is observed. The variation may be very small below 200°C treatment. From that to 800°C, V_P/V_{P0} decreases with increasing temperature in a nearly linear fashion, and exhibits a slightly mixed variation above 800°C.

Therefore, the physical properties of sandstones after high temperature treatment change indeed compared to those at room temperature. The variations can be too small to be neglected after thermal treatment in the order of 100–200°C, but normally becomes significant above 400 or 500°C treatment.

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