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Experimental investigation of thermomechanical behaviour of clay-rich sandstone at extreme temperatures followed by cooling treatments

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ABSTRACT

The aim of this study is to investigate the influence of extreme temperatures (from 25° to 1000°C) followed by two cooling methods (both rapid and slow) on the mechanical behaviour of clay-rich Hawkesbury sandstone under uniaxial conditions. A separate set of samples was tested under continuous heating conditions without cooling to compare the results with those for cooled samples. The stress-strain behaviours were analysed, with simultaneous recording of the acoustic signals and the failure mode. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) analyses were also performed to understand the changes observed in the mechanical tests. According to the results, the mechanical, mineralogical and microstructural characteristics of clay-rich sandstones are largely dependent on the thermal field, and, regardless of the cooling method, the compressive strength, Young's modulus, crack initiation stress and crack damage stress appear to increase when the preheating temperature increase from 25 °C to 600 °C and decrease with increasing preheating temperature for temperatures greater than 600 °C. The SEM results confirmed the transformation of the initial hexagonal kaolinite mineral structure into a fibre-like (needle-type) mineral structure, which is believed to be the reason for the strengthening phenomenon observed at preheated temperatures between 25 °C and 600 °C. Progressive dehydroxylisation of kaolinite in the sandstone cement at temperatures beyond 600 °C was found to be the main reason for the weakening and softening of the sandstone which was observed with increasing preheated temperature beyond 600 °C. Apart from these mineral degradations, induced inter-granular and intra-granular cracks at preheated temperatures beyond 600 °C also play a dominant role in the weakening of clay-rich sandstone.

1. Introduction

Underground coal gasification (UCG) is a promising means for the conversion of the world's coal resources into energy, and therefore has attractive economics.[1] Generally, the UCG process takes place in very deep coal seams (600–1200 m), which are bounded by permeable sedimentary rocks (mainly sandstone and siltstone). According to Bhutto et al.[2], continuous and stable production in UCG is highly dependent on the temperature field in the underground gasifier. Under the pure oxygen gasification condition, the average temperature rate rise of a gasified coal seam is around 4.15 °C/h and the highest temperature in the oxidation zone is about 1300 °C.[3] Such high temperature conditions not only gasify the coal seam, but also cause the surrounding rock mass morphology to be significantly altered, causing dramatic changes in the physical and mechanical properties of the surrounding rock body. As a result, the surrounding rock's corresponding physical and mechanical properties are no longer constants, but functions of temperature. Therefore, one risk associated with this process is thermally-induced mechanical failure of the surrounding sedimentary formation due to the associated extreme temperature conditions. In addition, the rate of cooling is also important when considering the physical and mechanical behaviours of the surrounding rock mass. The success of UCG projects is heavily reliant on the long-term integrity of the surrounding sedimentary rocks and will cease the spread of high temperatures into the atmosphere.

The thermally-induced mechanical damage that occurs in surrounding sedimentary formations during the UCG process is highly dependent on the distance from the gasified coal seam, as the temperature gradient varies with that distance. During long-term UCG, the sedimentary rocks adjacent to the coal seam experience extreme

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temperature conditions (approximately 600–1300 °C). However, the temperature gradient decreases with increasing distance from the gasified coal seam. There are differently heated rock masses in the coal seam during the UCG process, which can be basically divided into three thermal processes: a continuous heating region without cooling; an extreme temperature region with thermal shock; and a low temperature region with slow cooling conditions. These processes lead to changes in the physical and mechanical characteristics of the surrounding rock mass and consequently create temperature-dependent reservoir deformations, micro-cracking and dilation, which significantly affect the long-term integrity of the UCG process. Most importantly, these can have significant environmental consequences, such as ground uplift or heave, earthquakes and gas/steam leaks.[4,5] Therefore, it is of utmost importance to know the physical and mechanical behaviours of this kind of formation with different high temperatures and cooling rates.

Studies of the extreme temperature-induced mechanical behaviour of sedimentary rocks can be categorised into two types, based on the method adopted for the testing. In most previous studies,[6–9] the tests were conducted at a target temperature (continuous heating) under uniaxial compression. However, an aspect to be considered is the effect of confining stress on thermal cracking. Siddiqi and Evans[10] observed little effect on heated samples when high confining pressure was applied. Fig. 1 summarises the previous works carried out on the variation of uniaxial compressive strength of sedimentary rocks under various temperature conditions (continuous heating). As Fig. 1 indicates, the strength alterations of sandstone with increasing temperature show opposite trends in the cited studies. According to Vilarrasa et al.[11], this may be due to the different clay contents in the rock mineral structure, since the strength of clay-rich geometries tends to decrease with increasing temperature. The other important testing method when considering the physical and mechanical behaviours of sedimentary rocks is the influence of the high temperature followed by cooling. However, there is a still lack of knowledge related to this particular area. A small number of experimental studies[12,13] have set out to identify the combined temperature and cooling effects on the mechanical characteristics of sedimentary rocks, but the research is limited to low-temperature effects (only up to 600 °C), revealing nothing about the mechanical behaviour of the surrounding rock mass in the long-term UCG process where the general sub-surface temperature is more than 600 °C. Moreover, no data are available on the mineralogical and microstructural behaviours of sandstone under extreme temperatures followed by cooling treatments. This is a serious gap in our knowledge. Therefore, this research aims to address these gaps by providing a new dataset to improve the scientific understanding of the mineralogical, microstructural and mechanical processes that occur in surrounding sedimentary rocks during the UCG process.

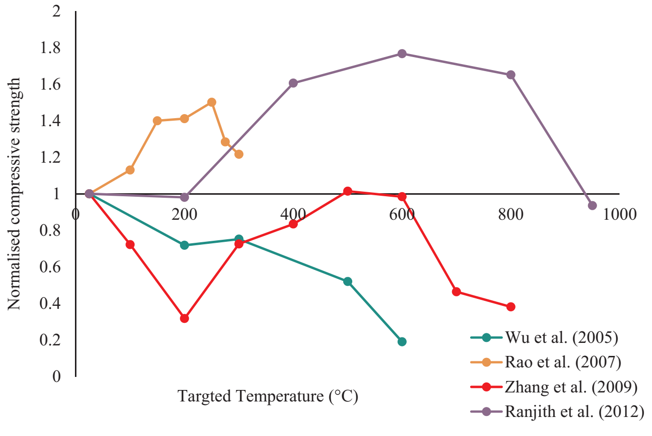

Fig. 1. Summary of compressive strength variation of sandstone with test temperature reported in the literature.

2. Materials and methods

2.1. Sandstone origin, mineralogy and engineering properties

The sandstone samples were collected from the Gosford Basin in New South Wales, Australia. The sandstone unit in the Gosford Basin is commonly known as "Hawkesbury sandstone" and belongs to the early Triassic age.[14,15] Based on microscopic observations, the sandstone samples can be considered as rather homogeneous, as the grain size varies between 0.01 and 1.0 mm within a predominantly argillaceous matrix (which can be considered as medium-coarse grained). The sandstone selected for the thermo-mechanical testing mainly consists of quartz, kaolinite, siderite, barite and calcite, and according to the XRD results, the mineral composition of the sandstone is 74% quartz, 12% kaolinite, 7% siderite, 4% barite, 2% calcite, < 1% smectite, and < 1% mica. The Hawkesbury sandstone used for this study has a porosity of 14% (from water absorption tests) and a bulk density of 2300 kg/m^3. The compressive strength, Young's modulus and Poisson's ratio for the Hawkesbury sandstone at room temperature is in the range of 35–50 MPa, 4–7 GPa and 0.2–0.35, respectively.

2.2. Specimen preparation and heating process followed by cooling

The sandstone samples were cored and cut using diamond coring and cutting devices to obtain cylindrical specimens 36 mm in diameter and 76 mm in length. Both ends of the specimen were then carefully ground using a face grinder to produce two perfectly smooth faces. To install thermal couples, sample centres were drilled up to mid-depth using a 1.6 mm drill bit and a ceramic paste was applied to ensure full contact between the probe tip and the specimen. For each condition, four replicates were used and the average values were taken for discussion purposes.

The rock sample heating process was carried out in a high-temperature oven (maximum temperature 1500 °C). The temperatures selected for the testing were 200, 400, 600, 800, and 1000 °C (The temperatures selected simulated the range of temperature conditions likely to be encountered in the UCG process) and the target testing temperature was reached using a modest heating rate of 5 °C/min to minimise thermal shock and the development of stress fractures during the heating process. In order to obtain the desired temperatures, specimens were tested with industrial calibrated high-temperature thermal couples installed to detect surface and inside temperature changes. After attaining the prescribed temperature, the samples were kept in the oven for 24 h and then cooled in two different ways: air cooling (slow cooling) at laboratory temperature and water immersion (quenching) at laboratory temperature in a 20 l vessel, in order to investigate the influence of the temperature followed by cooling method on the mechanical properties of the rock mass. Table 1 illustrates typical temperature changes of the surfaces and inside of the specimens after cooling treatments. To remove the water saturation effect, the quenched specimens were oven-dried at 60 °C for 24 h prior to the mechanical testing. The oven drying procedure was carried out to check the pure temperature followed by the cooling effect on compressive strength. In real field conditions rocks are fluid-saturated, but this drying process may occur in reservoirs due to seasonal changes of the water table.

2.3. Experimental methodology for uniaxial compressive strength testing

First, comprehensive uniaxial compressive strength tests were carried out on the heated samples after cooling treatments to quantify the influences of high temperatures followed by cooling methods on the mechanical behaviour of rock masses, following the specifications outlined in the ASTM standards.[16] A Shimadzu AG 9 compression machine (Fig. 2(a)) with a maximum compression load capacity of 300 kN was utilised to perform the uniaxial compressive strength tests,