Construction and Building Materials 168 (2018) 346–361

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Studying the acoustic emission response of an Indian monumental sandstone under varying temperatures and strains

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HIGHLIGHTS

- Mechanical properties of the rock are susceptible to temperature and strain rate.
- Strength and elastic properties increase till 400–600 °C and then decrease.
- Strength decreases at high strain rates due to the onset of plasticity.
- Acoustic emission helps in demarcating the stress thresholds and regimes.
- Crack initiation and damage thresholds are affected by temperature and strain rate.

ARTICLE INFO

Article history:
Received 24 May 2017
Received in revised form 15 February 2018
Accepted 22 February 2018

Keywords:
Sandstone
Thermal treatment
Strain rate
Acoustic emission
Microcracks
Fire

ABSTRACT

Study of rocks under high temperature and strain-rate condition can serve as vital information in the restoration process of fire damaged buildings. In this study, the mechanical response of thermally treated fine-grained Dholpur sandstone was observed under increasing strain rates. Dholpur sandstone, a popular construction material, has been used to build some of the iconic monuments in India, a list which includes the Parliament, House of Indian President and the Buddhist Stupas of Sanchi. Thermal treatment spanned across ten days which included heating of the samples (200, 400, 600, 800 and 1000 °C) for five days followed by cooling, in room condition, for the exact same duration. The samples were then tested to failure at three different strain rates (2×10^{-5}, 1×10^{-4} and $2 \times 10^{-4}\ S^{-1}$). The elastic modulus was measured using non-contact laser extensometer. Acoustic emission (AE) technique was used to observe the microcrack development under compressive loading. The results from AE were used to demarcate the various stress thresholds and the stress regimes. The result of the experimental analysis suggests that the strength and elastic properties of rocks tend to increase till 400–600 °C followed by a fall in the mechanical characteristics. Onset of plasticity can be observed at high temperature. Strength of the rocks decrease at high strain rates due to the influence of strain rate dependency. The threshold values follow the behaviour of the mechanical properties under the influence of temperature and strain rate.

1. Introduction

Before the era of modern construction materials, rocks and dimensional stones were extensively and widely used in constructing most of the buildings and monuments. Some of the most iconic structures in India and around the world have been constructed using rocks belonging to either igneous, sedimentary and metamorphic rock types. Since several of these structures are included in the list of UNESCO World Heritage site, the protocols for preservation and restoration have been constantly updated in order to maintain their structural integrity and aesthetic appeal. While voluminous studies have been conducted on the effect of environment and pollution, the research on restoration process of fire damaged buildings is relatively nascent and needs further enhancements [1–7].

So far, the research on fire-damage buildings have been primarily focussed on European rocks, with very little research on the Indian granites and basalts [8–14]. In the event of fire, a building structure endures several thermal and mechanical stresses which arise due to the alterations which occur within the rock lattice. Several chemical and physical changes are triggered when a rock

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https://doi.org/10.1016/j.conbuildmat.2018.02.180
0950-0618/

is subjected to thermal treatment (Tables 1 and 2). As studied by Clark [15] and Somerton [16], these chemical and physical changes subsequently alter the mineralogical and morphological features of a rock. Anisotropic thermal expansion of rock-forming minerals is one of the critical phenomena that alters the nature and volume of pores and microcracks within a rock specimen. Besides anisotropy, rock specimens that are rich in quartz experiences the phenomenon of quartz inversion that occurs at temperatures near about 573 °C. Due to the difference in the densities of low (α) and high (ß) quartz, the quartz inversion is associated with a volumetric increase of ~2.0% and a linear expansion of 0.7% [17–19]. It should however be noted that the effect of quartz inversion on the rock morphology is completely reversible, provided the sample is cooled at a slow rate.

In the case of failure of any part of the structure, the stresses are redistributed, which may cause the other parts of the building to endure higher strains. Therefore, the current study focuses on the effect of heat and strain rate on the geomechanical response of rocks. The study can find application in fields which encounter the thermal interaction of rocks. Many energy recovery processes such as underground coal gasification (UCG) involve the exposure of rocks to very high temperature conditions for long periods of time (>1000 °C) [20–22]. Microcracks stimulate deterioration by upsetting the internal morphology subsequently altering the physical and mechanical properties of the host rock [23–27]. Since host rocks govern the operational efficiency, stability and sustainability of a UCG project, it is imperative to study the cumulative effect of varying temperatures and loads on the mechanical behaviour of rocks.

While analysing the effects of strain rate on the geomechanical behaviour of Chunar sandstone, Singh et al. [28] reported a monotonic increase in compressive strength and elastic modulus when the strain rate was increased from 10^{-5}/s to 10^{1}/s. The phenomenon was attributed to the strengthening effect brought about at increasing loading rates. Under the influence of strengthening, a larger amount of energy is utilised in breaking the rock. Although the phenomenon of strengthening has been reported for rocks of various lithology, studies conducted by Blanton and Shockey suggest that rocks can display little to no change in strengths at varying strain rates [29–34]. This may be attributed to the difference in the mineralogy and internal arrangement of the rock, which bear an effect on the magnitude and nature of strengthening [35–37].

In their study, Wasantha et al. [38] conducted unconfined compression tests on sandstone of varying grain sizes, at strain rates varying from 10^{-6}/s to 10^{-3}/s. The tests which were performed on fine-grained 'FG' sandstone samples collected from the Perth, Australia and on medium 'MG' and coarse 'CG' grained sandstone samples collected from the Sydney, Australia suggested the dependence of peak strength and the elastic modulus on the loading rate. Although the FG and MG specimens have a non-linear and linear relationship with strain rate, respectively, the effect of increasing strain rate on CG specimen was chaotic and disorderly in nature. The disparity in behaviour is highlighted by the phenomenon and nature of microcracking which occur during the compressive loading. The inherent microcracks present within the rock lattice structure can either close or extend depending on their location. Together with the changes occurring in the inherent microcracks, the formation and coalescence of newly generated microcracks sum up the phenomenon of microcracking.

Table 1
Thermal expansion of various minerals (modified after Clark, 1966 [15]).

Mineral	Axis*	Percent Expansion from 20 °C to			
		100 °C	200 °C	400 °C	600 °C
Quartz	⊥c	0.14	0.3	0.73	1.75
	‖c	0.08	0.18	0.43	1.02
Orthoclase	‖a	0.05	0.14	0.48	0.9
	‖b	0	0.1	0.04	0.13
	⊥001	0	0.005	0.065	0.155
Plagioclase	‖a	0.09	0.22	0.5	0.83
	⊥010	0.03	0.06	0.16	0.29
Calcite	⊥c	0.19	0.48	1.12	1.82
	‖c	−0.04	−0.1	−0.18	−0.22
Hornblende	⊥100	0.05	0.12	0.29	0.48
	‖b	0.06	0.17	0.39	0.64
	‖c	0.05	0.13	0.29	0.46

* ⊥ = perpendicular to, ‖ = parallel to.

Table 2
Key Thermal Reaction occurring in a rock (modified after Somerton, 1992 [16]).

Temperature Range (°C)	Mineral	Reaction
25–220	Clay Minerals	Desorption
400–723	Clay Minerals	Decomposition
573	Quartz	α–ß transition
700–830	Carbonate	Decomposition
790–908	Clay Minerals	Decomposition

In order to investigate the combined effect of temperature and strain rate on the mechanical properties, Tang et al. [39] performed experimental analysis on the samples of Xuzhou limestone at 700 °C for the strain rates ranging from 1.1×10^{-5}/s to 1.1×10^{-1}/s. They reported an increase in the values of peak strength, peak strain and elastic modulus between 1.1×10^{-5}/s to 1.1×10^{-4}/s followed by monotonic decrease. The degradation in the mechanical properties was attributed to the thermal damage endured by the samples which resulted into the formation of microcracks. While shear failure was observed in the specimens tested at the slowest strain rate, formation of cones and crushed zones were reported for the samples tested at rates greater than 1.1×10^{-4}/s. Since the tests were conducted at only one temperature (700 °C), it is rather difficult to understand and comment on the exact nature of failure with variable temperature.

On the other hand, specimens of Xuzhou mudstone were tested under high temperature conditions (25, 200 and 400 °C) at increasing loading rates (0.003, 0.03, 0.3 and 3 mm/s) [40]. When tested at room temperature, an initial decrease in the peak strength and the elastic modulus was observed between loading rates of 0.003 and 0.03 mm/s. At rates above 0.03 mm/s, the rock regained its strength, and the values of elastic modulus and the strength at 3 mm/s were similar to that at 0.003 mm/s. This however, was not true for the samples tested at 200 and 400 °C and the value decrease monotonically with increase in loading rate. Although higher loading rates highlighted the mudstone's stiffness and its resistance to failure at room temperature, microcracking at high temperatures drastically reduced its stiffness thereby, accelerating the deformation of the specimen. Additionally, a detailed study of the tested samples revealed that the combined influence temperature and faster loading rates stimulated the growth of microcracks which led to the crushing and fragmentation.

In the case of sandstone, Su et al. [41] tested the thermally treated specimens to understand the behaviour of rock under tensile loading. Having been treated at temperatures between 200 and 800 °C, the samples were tested at six strain rates varying between 3.3×10^{-6}/s to 3.3×10^{-3}/s. At the slowest strain rate (3.3×10^{-6}/s), maximum tensile strength was obtained at 400 °C. Besides observing similar trend, increase from 25 to 400 °C followed by a decrease, for all the higher strain rates, a regular increase in tensile strength with increasing strain rates was also noticed. It was also seen that, higher strain rates assisted microcracking almost all