SSIM 2023 – PM Dight (ed.)

doi:10.36487/ACG_repo/2335_23

Tensile strength of Hawkesbury sandstone exposed to high temperatures: considerations for exposed mine batters

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Abstract

Infrastructure projects and mine site haul roads both often use heavy machinery transport. These high-powered machines are nearly always powered by fuel sources that are highly combustible and pose a fire risk to the surrounding rock structures. This scenario can also be seen in open pit coal mines where batters have the potential to combust spontaneously and are therefore exposed to high temperatures. This research aims to investigate the effects of exposure to high temperatures due to fires on the tensile strength of Hawkesbury sandstone by subjecting them to peak temperatures of 1,100°C – similar to the peak temperature of the hydrocarbon fire curves. The results of the Brazilian tensile strength test showed a 60% reduction in tensile strength due to high temperature exposure and less brittle characteristics when heated compared to untreated samples. The findings of this study can provide an initial understanding to slope stability assessments for fire-resilient slope design.

Keywords: *tensile strength, sandstone, high temperature, slope stability*

1 Introduction

Rocks undergo marked alterations in mechanical properties following exposure to extreme temperatures. In the context of open pit mines and transport roads, where minimising cut-and-fill is paramount, the resulting hauling and transport roads – typically subjected to heavy loads, constructed to a minimal width, and carrying large volumes of fuel on petroleum-based tyres – introduce the potential for fire hazards. These hazards include the threat of spontaneous combustion within batters – particularly pertinent to open pit coal mines.

The risk of fire isn't limited to transporting what is understood as traditionally flammable materials. A review by Larsson (2006) on rock tunnel fires found that most heavy vehicles in civil transport weren't carrying dangerous goods, yet resulting fires were as impactful as those from fuel tankers. Smith & Pells (2008) used a brick-lined charcoal furnace on exposed sandstone to investigate heat treatment's impact on tunnel fires. Heat treatments between 250 and 950°C for two and four hours revealed strength reduction with rising temperatures. While tunnel environments differ, open pit haul trucks pose risks, including tyre fires sparked by various causes. Although interventions aim to extinguish fires, this isn't always applied in a consistent manner, and extended exposure to elevated temperatures remains a concern.

Further exploration by Smith & Pells (2009) involved a truck crash into a 40 m high exposed batter on a highway in Sydney, Australia. The ignited vehicle was 1 m from the sandstone batter, with flames reaching 15 m from the ground. After 22 minutes of uncontrolled flames, firefighters arrived at the scene. Scorch marks and rock spalling were evident on the batter, and observations indicated saturated pre-split drill holes with visible steam rising from the drill holes, hinting at prolonged heat absorption and retention in the batter beyond the period with flames, potentially weakening the rock structure even further.

Promat (2020) presents a list of fire curves collating rapid heating rates from different sources, showing varied modelling techniques to simulate different types of fires. The heating rates of these curves are rapid and non-linear in most cases, with peak temperatures reaching well above 1,000°C. Existing experimental studies focus on how heating alters rock properties but often target lower peak temperatures than those reached by fires in the Promat list. Ranjith et al. (2012) tested Hawkesbury sandstone samples between 25 and 950°C at a linear 5°C/min rate, showing an increased uniaxial compressive strength (UCS) up to 600°C, then a decrease. Wei et al. (2019) reported similar findings, heating at 10°C/min up to 1,000°C, with UCS increased up to 500°C and subsequent mechanical decline. Brotóns et al. (2013) heated a calcarenite to 600°C at 10°C/min, then intervened with post-test cooling, showing an additional 15% UCS reduction due to thermal shock created by water cooling.

Yavuz et al. (2009) studied carbonate rocks heated up to a peak temperature of 500°C, with varying durations at the peak temperature. A range of 1–6 days showed the most change within the first 24 hours, then negligible strength variations from 1–6 days, demonstrating the significance of factors in assessing heat treatment effects. Li et al. (2020) found no significant change in tensile strength for Sichuan sandstone heated to 600°C at a rate of 5°C/min but decreased elastic modulus. Peak temperatures were maintained for an hour and led to dihydroxylation of the clay, showing a chemical composition change while maintaining unchanged mechanical properties.

Mine fires and spontaneous combustion coal mines is another example where rocks could be exposed to extreme temperatures where the neighbouring sedimentary strata are directly subject to fire in coal seams. The resulting weakening in these strata may lead to slope failures and collapses. In 2014, the Hazelwood coal mine in Victoria, Australia, experienced a mine fire ignited by a nearby grass fire, resulting in a 45-day-long battle with over 500 firefighters engaged at any given time (Reisen et al. 2017). A comparable scenario is reported in Ozcelik (2023) where a fire has been burning for more than 10 years in Bengiler, Turkey, and resulted in the closure of the mine; geological faults frequently run parallel to the vein direction, leading to crushed coal near the faults. Both the Hazelwood mine fire and the insights from Bengiler reveal a complex interplay between fire propagation, geological features and reactive measures; all of which risk lengthy fires that would impact the adjacent rock structures even with successful and timely firefighting intervention.

This study used Hawkesbury sandstone specimens from the Sydney Basin, Australia, and heated to 1,100°C at a rate of 2°C/min, to investigate the extreme high temperature exposure's impact on indirect tensile strength. The aim is to provide practitioners with important firsthand data for the design of rock structures.

2 Experimental method

2.1 Material and sample preparation

Cylindrical samples were cored at a diameter of 50 mm and cut to a length of 25 mm to satisfy the sample dimension requirements of the American Society for Testing and Materials (ASTM) standards for tensile strength determination (ASTM International 2001). Three replicates were prepared for testing under untreated conditions and heat-treated conditions. Sample preparation was performed at the Rock Mechanics Laboratory of Victoria University, Melbourne, Australia.

2.2 Heat treatment

Heat treatment was performed with a muffle furnace at the Werribee campus of Victoria University. A linear heating rate of 2°C/min was used to heat the specimens to a peak temperature of 1,100°C, which was maintained for an hour before the furnace was turned off with no intervention for cooling. Samples were tested after returning to room temperature of ~25°C.

2.3 Brazilian tensile strength testing

The deformation characteristics of specimens during loading were studied using the digital image correlation technique. Therefore, the specimen surface was first painted white, followed by a random speckle pattern using black paint. The complete loading duration was video recorded using a 48-megapixel camera for post-testing analyses of strain/damage evolution behaviour during loading by tracking the movement of the black speckles. A typical specimen prepared in this manner is shown in Figure 1.

Figure 1 The arrangement of a typical specimen set up for testing

Brazilian tensile strength testing was undertaken at the Rock Mechanics Laboratory of Victoria University following the guidelines of ASTM standards (ASTM International 2001). The failure of samples was achieved between 1–10 minutes, accordingly. The measured peak axial load was converted to a tensile strength using Equation 1.

$$\sigma_t = 2P/\pi LD \tag{1}$$

where:

P = load at failure (N).

D = diameter of test specimen (mm).

L = thickness of the test specimen measured at the centre (mm).

2.4 Digital image correlation analysis

Digital image correlation (DIC) analysis was performed using Ncorr v1.2 (Ncorr 2017), a MATLAB-based open-source program. The footage was cropped to start as the load was applied and finish as the first cracks appeared, deemed a tensile failure. The video was converted into 50 images to explore the damage evolution characteristics. These images were then processed through Ncorr, which provided surficial strain distributions on specimens using the Green–Lagrangian method.

2.5 Mineralogy analysis using X-ray diffraction

X-ray diffraction (XRD) testing was conducted on both untreated and heated specimens. These tests aimed to analyse the changes in mineralogy due to exposure to extreme high temperatures. All XRD testing was completed at the Materials Characterisation and Fabrication Platform at the University of Melbourne.

3 Results and discussion

3.1 Tensile testing

The indirect tensile testing results demonstrate an evident decrease in peak load, as depicted in Figure 2. The calculated average tensile strength for the untreated samples stood at 2.5 MPa, while the treated samples had an average of 1.0 MPa, as shown in Table 1, indicating a substantial 60% reduction. The findings align with existing heat treatment research, in which treatments past 400–600°C, irrespective of heating rate, consistently lead to diminished rock strength.

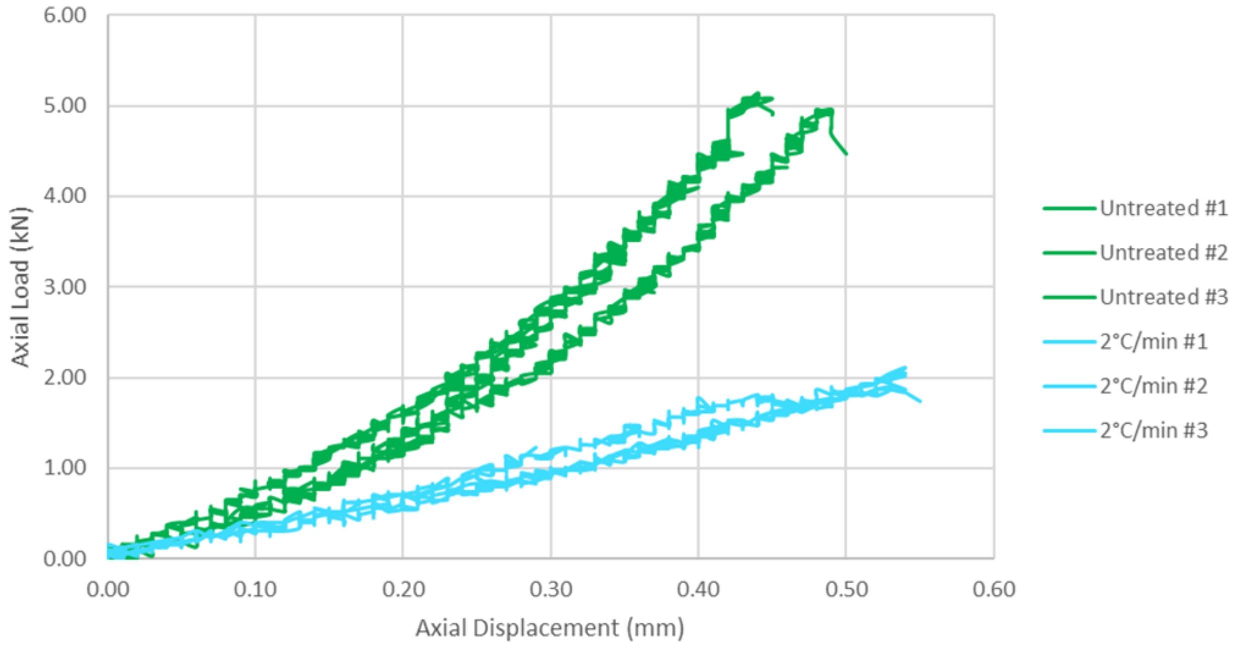

Figure 2 Axial load versus axial displacement curves for tested untreated and heated specimens

Table 1 Tensile strengths (MPa) calculated for each specimen

Untreated sample #1	Untreated sample #2	Untreated sample #1	2°C/min sample #1	2°C/min sample #2	2°C/min sample #3
2.53	2.62	2.34	**0.92**	**1.07**	**0.98**
	Average	2.49		Average	**0.99**

In aggregate, the strength testing outcomes indicate a reduction in strength coupled with heightened strain capacity post heat treatment. This implies that the sandstone exhibits increased elasticity and, potentially, a lower modulus following the heat treatment.

Acknowledging the limitations of this research, the sample size warrants careful generalisation. Sandstone's mechanical and chemical properties will change between sites, and the heat treatment tested is dissimilar to realistic fire events. Spontaneous combustion and tyre fires will have varied heating rates – likely much quicker than a linear 2°C/min – and the peak temperature will depend on the material igniting. Extrapolating these findings to slope stability will need to consider how heat was transferred to exposed rock mass and does not capture the depth this is to apply to. Further research is needed to understand how deep the heat treatment would penetrate the surface, the duration of the heat and the intervention used, which may risk thermal shock.

3.2 Digital image correlation

In the DIC analysis, the movements of black speckles with increased loading are tracked to determine the strain in horizontal and vertical directions.

The typical deformation evolution characteristics with increased loading (at 0, 20, 40, 60, 80 and 100% of the peak load) of an untreated and heated specimen are shown in Figures 3–6. According to Figure 3, it is clear that the horizontal strains are small and pervasive until beyond 80% of the peak load. A clear high-strain localisation zone, resembling the tensile fracture, can be seen at the peak load (i.e. 100% case). This indicates a more brittle behaviour of untreated specimens where the failure fracture develops rather suddenly – very close to the peak load. The vertical stress distributions of Figure 4 support these observations, where a high-strain zone surrounding the tensile fracture due to vertical compression is only visible after 80% of the peak load; although this is not as pronounced as horizontal strains in Figure 3.

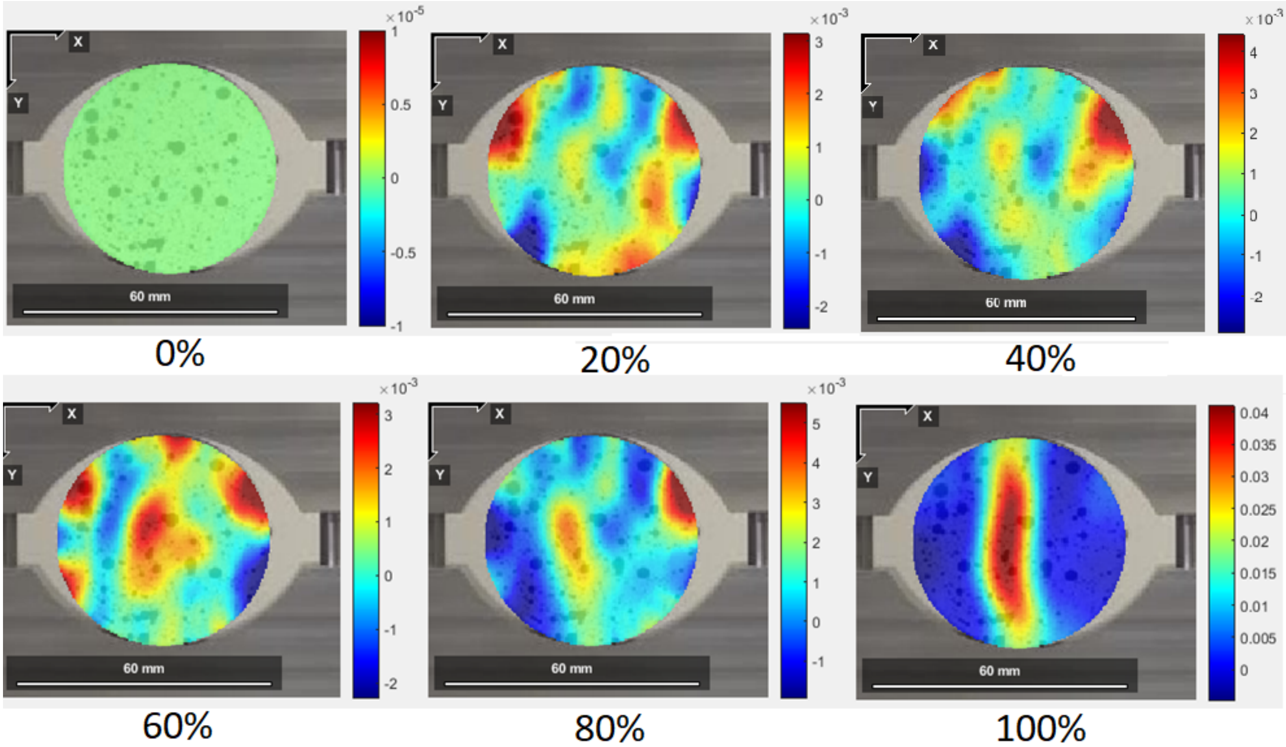

Figure 3 Progressive horizontal strain (Exx) distribution patterns of untreated specimen #1

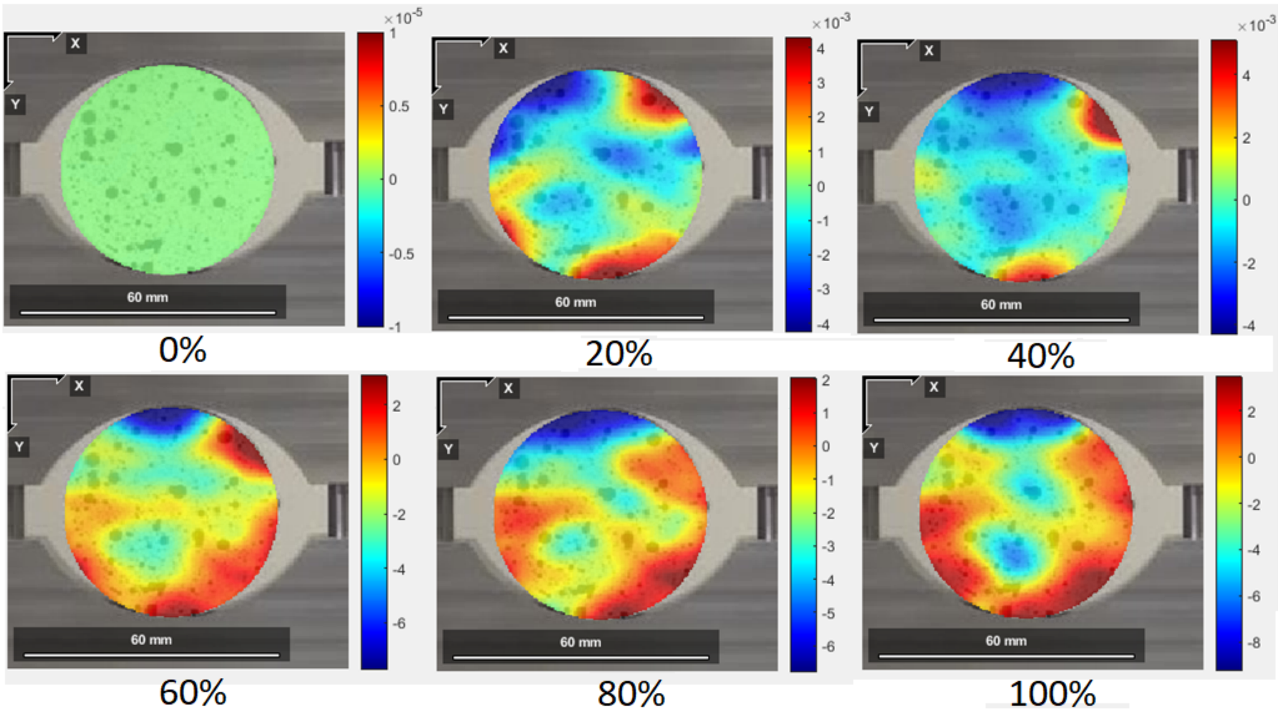

Figure 4 Progressive vertical strain (Eyy) distribution patterns of untreated specimen #1

The horizontal strain distributions of heated specimens, as shown in Figure 5, indicate that the strain localisation surrounding the impending primary tensile fracture begins at around 60% of the peak load; much earlier than the untreated specimen case in Figure 3. This can be viewed as the material becoming less brittle, as evidenced by the axial load–axial displacement curves in Figure 2. The vertical strain distributions of

Figure 6 are also supportive of this trend despite not being as consistent as horizontal strain distributions. In addition, the strain distributions at failure demonstrate that the strains of heated specimens are approximately twice those of the untreated specimens for both Exx and Eyy. This observation is in agreement with the greater strain capacity of heated specimens, as observed in Figure 2.

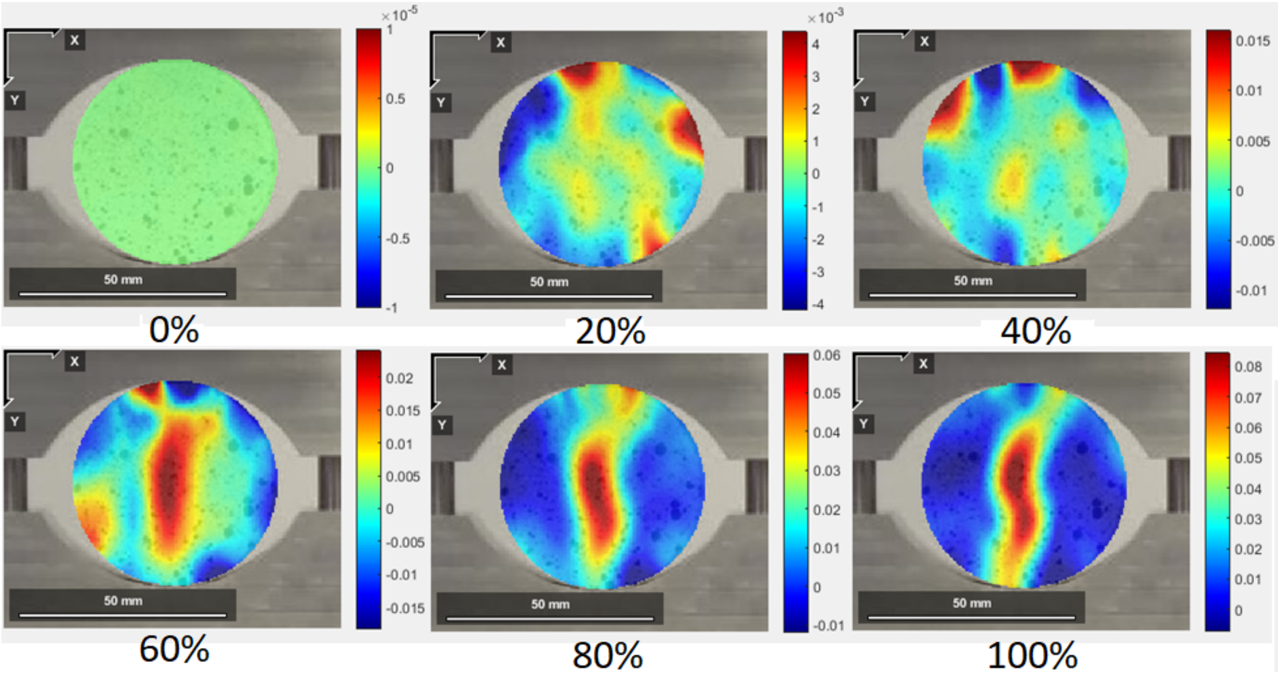

Figure 5 Progressive horizontal strain (Exx) distribution patterns of heated specimen #3

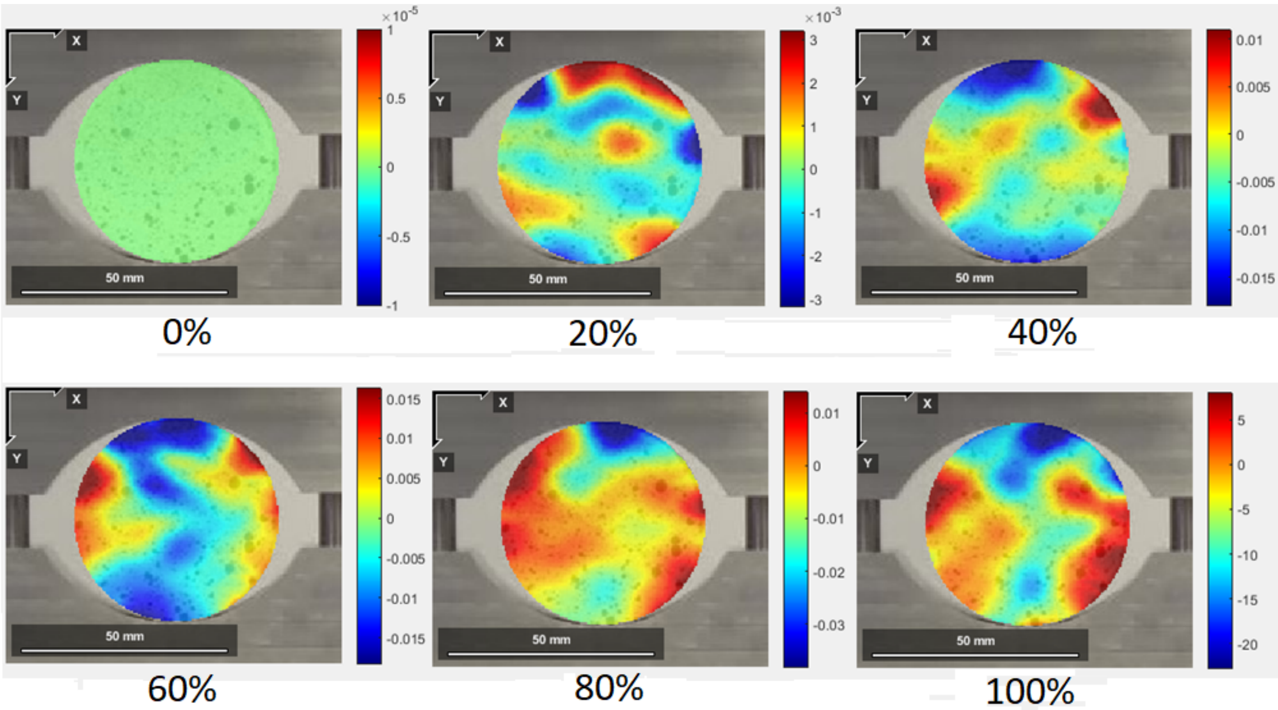

Figure 6 Progressive vertical strain (Eyy) distribution patterns of heated specimen #3

3.3 Mineralogy analysis using XRD

XRD analysis was conducted to capture any potential mineralogical changes arising from the heat-treating process. The mineral compositions of untreated and heated specimens after XRD analyses are shown in Figures 7 and 8, respectively. The XRD results show a potential trend in crystallinity percentage and quartz content percentage, as outlined in Table 2. With sandstone being a clastic sedimentary rock, it is unsurprising to observe a high percentage of quartz as SiO_2, with small amounts of clay likely being present. According to the results, the heat treatment has markedly increased the quartz content in the sandstone while reducing their crystallinity. Additionally, the identification of copper, titanium and manganese in the analysed specimens can be attributed to the contamination from black and white paint during the laboratory testing process for DIC analysis.

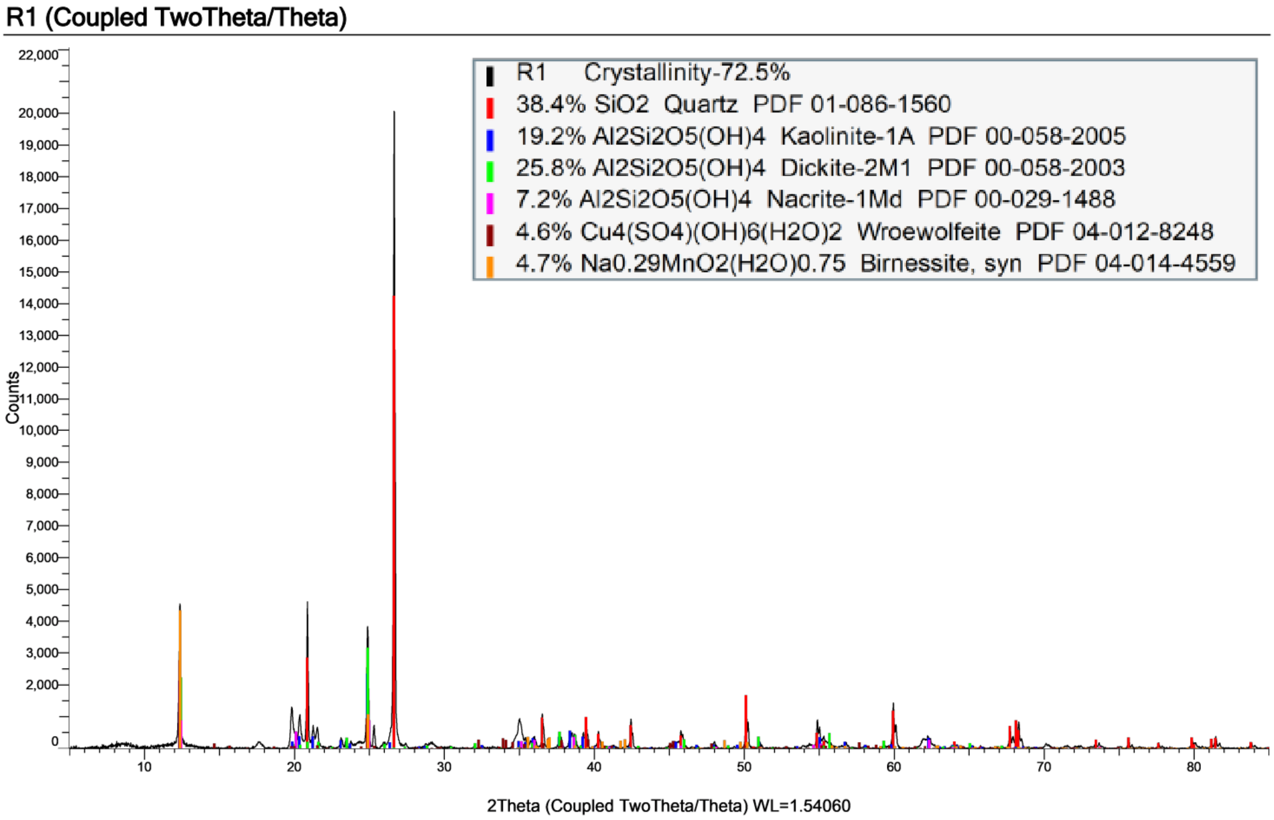

Figure 7 Mineralogical composition of untreated Hawkesbury sandstone

Table 2 XRD test results comparison between untreated and heated specimens

Heating scenario	Peak temperature	Crystallinity	Quartz
Untreated	25°C	72.5%	38.4%
Heated at 2°C/min	1,100°C	67.2%	64.1%

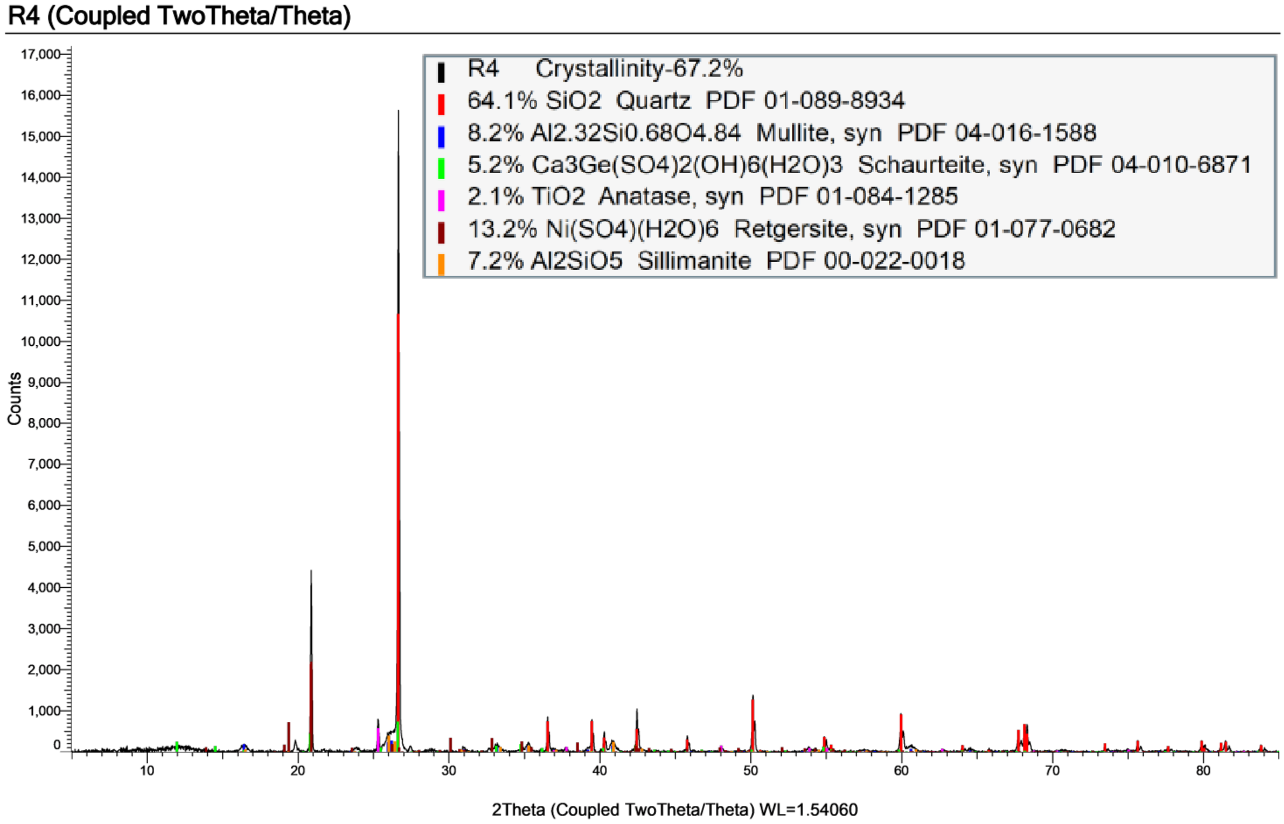

Figure 8 Mineralogical composition of heated Hawkesbury sandstone

4 Conclusion

This study investigated the impact of high temperature exposure on the tensile strength of Hawkesbury sandstone, after heating to 1,100°C at a rate of 2°C/min. The research presents some preliminary data for slope stability assessments and the design of fire-resilient rock structures, particularly relevant to open pit mines and transport roads where these rock structures can be exposed to fire due to various reasons.

The key findings were:

- Tensile strength reductions from 2.5 MPa down to 1.0 MPa due to heating, indicating a substantial reduction of 60%. This aligned with previous heat treatment research, consistently indicating diminished rock strength past the temperature range of 400–600°C.
- Increased elasticity due to heating with the results showing a reduction in strength while strain capacity post heat treatment is increased.
- Heating to 1,100°C has a measurable change to the mineralogy, as shown by XRD testing, with clay content considerably reducing post heat treatment.
- The research is the first step down the path of understanding the many factors that can influence damage due to heat, and each variable must be investigated in isolation to understand their impact.

Considering mine safety, reduced strength and volume changes due to combustion or fires near batters could destabilise slopes – particularly around the toe of a batter. This experiment highlights the multidimensional impact on sandstone and that further studies on scale effects and practical scenarios are essential for a comprehensive understanding. Overall, the results of this study provide practitioners with some firsthand data for designing fire-resilient rock structures.

Acknowledgement

The support from the technical staff at Victoria University for setting up equipment and conducting experiments is greatly appreciated.

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