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Thermal effects on the strength of marine psammitic building stones

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Abstract

Natural stones have been widely used as building materials for important structures and monuments. Such structures can be significantly damaged during fire incidents (e.g., the Notre-Dame fire in 2019), as prolonged exposure to elevated temperatures may substantially alter the properties of most rock types. Therefore, understanding the temperature impact on rock properties is crucial for assessing fire-induced damage and designing effective remedial procedures.

The main objective of this study is to present a preliminary analysis of the thermomechanical behaviour of three marine psammitic building stones from the Czech Republic: (1) Hořice-type quartz-rich sandstone from the Bohemian Cretaceous Basin, (2) Godula-type glauconitic sandstone from the Outer Western Carpathians flysch belt, and (3) Myslejovice formation greywacke from the Lower Carboniferous Culm Basin. These lithotypes were selected to represent different strength and porosity levels, enabling a general overview of the thermomechanical response of marine sandstones.

Cylindrical specimens were prepared from sampled blocks and subjected to heating following a firing curve. This procedure also allowed investigation of the temperature effect on bulk density and volumetric changes of the sandstones. The fired specimens were then tested under uniaxial compression to determine rock strength. The temperature limits were selected based on the amount of available material and the response of each rock type: 800 °C for glauconitic sandstone, 1200 °C for greywacke, and up to 1600 °C for quartz-rich sandstone. The obtained data were subsequently interpreted with respect to rock composition and density.

Keywords

Marine sandstones, Building stones, Rock thermomechanics, Temperature influence, Compressive strength.

1 Introduction

Marine psammitic sediments represent a major group of building stones in Europe. For centuries, these rock types were used for construction of important monuments – cathedrals, castles, city walls or bridges. Typically, suitable local material was used whenever possible, resulting in a wide range of rock types being employed – e.g., Hořice- (Dunčková et al. 2022) and Božanov- (Jankovičová et al. 2025) -type quartz-rich sandstones, Godula-type glauconitic sandstone (Vavro et al. 2016) or various greywackes (Bachrach and Bachrach 2021; Mota-López et al. 2025).

As the Notre-Dame incident in 2019 demonstrated, these historical monuments can be vulnerable to unintentional fires. Elevated temperatures inevitably alter rock-based structural elements, which require assessment prior to the design of remedial measures (Guibaud et al. 2023). Understanding the thermomechanical behaviour of individual rock types is therefore crucial.

Three candidate psammitic sediments were selected to represent different expected behaviours: 1) Hořice-type quartz-rich sandstone, composed predominantly of quartz grains with minor percentages of K-feldspar, micas, kaolinite and illite, and goethite (Svobodová et al. 2003; Dunčková et al. 2022). 2) Godula-type glauconitic sandstone, containing quartz, feldspar, glauconite and muscovite grains with lithic fragments, cemented by a clay-based matrix (Vavro et al. 2016). 3) Myslejovice formation greywacke made of quartz, feldspar and mica grains with lithic fragments, with a low-grade metamorphic overprint, also containing a clay-based matrix (Brabec et al. 2024).

2 Materials and methods

2.1 Data and sample sources

The data presented in this paper originate from two sources – our published thermomechanical studies and unpublished preliminary data prepared for future studies. The quartz-rich sandstone material was obtained in a block form stored in the Institute of Geotechnics collection, originally sampled near Hořice (Bohemian Cretaceous Basin), allowing for subsequent production of 42 specimens. The glauconitic sandstone published dataset (Brabec et al. 2025) was obtained by testing pre-sampled rock cores stored in the Institute of Geotechnics collection and consists of 8 specimens heated up to 800 °C. The greywacke datasets consist of two parts – published dataset (Brabec et al. 2024) containing 19 specimens fired up to 400 °C and new dataset prepared for future study, together forming a set of 48 specimens. Material for both sets was obtained as blocks sampled from Kobeřice quarry (Myslejovice formation of the Lower Carboniferous Culm Basin).

2.2 Specimen preparation

Next, core samples were prepared from the block specimens using a 38 mm diamond-tipped core drill. The small diameter was selected with regards to the recommendation of the German Society for Geotechnics (Mutschler 2004) and fine-grained structure of the rocks to maximise specimen output. The cores were then cut to length matching a length-to-diameter ratio L/D of 2.0 per ASTM D7012-23 (2023) standard. A special modification was necessary for the quartz-rich sandstone and greywacke specimens fired above 1200 °C due to the significant volumetric expansion and specimen base distortion. A larger cylinder (107 mm diameter, L/D = 1.55) was prepared for firing and monitoring procedure, and the standardised specimen was then cored from it after the firing process.

2.3 Bulk density and specimen volume monitoring

The dimensions of the prepared specimens were measured using a digital calliper with multiple readings taken and averaged to calculate the cross-sectional area and specimen volume. The specimens were carefully air dried after the water-cooled cutting process and then weighed on a laboratory scale to calculate unaltered bulk density. This procedure was repeated after the firing process to monitor the temperature effect on the bulk density and specimen volume. The unaltered property values and volume of the thermally altered specimens were determined on the larger samples in case of the quartz-rich sandstone and greywacke specimens fired above 1200 °C.

2.4 Firing process

The firing process was guided by an already established firing curve (Brabec et al. 2025; Fig. 1a): heating rate of 5 °C/min and soaking time of 60 min, followed by gradual air-cooling. The quartz-rich sandstone was able to withstand temperature up to 1600 °C (Fig. 1b) during test firing of a smaller

fragment, presenting a possibility to obtain a unique dataset. The glauconitic sandstone set was limited by the available number of specimens and was therefore fired only up to 800 °C (Fig. 1c). The greywacke was fired up to 1200 °C (Fig. 1d) based on previous experience with conglomerate of similar composition (Brabec et al. 2024).

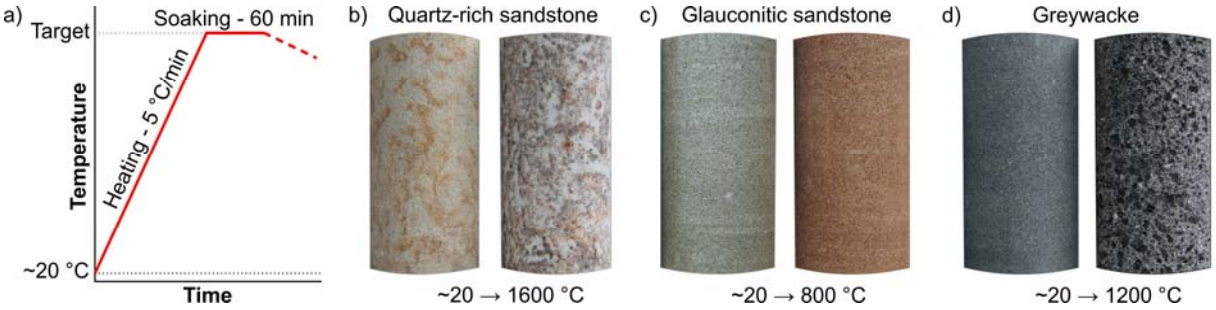


Fig. 1 a) general firing curve used in this study, b) macroscopic alteration range of the quartz-rich sandstone, c) macroscopic alteration range of the glauconitic sandstone, d) macroscopic alteration range of the greywacke.

2.5 Uniaxial compressive test

The newly prepared specimens were tested in load-control mode using two load rates based on the expected material strength: most greywacke specimens with 500 N/s, all quartz-rich sandstone specimens and greywacke specimens fired to 1200 °C with 50 N/s. The glauconitic sandstone specimens from previous study were tested in displacement-control mode with a load rate of 2.5 μm/s.

3 Results and discussion

3.1 Macroscopic alteration

The quartz-rich sandstone remains visually unaltered up to 150 °C, after which the iron oxide streaks gradually change to redder tones up to 800 °C and to purplish tones up to 1000 °C. At 1400 °C, the sandstone is at critical state with dark streaks and almost loose sand grains. At 1600 °C, the sandstone grains are covered with melted remains of the matrix minerals and bound together (Fig. 1b).

The glauconitic sandstone follows a simpler transformation – the matrix is gradually fired to brick red colour at reaching 800 °C (Brabec et al. 2025; Fig. 1c).

In case of the greywacke, the matrix is also gradually fired to the brick red colour at 800 °C and continues up to 1000 °C. At 1050 °C, the matrix starts to darken, and the greywacke develops small surface cracks, likely due to the volumetric expansion and decreasing strength. After reaching 1200 °C, the greywacke develops a new pore system and drastically expands. The remaining matrix mass is partially/fully melted and coats the remaining sand-sized grains (Fig. 1d).

3.2 Bulk density

The selected rock types (in unaltered state) each cover different bulk density range. The quartz-rich sandstone has lowest bulk density and highest variability of the tested rock types – 1989 ± 71 kg/m^3 (n = 42), the glauconitic sandstone has a bulk density of 2503 ± 2 kg/m^3 (n = 8) and the greywacke has highest bulk density of this selection – 2672 ± 15 kg/m^3 (n = 48).Next, the bulk density values obtained after firing process were plotted against the reached temperature in absolute values (Fig. 2a) and in normalised form (Fig. 2b) using the average unaltered bulk density values.

The relatively porous quartz-rich sandstone does not significantly alter in terms of the bulk density up to 1000 °C, dropping only to ~96 % of the unaltered value (Fig. 2b). With further increase in temperature, the bulk density is lowered more significantly, dropping to ~80 % of the original value at 1600 °C (Fig. 2b). The denser glauconitic sandstone starts to noticeably degrade above 573 °C (quartz α-β transition; Ringdalen 2015), decreasing to ~95 % of the unaltered value at 800 °C (Fig. 2b). The greywacke (densest of the selected rock types) follows the same trend as the glauconitic sandstone, reaching ~90 % of the original bulk density at 1000 °C (Fig. 2b). However, with increasing temperature, the greywacke starts to significantly degrade and reaches only ~45 % of the original bulk density value by 1200 °C (Fig. 2b), surpassing even the more porous quartz-rich sandstone fired to 1600 °C (Fig. 2a).

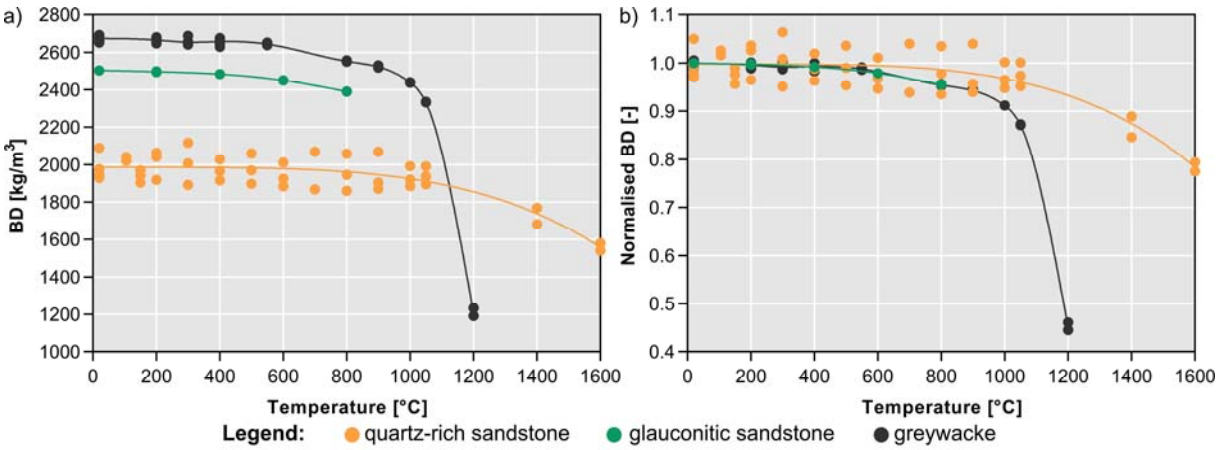


Fig. 2 Bulk density (BD) comparison of the selected marine sandstones, a) in absolute values, b) normalised.

3.3 Volumetric expansion

The permanent volumetric expansion (excluding the thermal expansion experienced during heating, expressed as the difference between original and altered specimen volume) follows inverted trends to the bulk densities (cf. Fig. 2 and Fig. 3). It is also responsible of major percentage of the bulk density loss in case of the thermally-altered rock types.

Comparing the three marine sandstones: The quartz-rich sandstone follows a gradual exponential trend with ~1 % of volumetric expansion reached at 800 °C, ~4 % at 1200 °C and finally ~27 % at 1600 °C (Fig. 3). The glauconitic sandstone and greywacke both follow a different trend with ~2 % of volumetric expansion already reached at 800 °C (Fig. 3). The greywacke then starts to significantly expand, reaching ~8 % at 1000 °C and even ~105 % at 1200 °C (Fig. 3).

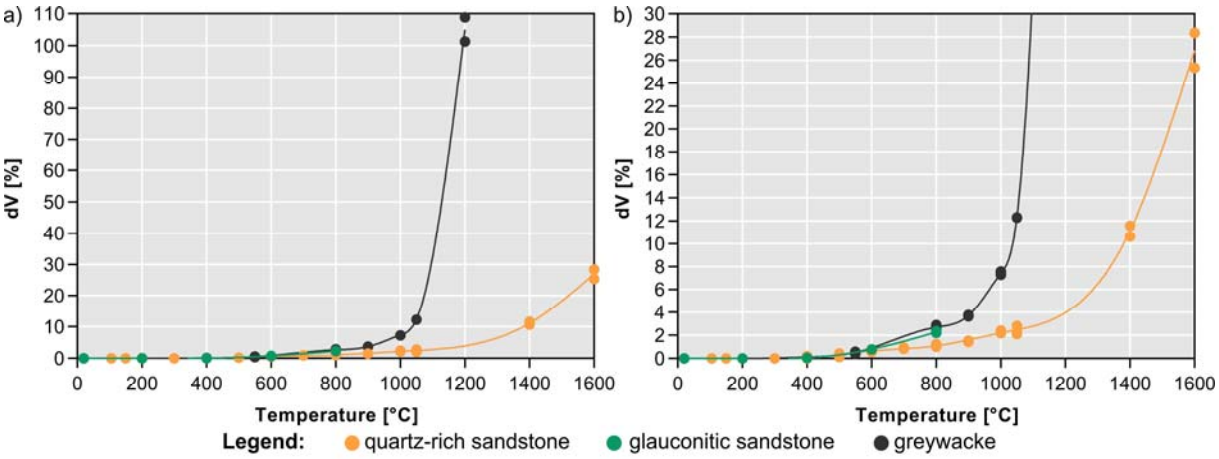


Fig. 3 Volumetric change (dV; in this case expansion) comparison of the selected sandstones, a) full range, b) zoomed.

3.4 Uniaxial compressive strength (UCS)

Similarly to bulk density, the selected rock types cover different strength ranges, following the same order. The quartz-rich sandstone has an unaltered UCS of 14.5 MPa, the glauconitic sandstone is stronger with UCS of ~94 MPa and the greywacke is the strongest with UCS of ~144 MPa. When plotted against the reached temperature in absolute values (Fig. 4a) and in normalised form (Fig. 4b), the rocks can be easily compared.

The quartz-rich sandstone slowly degrades with UCS dropping to ~65 % of the unaltered value at reaching 800 °C and ~20 % at 1200 °C. At 1400 °C, the sand-sized grains barely hold together, resulting in only ~5 % of the unaltered UCS value. With further increase of temperature to 1600 °C, the sandstone is partially re-melted and regains ~75 % of the unaltered strength. The glauconitic sandstone and greywacke follow a different trend, starting with a slight decrease in strength to ~90 % of the unaltered UCS at 200 °C. Both rocks then strengthen with maximum UCS at different temperatures: glauconitic sandstone reaches a maximum of ~135 % of the unaltered UCS at 600 °C, while the greywacke reaches only a maximum of ~115 % of the unaltered UCS at 800 °C. After the maximum, both rocks relatively quickly degrade. The glauconitic sandstone drops back to the

unaltered UCS value by the greywacke maximum at 800 °C, while the greywacke UCS decreases to the same level at ~850 °C. By 1200 °C, the greywacke retains only ~5 % of the original UCS value.

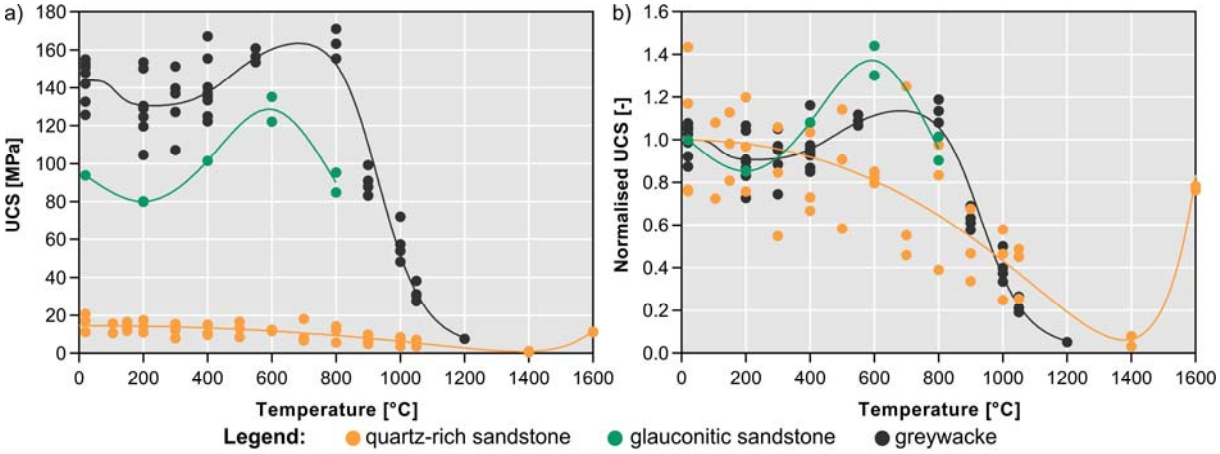


Fig. 4 Uniaxial compressive strength (UCS) comparison of the selected sandstones, a) in absolute values, b) normalised.

3.5 Comparative thermomechanical behaviour

The tested marine psammitic sediments represent a range of possible clastic lithotypes used as building stones. The two denser types (i.e., glauconitic sandstone and greywacke) react to the elevated temperature similarly, but with minor differences. Both first experienced slight weakening at 200 °C with subsequent strengthening to a peak value before final disintegration (Fig. 4), along with similar bulk density (Fig. 2) and volumetric change (Fig. 3) trends. The weakening phase is comparable in relative terms for both rock types. However, the strengthening phase of the glauconitic sandstone is approximately 20% higher and reaches its peak at a lower temperature (~200 °C; Fig. 4b), than that of the greywacke. In contrast, the more porous quartz-rich sandstone degrades gradually without a strengthening phase below 1000 °C (Fig. 4), while also exhibiting more gradual changes in bulk density (Fig. 2) and volumetric expansion (Fig. 3).

Based on the presented data, a generalised thermomechanical behaviour for the whole marine psammitic sediment group cannot be described. However, the behaviour can likely be estimated based on the initial bulk density and also possibly the mineralogical composition. With further datasets possibly available in the future, the typical marine psammitic sediment subgroups with similar thermomechanical behaviour could be defined and established.

3.6 Limitations and implication to heritage fire incidents

The tests conducted for this study correspond to a slower and gradual heating of the rock, producing a still-intact and thermally-altered rock mass.

However, in-situ conditions during the heritage fire incidents may vary from the gradual heating to rapid temperature increase. These abrupt thermal shocks typically produce macroscopic cracks or spalling, as can be seen on the photos of the affected Notre-Dame structures (Guibaud et al. 2023). Another additional factor which should be considered is the quick water-cooling of the heated rock mass during the firefighting operations, which also may result in additional cracking.

These additional factors behind the formation of macroscopic cracks could be incorporated in the thermally-altered rock strength in a similar manner, as the naturally-occurring discontinuities are in case of the standard rock mass. With addition of triaxial tests, a Hoek-Brown failure criterion could be calibrated and enhanced to be temperature-dependent. Thus the geological strength index and disturbance factor could be used for description of the thermally-produced macroscopic cracks. The obtained model could then be used for complex simulations and assessment of the thermally-altered rock-based structures with all factors included.

4 Conclusions

The paper presents a comparison of three different marine psammitic sedimentary rock types fired to elevated temperatures based on the material reaction:

(1) Concerning the bulk density: The quartz-rich sandstone follows a gradual decreasing trend, while the glauconitic sandstone and greywacke both follow a different trend with two thresholds (at ~600 and ~1000 °C), and with significantly faster degradation rates.

(2) The volumetric change trends are similar to the bulk density ones, implying that the volumetric increase is the main factor in decreasing bulk density value.

(3) The glauconitic sandstone and greywacke first experience slight weakening with subsequent strengthening to a peak value before final disintegration, with minor differences between the peak strength temperature and ratio. In contrast, the quartz-rich sandstone does degrade gradually to a negligible strength at 1400 °C before significant strengthening leading up to 1600 °C.

The three available datasets do not suggest a generalised thermomechanical behaviour for the marine psammitic sediment group.

Acknowledgement

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