International Journal of Architectural Heritage
Conservation, Analysis, and Restoration

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/uarc20

Evaluation of the Loss of Uniaxial Compressive Strength of Sandstones Due to Moisture

Adrienn K. Tomor, John M. Nichols & Zoltán Orbán

To cite this article: Adrienn K. Tomor, John M. Nichols & Zoltán Orbán (2023): Evaluation of the Loss of Uniaxial Compressive Strength of Sandstones Due to Moisture, International Journal of Architectural Heritage, DOI: 10.1080/15583058.2023.2188313

To link to this article: https://doi.org/10.1080/15583058.2023.2188313

Published online: 17 Mar 2023.

INTERNATIONAL JOURNAL OF ARCHITECTURAL HERITAGE
https://doi.org/10.1080/15583058.2023.2188313

Evaluation of the Loss of Uniaxial Compressive Strength of Sandstones Due to Moisture

Adrienn K. Tomor[a], John M. Nichols[b] and Zoltán Orbán[c]

[a]University College London, UK and University of Pecs, Institute of Smart Technology and Engineering, Pecs, Hungary; [b]Rezzona Consultants, Texas, USA; [c]University of Pecs, Hungary

ABSTRACT

The reduction in uniaxial compressive strength (UCS) was investigated for sandstones under various moisture levels. Thirty-four UK Darney sandstone samples were tested under six different moisture conditions. The time-dependent moisture gain and loss were also evaluated. For 77 sandstones identified in the literature, the loss of UCS between oven-dry and saturated conditions was up to 45%, with an average of 20%. For Darney stone, the average loss of UCS was around 20%, with UCS around 72 N/mm^2 when oven-dry and 58 N/mm^2 when fully saturated. During saturation, significant loss of UCS occurred soon after exposure to water with 80% of UCS being lost within the first 2.5–6 hours. For Darney stone 50% of UCS was lost at air-dry conditions. Results from the 78 sandstone types were compared with the equivalent compressive strength defined by BS EN 772–1:2011 for oven-dry, air-dry, and saturated conditions. The estimated values by BS EN 772–1:2011 for dry and saturated UCS agreed well with the available test data and indicated a lower-bound solution. For immersed conditions, BS EN 772–1:2011, however, overestimates the reduction in UCS for a large number of samples and provides an average, instead of a lower-bound solution.

ARTICLE HISTORY
Received 28 November 2022
Accepted 27 February 2023

KEYWORDS
BS EN 772-1:2011; sandstone; saturation; UCS; Uniaxial compressive strength; water content

1. Introduction

The uniaxial compressive strength (UCS) of building stones is known to reduce with increasing moisture levels. This can have notable influence on the assessment of historical and design of new structures. The study focuses on sandstones widely used as cut stone or random rubble masonry. The engineering, mechanical and mineralogical properties of sandstones vary widely. Engineering properties (such as UCS) are influenced by a range of factors, such as mineral composition (quartz, feldspar, lithic grains, clay other constituents), porosity, grain size, pore size and distribution, density, in-situ stresses (Xi et al. 2015; Lai et al. 2018; Khanlari and Abdilor 2015; Yao et al. 2020), and moisture content.

Moisture content is a balance between moisture transport and the rate of evaporation (Rirsch and Zhan 2010; Verstrynge et al. 2014). Water rises in the structure through capillarity action (as a function of pore structure and viscous forces). It is greatest for small capillaries and inversely proportional to the pore radius. Factors controlling evaporation include temperature, humidity, air movement, and surface conditions.

Testing the UCS of stones as a function of moisture level is typically carried out under laboratory conditions. Results may be presented as a direct relationship between dry and saturated UCS values or as an exponential relationship between UCS and moisture content. A more complex relationship has been proposed by Majeed and Abu Bakarb (2018) between saturated UCS, dry UCS, dry Brasilian tensile strength, dry density, and pore space volume.

Apart from the wide range of material properties, results are also influenced by testing procedures and chemical changes over longer periods of time. For example, the height of capillary rise can increase with age in masonry walls (about seven times over 100 years) if slightly acidic water washes out lime from the mortar (Rirsch and Zhan 2010) or the internal pore pressure is influenced by salt deposition in the pores (Mol and Viles 2013).

A wide range of literature is available for the preservation of historic masonry but no specific guideline has been identified for structural assessment of the reduction of UCS related to moisture. For design, the

CONTACT Adrienn K. Tomor a.tomor@ucl.ac.uk Bartlett School of Sustainable Construction, UK and Structural Diagnostics and Analysis Research Group, Faculty of Engineering and Information Technology, University of Pécs, 1-19 Torrington Place, WC1E 7HB, Boszorkány u. 2, Pécs, London H-7624, Hungary

European Standard BS EN 1996-1-1:2005 (BSI 2005) uses the equivalent compressive strength of air-dry units from BS EN 772–1:2011 (BSI British Standards Institution 2011) but does not consider the variability between different stone and unit types.
The key objectives of the paper are to:

- estimate the average reduction of UCS for sandstones based on available literature
- estimate the time-dependent relationship between UCS and moisture gain/loss
- evaluate the equivalent compressive strength by BS EN 772-1:2011 (BSI 2011) based on available test data.

2. Literature review

2.1. Guidelines

In masonry structures the source of moisture (Hall and Hoff 2001) may be rising damp (Hall and Hoff 2007), wind-driven rain (Orr et al. 2020), humidity, or from soils in retaining walls.

Water absorption (W_s) can be measured according to BS EN 13,755–2008 (BSI British Standards Institution 2008) or ASTM C97–18 (ASTM American Society for Testing and Materials 2018) for stone (Equation 1). It is the ratio of the maximum mass of water taken up by the specimen and mass of dry specimen. Water absorption can be considered as the upper limit of water content when immersed in water. It is closely related to effective porosity and describes the percentage of pores accessible for the water under normal conditions

$$W_s = \left(\frac{M_{sat} - M_{dry}}{M_{dry}}\right)100\% \quad (1)$$

wWhere W_s is the water absorption, M_{sat} is the mass of specimen after soaking (saturated), and M_{dry} is the mass of specimen after oven drying.

The degree of saturation (S) is the ratio of the volume of water and volume of voids (Equation 3)

$$S = \left(\frac{V_{water}}{V_{voids}}\right)100\% \quad (2)$$

where S is the degree of saturation, V_{water} is volume of water and V_{voids} is the volume of voids in the specimen.

Water (moisture) content (W) can be measured according to ASTM D2216–19 (ASTM American Society for Testing and Materials 2019) for stones and is the ratio of the mass of water and mass of the stone (Equation 3). BS EN 772-10-1999 (BSI British Standards Institution 1999b) describes the same method but it is specifically for calcium silicate and autoclaved aerated concrete units

$$W = \left(\frac{M_{specimen} - M_{dry}}{M_{dry}}\right)100\% \quad (3)$$

where W is the water (moisture) content, $M_{specimen}$ is the mass of the specimen and M_{dry} is the mass of the specimen after oven drying.

The uniaxial compressive strength (UCS) of stone can be measured according to BS EN 1926–2006 (BSI 2006a) or ASTM C170–17 (ASTM American Society for Testing and Materials 2017). According to BS EN 1926–2006 (BSI British Standards Institution 2006b), the sample is dried at (70 ± 5)°C to constant mass, stored at (20 ± 5)°C until the thermal equilibrium is reached and tested within 24 hours.

According to BS EN 1996-1-1:2005 (BSI British Standards Institution 2005) the strength of masonry is based on the equivalent compressive strength of air-dry units. The compressive strength of units is determined according to BS EN 772–1:2011 (BSI British Standards Institution 2011) and can be tested under three moisture conditions:

1. air-dry: storing the specimens at ≥ 15°C and≤65% relative humidity for≥14 days or drying at 105°C for≥24 hours and cooling for≥4 hours
2. oven-dry: drying the specimens at 105°C or at 70°C and storing them at 20°C until thermal equilibrium is reached
3. 6% moisture content: drying the specimens at ≤ 50°C until 6% moisture is reached and storing them at room temperature for≤5 hours
4. Immersed: immerse the specimens in water at 20°C for≥15 hours.

The compressive strength of specimens is converted into the equivalent compressive strength of air-dry units using multipliers 1.0 for air-dry and 6% moisture, 0.8 for oven-dry, and 1.2 for immersed conditions.

While BS EN 1996-1-1:2005 (BSI British Standards Institution 2005) uses full immersion but can leave air trapped in the specimens. In laboratory experiments, saturation can alternatively be achieved by progressive saturation using capillary action (Majeed and Abu Bakarb 2018), vacuum saturation (Verstrynge et al. 2014), or fluid injection at low pressures (Rirsch and Zhan 2010). Mortar is also a key factor in controlling water ingress and evaporation (Rirsch and Zhan 2010) but the interaction between mortar and units is outside the scope of the paper.

2.2. Measuring moisture content in field conditions

For measuring the moisture content in historical structures, BS EN 16,682:2017 (BSI British Standards Institution 2017) and Camuffo (Camuffo 2018) group methods into relative and absolute categories and evaluate their application. For masonry the gravimetric method is the relevant absolute method. The gravimetric method is the ratio between the mass of the removed water and the mass of the dried sample expressed as % by mass while the volumetric method is the ratio between the volume of the removed water and the volume of the moist sample expressed as % by volume. The gravimetric method requires samples to be extracted in the field and tested under laboratory conditions. Due to its destructive nature and requiring new samples to be extracted every time, the method can only be used for heritage structures in exceptional circumstances and under strict supervision.

Sandrolini and Franzoni (2006) proposed a lower impact gravimetric method for heritage structures that uses the same drilled holes every time. They extract brick fragments and power from small drilled holes (Ø15–20 mm) up to 150–200 mm depth where the moisture content is less affected by the outdoor conditions and is more representative of the overall material. After the moisture content is measured, the fragments and power are reinserted into their original locations (hole cavities) and sealed. The samples can be extracted periodically and moisture content measured on the same samples at the same locations.

BS EN 16,682:2017 (BSI British Standards Institution 2017) lists a wide range of relative methods that are suitable for masonry, as shown in Table 1. Relative methods are generally easy to use but results are not directly comparable. Electrical resistance can be a useful tool to identify complex moisture movement by capillary rise in sandstones over time. Capacitance provides a better response to moisture variation, while the relative humidity (RH) moisture sensor is ideally suited for measuring the moisture content (MC) due to sensor "saturation" (Larsen 2012; Mol and Viles 2013; Semerák and Cerny 1997; Zhao et al. 2012). Microwave is able to distinguish between different moisture regimes and the overall moisture distribution (Orr et al. 2020). Evanescent-field dielectrometry (EFD) can detect moisture and salt content but is less widely used for building stones (Di Tullio et al. 2010). Time-domain reflectometry can is a highly sensitive tool for monitoring changes in internal moisture levels over time up (to ca. 65 mm depth). However, it requires careful installation and provides relative results (Mollo and Greco 2011; Phillipson et al. 2008). Nuclear magnetic resonance (NMR) and near infrared spectroscopy (NIRS) can be useful tools for specialist applications but are less widely used for field applications (Proietti et al. 2021). Ultrasound pulse velocity is an easy-to-use tool but is difficult to calibrate under field conditions and for inhomogeneous masonry (Verstrynge et al. 2014; Binda, Cardani, and Zanzi 2010). Thermography detects thermal differences on surfaces but does not directly identifying moisture content. It can, however, be used as in indirect tool for identifying differences in moisture levels (Di Tullio et al. 2010; Edis, Flores-Colen, and De Brito 2014). Radar, similarly to microwave can be a very useful tool to identify localized variation of water content. It can detect surface moisture content due to condensation and areas where water penetrated through the mortar joints to the interior of a construction (Orr et al. 2020; Agliata et al. 2018]). X-ray radiography can accurately determinate the two-dimensional transient moisture profiles in stones, although it is only suited for specialist laboratory applications (Roels and Carmeliet 2006).

2.3. Relationship between UCS and moisture content

A number of researches have investigated the effect of water content on the uniaxial compressive strength (UCS) of sandstones. They tested either (a) a large number of samples from one or two stone types at various water contents to establish the relationship between UCS and water content or (b) a limited number of

Table 1. Relative methods for measuring moisture content (BS EN 16,682:2017).

Clause	Method	Physical principle
B.2	electrical resistance	Ohm's law
B.3	capacitance	dielectric capacity of water
B.4	equilibrium RH	equilibrium between RH and MC
C.2	microwave	interference of the water molecule with the electromagnetic radiation (microwave frequency)
C.3	evanescent-field dielectrometry (EFD)	interference of the water molecule with the electromagnetic radiation (microwave frequency)
C.4	time-domain reflectometry (TDR)	interference of the water molecule with the electromagnetic radiation (radio frequency)
C.5	nuclear magnetic resonance (NMR)	magnetic moment and resonant frequency of the water molecule
C.6	near infrared spectroscopy (NIRS)	reflection of the near infrared radiation
C.7	ultrasound pulses	speed of ultrasound pulses
C.8	thermography	thermal emission of bodies

samples from a large number of stone types at mostly dry and saturated conditions to establish the loss of strength across a range of stones.

Price (1960) tested four different sandstones under oven-dried, air-dried, and saturated conditions and observed up to 55% reduction in compressive strength.

Van Eeckhout (1976) summarized test data available in the literature 1946–1973 for coal mine shales for a wide range of stones, such as sandstone, limestone, marble, granite, and shale. He tested the compressive strength of coal mine shale and found significant reduction in strength over 60% humidity, with around 50% loss of strength at 100% humidity. The results were similar to findings by Wiid (1967) with reduction in compressive strength around 20–30% up to about 60% humidity and up to around 50% at 100% humidity. Van Eeckhout found that the strength of coal mine shales reduced by humidity fluctuations and with less than 60% humidity the strength can be kept relatively high and expansion-contraction at a minimum.

Ballivy, Ladanyi, and Gill (1976) tested the effects of saturation history (drying and re-saturating prior to testing, saturation method and type of saturating fluid) on the mechanical properties of three rock types (gneiss, cemented sandstone, fine-grained limestone). Results showed that a drying and wetting prior to testing increased the strength through over-consolidation. They suggested rock samples to be kept in the at the same moisture level until testing as they were extracted in the field, without additional drying and/or wetting cycles. If this condition cannot be met, specimens should be saturated using a natural saturation fluid and using a suitable saturation technique (for example, axial channel saturation).

Bell (1978) tested 29 samples of Fell sandstone and found strength reduction between 10–50% with an average of 32% for 6.5% and 20.7% porosity. He showed that the strength reduction due to water is proportional to the porosity of rock.

Priest and Selvakumar (1982) studied two sandstones and three limestones and formulated a relationship between uniaxial compressive strength and moisture content for each rock type (Equation 4)

$$\sigma_c = ae^{-bw} + c \quad (4)$$

where σ_c is the uniaxial compressive strength (MPa), w is the moisture content (%), and a, b, and c are constants tabulated for each of the sandstones.

Hawkins and McConnell (1992) and Hawkins (1998) tested the uniaxial compressive strength of 35 British sandstone types under oven dry and saturated conditions, four samples each. The reduction in strength ranged widely between 8–78% with 32% on average. Studying the relationship between strength and moisture content they found 80–90% of strength loss below 1% moisture content (at ca.<40% saturation) as shown in Figure 1. For these sandstones, the moisture content at saturation ranged between 0.75% and 26.7% (2–38% porosity). They applied the empirical model proposed by Priest and Selvakumar (1982) to estimate the loss of strength as a function of moisture content and proposed a classification scheme for sandstones (sensitivity classes) according to their loss of strength due to moisture.

Winkler (1994) summarized a number of earlier studies on changes in compressive strength due to saturation. He suggested the "wet-to-dry" strength ratio as a rough indicator of durability for stone with the following bands:

(a) 0.8–1.0 Excellent durability
(b) 0.7–0.8 Good to excellent durability
(c) 0.6–0.7 Fair to poor durability
(d) 0.5–0.6 Poor durability
(e) <0.5 Very bad durability.

Bell and Culshaw (1998) tested 12 samples of Sneinton Formation from the UK and considered the relationship

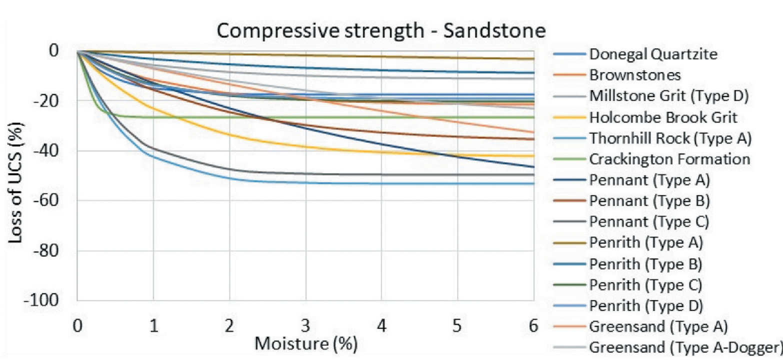

Figure 1. Test results by Hawkins and McConnell (1992) (Reproduced).

between petrographic characteristics, physical, and mechanical properties. They found that saturation reduced UCS by 36% on average. The petrographic properties were found to have little influence on the physical and mechanical properties of the tested sandstones.

Vasarhelyi (2003) analyzed the relationship between dry and saturated sandstone samples tested by Hawkins and McConnell (1992) and found linear relationship between the dry and saturated strengths, as shown in Equation 5 and Figure 2.

$$\text{UCSsat} = 0.759\ \text{UCSdry}\ (\text{R2} = 0.906) \tag{5}$$

Jeng et al. (2004) and Lin et al. (2005) tested 13 types of sandstones from 8 geological formations in northern Taiwan and studied the relationship between saturation and UCS through petrographic analysis. They proposed relationship between UCS and the petrographic parameters (grain area ratio and porosity), expressed as grain–matrix–porosity content. The porosity was identified to have more influence on the UCS than the grain and matrix content.

Vasarhelyi and Ván (2006) analyzed published data on 35 British sandstone types by Hawkins and McConnell (1992) and proposed a relationship between water content and dry and saturated UCS, as shown in Equation 6

$$\begin{aligned} c(w) &= a' + c'e^{-b'w} \\ &= \left(\sigma_{c0} - \left(\frac{\sigma_{c0} - \sigma_{csat}}{1 - e^{-b'}}\right)\right) + \left(\frac{\sigma_{c0} - \sigma_{csat}}{1 - e^{-b'}}\right) e^{-b'w} \end{aligned} \tag{6}$$

where $a' + c' = \sigma_{c0}$, $c' = \frac{\sigma_{c0} - \sigma_{csat}}{1 - e^{-b'}}$, $b' = -ln\left(\frac{0.1}{\sigma_{c0} - \sigma_{csat}}\right)$ and w is the water content. The constant b' can be related to the constant b used by Hawkins and McConnell (1992) as given in Equation 7

$$b = \frac{b'}{n_{eff}} \tag{7}$$

where n_{eff} is the effective porosity and for the analyzed test data b' is 6.0259. The model is demonstrated in Figure 3a for the various stoned types and normalized results are shown in Figure 3b. The model shows rapid reduction in strength within around 30% of moisture content.

Fahimifar and Soroush (2007) tested 220 samples from a range of rock specimens for the relationship between saturated UCS and 6 key parameters (water absorption, porosity, weathering, swelling index, number of microfissures, and grain size) (Figure 4). They proposed a Moisture Index Classification system based on the test results with five rock classes (very strong,

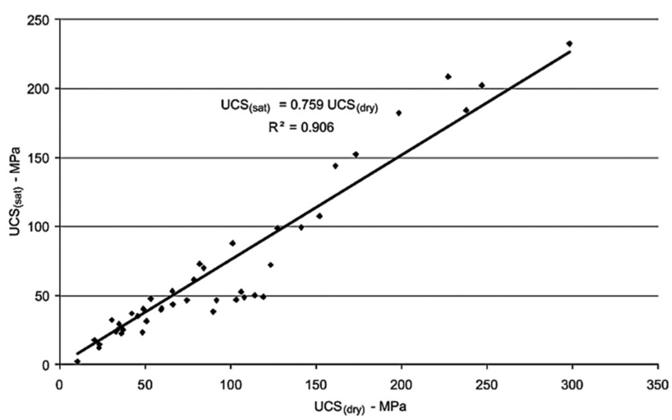

Figure 2. Relationship between the dry and saturated UCS (Vasarhelyi 2003).

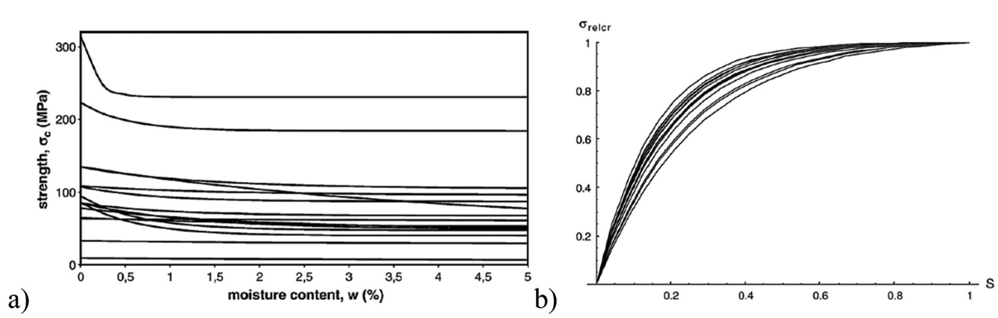

Figure 3. a) UCS vs moisture content and b) relative UCS vs. water content (Vasarhelyi and Ván 2006).

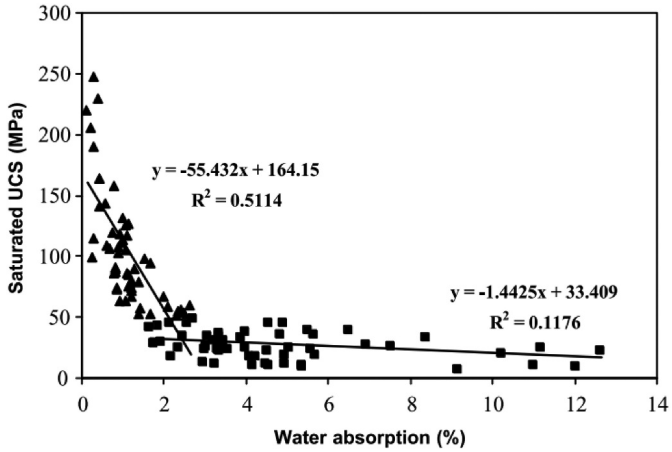

Figure 4. Saturated UCS vs. water absorption (Fahimifar and Soroush 2007).

strong, medium, weak and very weak). While the strength of strong rocks was not notably affected by moisture, the strength and other rock properties were increasingly affected for weaker rocks.

Agustawijaya (2007) tested 39 partially and fully weathered soft sandstone and siltstone rocks (<20 N/mm^2). Saturation reduced the UCS between 8% and 75% for with an average of 38%. They found a direct relationship between UCS, porosity, and density. UCS was also correlated to the point load strength index (Is (50)) (ASTM American Society for Testing and Materials 2016) as a useful tool for field testing. The correlation between UCS and IS(50) was around 14 for soft rocks that is significantly lower than IS(50) 24 for hard rocks.

Karakul and Ulusay (2013) tested the effect of saturation on the UCS and tensile strength for 14 different rock types from Turkey. They found that porosity (n) and clay content (cl) jointly affected the UCS and expressed them as Effective Clay Content (ECC) (Equation 8). The ECC is considered as the percentage of clay minerals which contribute to the decrease in strength due to moisture content. They proposed a model for predicting UCS as a function of P-wave velocity (V_p), degree of saturation (Sr) and ECC as shown in Equation 9

$$ECC(\%) = ncl \tag{8}$$

$$\log(\sigma_c) = 1.368 + 0.794\log(1 + V_p) - 0.201S_r - 0.056ECC\left(\mathrm{R}^2 = 0.911\right) \tag{9}$$

Verstrynge et al. (2014) and Verstrynge, Schueremans, and Van Gemert (2012) tested the UCS for low- and high-quality Diestian and Brusselian ferruginous sandstone under quasi-static and creep loading. They found that saturation reduced the strength between 40–59% and the effect of moisture content was larger for lower quality sandstones. Under creep loading all dry specimens showed stable secondary creep phase but failed rapidly after water was added at the base of the specimens. Acoustic emission monitoring was used to identify the failure development process under creep loading, distinguish between the three phases of creep failure process, and identify rapid failure after saturation.

Zhou et al. (2016) tested ca. 50 sandstone samples from Yunnan Province, China under static and dynamic compression and tension (using Split Hopkinson pressure bar for dynamic tests). Saturation reduced the compressive strength by an average of ca. 30% under static loading and ca. 35% under dynamic loading. The effect of water content on the strength under static and dynamic loading and during saturation and drying processes are summarized in Equations 10-13.

$$\text{Static} - \text{Saturation process } \sigma_c(\omega_w) = 46.80 + 19.95e^{-0.659\omega_w} \; R^2 = 0.944 \tag{10}$$

$$\text{Static} - \text{Drying process } \sigma_c(\omega_w) = 46.21 + 19.89e^{-0.583\omega_w} \; R^2 = 0.901 \tag{11}$$

$$\text{Dynamic} - \text{Saturation process } \sigma_c(\omega_w) = 51.24 + 35.971e^{-0.576\omega_w} \; R^2 = 0.929 \tag{12}$$

$$\text{Dynamic} - \text{Drying process } \sigma_c(\omega_w) = 52.68 + 33.368e^{-0.585\omega_w} \; R^2 = 0.924 \tag{13}$$

Wong, Maruvanchery, and Liu (2016) carried out an extensive study collecting and analyzing test results available in the literature since 1940s. They summarizsed the effect of moisture on UCS and the key influencing factors. Through statistical analysis they found the reduction of UCS due to saturation to be more severe in sedimentary compared to igneous and metamorphic rocks. The loss of compressive strength had a normal (bell-shaped) distribution for sandstone with a mean of around 40% and a positively skewed distribution for limestone with a lower mean.

Zhang et al. (2017) tested siltstone samples from were Eidsvold, Queensland, Australia at different saturations levels. Although siltstones are not sandstones, they are included in the review as they are closely related to sandstones and shales. For the samples, the loss of UCS due to saturation was around 32% as indicated. The test data shows good agreement with the proposed model by Priest and Selvakumar's (Equation 14)

$$\sigma_c = 22.104e^{-7.782w} + 48.571 \quad (14)$$

where w is the saturation level with w = 0 for dry and w = 1 for full saturation.

Karakul (2017) investigated the relationship between UCS and Schmidt hammer rebound as a function of moisture content. He tested 14 volcanic, sedimentary, and volcano-sedimentary rock types from Turkey in dry and saturated conditions. The relationship between tested and predicted UCS (σ_c), Schmidt hammer rebound value (N), and degree of saturation (S_r) is shown in Equation 15

$$\log(\sigma_c) = -1.656 + 2.269\log(N) - 0.1023(S_r) \quad (\mathrm{R2} = 0.94) \quad (15)$$

Kim et al. (2017) tested three different dry and saturated sandstones (Red, Berea, and Buff) under static and dynamic loading. They proposed relationships between compressive strength, water content, bulk density, and porosity.

Masoumi, Horne, and Timms (2017) tested 71 Gosford sandstone samples using UCS, point and tensile tests. When saturated, UCS reduced by ca. 70% and the majority of the strength loss occurred below 1% water content. They applied the empirical model proposed by Hawkins and McConnell (1992) and Priest and Selvakumar (1982) and found good agreement between the predicted and experimental values.

Majeed and Abu Bakarb (2018) tested 34 sedimentary rock types in Pakistan. The reduction in UCS was around 57% due to saturation and they proposed a correlation between wet and dry USC, as shown in Figure 5. Using regression analysis, the best fit between the porosity and the uniaxial compressive strength was negative exponential correlation for both dry and saturated rock conditions. They also proposed a multiple regression model for the prediction of saturated UCS (UCS_{sat}) based on the dry UCS (UCS_{dry}), dry Brasilian Tensile Strength (BTS_{dry}), dry density (ρ_{dry}), and pore space volume (V_v), as shown in Equation 16.

$$\mathrm{UCSsat} = 84.110 + 0.385\,\mathrm{UCSdry} + 2.282\,\mathrm{BTSdry} - 28.727\,\rho\mathrm{dry} - 1.727\mathrm{Vv} \quad (16)$$

Tang (2018) tested 41 sandstone samples from Longchang, Sichuan Province, China at different moisture contents and found exponential relationship between UCS at low water content. He applied the empirical relationship proposed by Priest and Selvakumar (1982) given in Equation 4 with constants

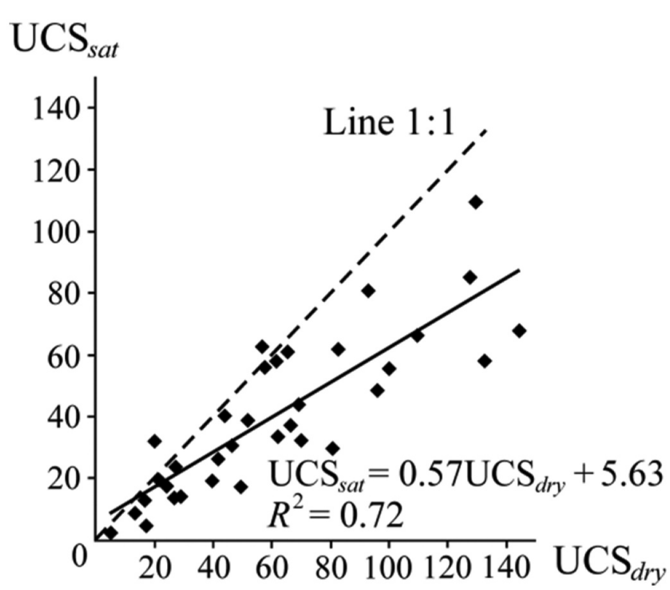

Figure 5. UCS_{sat} vs. UCS_{dry}.

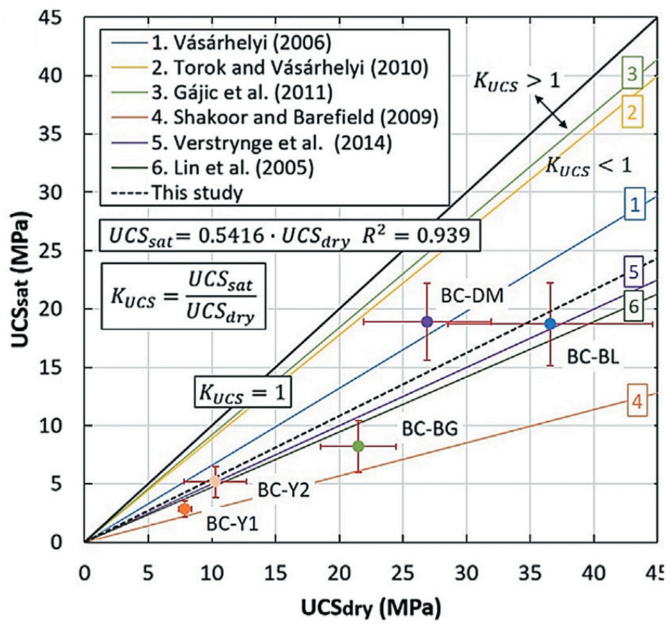

Figure 6. Review of literature and test data (Rabat, Cano, and Tomas 2020).

of a, b, and c as 80.604, −0.9044, and 43.17, respectively, and found good correlation with the tests results.

Liu et al. (2020) tested 42 samples of clay-bearing red sandstone from Yichang, Hubei Province, China for a range a different saturations levels and number of freeze-thaw cycles. For dry samples UCS reduced by 37% after 50 freeze-thaw cycles. Critical saturation was around 60%, beyond which freeze-thaw damage increased rapidly up to 90% under similar freeze-thaw cycles.

Rabat, Cano, and Tomas (2020) reviewed the test data and models proposed by other researchers for various stone types and tested four porous calcarenite building stones from Spain (Figure 6). The loss of UCS for the four stone types was around 45.8% that agreed closely with other models. They found strong correlation between UCS, Point Load Strength Index $I_{s(50)}$ and Young's Modulus.

Yasar (2020) tested the long-term wetting characteristics and saturation induced strength reduction of tuffs and andesites. He found reduction in UCS due to saturation between 16–53%. Before testing under air-dry conditions, samples were left in laboratory conditions for three months. Atmospheric moisture reduced the UCS between 12% and 30%. For field and laboratory testing, it is therefore particularly important to ensure that the moisture content of samples is not affected by atmospheric moisture.

2.4. Time-dependent strength loss

Test data and models on the rate of saturation and time-dependent strength loss is next summarized. As only limited data is available for sandstones, results from other stones are also included.

Liu, Yang, and Yu (2015) tested time-dependent saturation of low-grade metamorphic slate. Although not a sandstone, 75% of the saturation in slate occurred within the first 24 hours and reduced the UCS by over 35%.

Celik and Ergul (2015) tested two different types of tuffs for the reduction of strength after four different times of saturation (1, 6, 24, 48 hours). Although not sandstones, the greatest strength reduction for tuffs occurred within the first hour (31.96% and 40%) of saturation and the total strength loss during 48 hours was 43.99% and 52.44% for the two tuff types. The relationship between dry and saturated strength was linear for each saturation time and correlations were identified.

Zhou et al. (2016) tested sandstones where ca. 90% of saturation occurred during the first 5 hours. During the drying process samples remained around 90% saturated up to ca. 70 hours. The effect of moisture content on the strength under both soaking and drying processes was around the same.

Tang (2018) tested the relationship between UCS, soaking time, and water content with 80–90% of UCS lost during the first 15 hours of saturation. Tang also found homogeneous water distribution to cause lower UCS compared to non-homogeneous water distribution.

Yates, Richardson, and Miglio (2012) reviewed the current codes for testing engineering properties of natural stone under dry and wet conditions. They tested the compressive strength and the effect of soaking time for a sandstone and a limestone at three saturation times (1, 60, 2880 minutes). For sandstone the greatest, 30%, reduction in strength occurred within 1 hour of saturation. When fully saturated, the strength reduced up to 43% for sandstones and up to ca. 25% for limestones. They reviewed the current codes of practice and highlighted that the flexural strength in European Standards is tested dry and used together with a safety factor of generally 6. Alternatively, the lower expected value (LEV) can be used instead of the mean value with a safety factory of 3 (instead of 6) to take the statistical variation into account. In the United States, safety factors between 6 and 8 are used depending on stone types (e.g., limestone, sand-

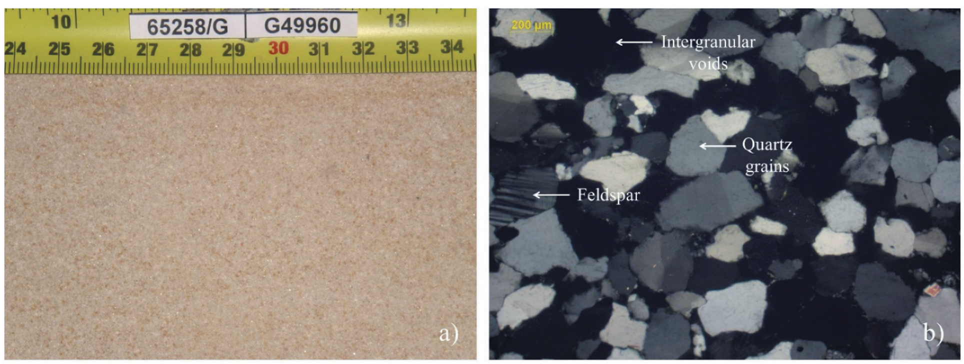

Figure 7. a) Stone appearance and b) micrographic details using cross-polarized light.

Figure 8. Testing process.

stone, granite) that can better reflect the variability of results for the stones.

Liu et al. (2020) tested dehydration of sandstones and found that over 90% of UCS was lost at low degree of saturation below 60%. Critical saturation was around 60% for freeze-thaw damage.

3. Uniaxial compressive testing

3.1. Stone specification

To explore the relationship between UCS and moisture content, Darney lower carboniferous sandstone (quarts arenite) was selected from Northumberland, UK. The sandstone has a light-yellow color with fine, well-sorted subangular and high sphericity grains. The petrographic analysis indicates quartz grains, intergranular voids, and some feldspar, as shown in Figure 7

The density of the stone was 2150–2170 kg/m^3 and porosity 16.0–17.1%, tested according to BS EN 1936:2006 (BSI British Standards Institution 2006c). Water absorption was 4.9–5.3% (BS EN 13,755:2008, (2008)) and water absorption coefficient of capillarity 23.82 g/m^{2}sec$^{0.5}$ (BS EN 1925:1999, BSI 1999a). The compressive strength perpendicular to bedding plane at oven dried condition was 35.3–65.1 N/mm^2 (BS EN 772–1:2011, (2011)), flexural strength under (3-point) concentrated loading 3.5–4.1 N/mm^2 (BS EN 12,372:2006, (2006a)), frost resistance (56 cycles) technological test A 3.4–4.1 N/mm^2 (BS EN 12,371:2010, (2010)) and breaking load at dowel hole 0.87–1.43 parallel (Type IIa), and 0.81–1.74 kN parallel to edge (Type IIb) (BS EN 13,364:2002, (2002)).

3.2. Testing procedure

Within the current test series 35 samples of Darney stone samples of 100 mm x 100 mm x 100 mm dimension were tested for UCS at six different moisture levels.

Moisture absorption was measured according to BS EN 13,755–2008 (BSI British Standards Institution 2008). Specimens were dried at (70 ± 5) Celsius in an oven to constant mass (m_d) and weighed to an accuracy of 0.01 g. Samples were next placed in water at (20 ± 10) Celsius initially to half the height and next fully submerged until constant mass was reached (m_s), see Figure 8. Water absorption (A) was calculated using Equation 17 and

Table 2. Test results.

Set	Sample No.	Moisture (%)	Dry density (g/cm^3)	UCS (N/mm^2)		Moisture (%)	UCS (N/mm^2)	UCS of oven dry (N/mm^2)
1 Oven dry	1	0.05	2.1	69.5	Mean	0.05	71.7	100%
	2	0.04	2.2	73.1	CoV (%)	27	3.4	
	3	0.05	2.1	69.9				
	4	0.05	2.1	71.6				
	5	0.05	2.2	69.1				
	6	0.04	2.2	74.9				
	7	0.04	2.2	74.4				
	8	0.09	2.2	72.7				
	9	0.04	2.2	74.3				
	10	0.05	2.2	67.6				
2 Air dry	11	0.18	2.2	60.5	Mean	0.16	61.4	86%
	12	0.13	2.1	62.8	CoV (%)	21.86	1.4	
	13	0.14	2.1	61.4				
	14	0.14	2.1	61.9				
	15	0.22	2.1	60.7				
3 Wet (24 hrs oven dry)	16	0.45	2.2	57.9	Mean	0.45	60.9	85%
	17	0.54	2.1	60.4	CoV (%)	11.45	3.3	
	18	0.40	2.2	61.4				
	19	0.40	2.2	60.8				
	20	0.45	2.1	64.1				
4 Wet (19 hrs oven dry)	21	0.45	2.2	60.4	Mean	0.60	59.9	83%
	22	0.95	2.2		CoV (%)	33.8	2.3	
	23	0.62	2.2	61.9				
	24	0.36	2.1	58.7				
	25	0.59	2.1	58.5				
5 Wet (5 hrs oven dry)	26	4.33	2.2	57.9	Mean	4.43	59.4	83%
	27	4.33	2.1	59.6	CoV (%)	2.48	1.4	
	28	4.36	2.2	59.3				
	29	4.59	2.1	59.7				
	30	4.53	2.2	60.3				
6 Saturated	31	6.03	2.2	57.4	Mean	6.07	57.9	81%
	32	6.44	2.1	57.2	CoV (%)	3.15	1	
	33	5.96	2.1	58.0				
	34	5.89	2.1	58.2				
	35	6.03	2.1	58.8				

results are listed in Table 2. Water absorption was around 6% when fully saturated.

$$A = \frac{m_s - m_d}{m_d} \times 100 \qquad (17)$$

To test the UCS at six different moisture levels, samples were dried either in air or in the oven for different periods of time following the water absorption measurement:

- Set 1 - Oven-dry: 10 samples dried in the oven to a constant mass (0.05% moisture)
- Set 2 - Air-dry: 5 samples air dried to a constant mass (0.16% moisture)
- Set 3 - Oven-dry (24 hours): 5 samples dried in the oven for 24 hours (0.45% moisture)
- Set 4 - Oven-dry (19 hours): 5 samples dried in the oven for 19 hours (0.6% moisture)
- Set 5 - Oven-dry (5 hours): 5 samples dried in the oven for 5 hours (4.43% moisture)
- Set 6 - Fully saturated: 5 samples tested fully saturated (6.07% moisture).

UCS was tested parallel to the bedding plane in a VJT6000 concrete cube testing machine at 5 kN/s loading rate. Test results are listed in Table 2 with the mean and coefficient of variation (CoV) for each set. UCS was around 70 N/mm^2 for oven dry and 58 N/mm^2 for saturated samples. Saturation reduced the UCS by around 20%.

The relationship between UCS and moisture content are shown in Figure 9 with an indicative correlation of 61.004 x$^{-0.039}$ ($R^2 = 0.6828$). About half the loss in UCS occurred within 0.16% moisture gain, at air-dry conditions.

4. Analysis

4.1. Loss of UCS due to saturation

All available test data on the reduction of UCS for sandstones due to saturation was collated from the literature (Bell 1978; Bell and Culshaw (1998); Masoumi, Horne, and Timms (2017); Zhou et al. (2016); Majeed and Abu Bakarb (2018); Hawkins and

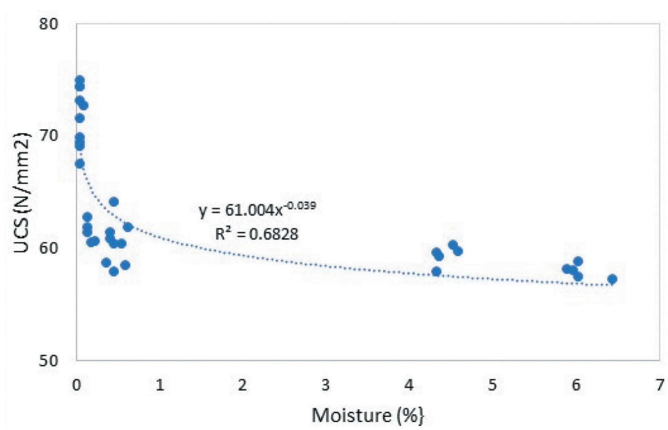

Figure 9. UCS vs. moisture for test data.

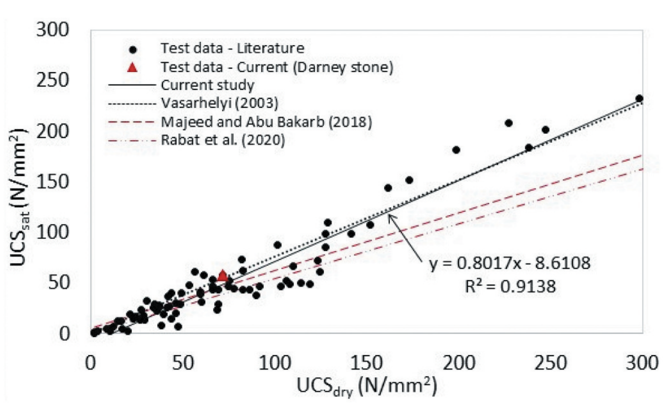

Figure 10. Summary for all data.

Table 3. Average relationship between UCS_{sat} and UCS_{dry} from literature.

Source	Stone type	Model
Current study	Sandstones	UCSsat = 0.8017 UCSdry − 8.6108 (R2 = 0.9138)
Vasarhelyi (2003) for Hawkins and McConnell (1992)	Sandstones	UCSsat = 0.759 UCSdry (R2 = 0.906)
Majeed and Abu Bakarb (2018)	Various	UCSsat = 0.57 UCSdry + 5.63 (R2 = 0.72)
Rabat, Cano, and Tomas (2020)	Various	UCSsat = 0.5416 UCSdry (R2 = 0.939)

McConnell (1992); Tang (2018); Jeng et al. (2004); Agustawijaya (2007); Liu et al. (2020)) to identify the average relationship. Tests focused on either the (a) variability of UCS for individual stone types or (b) on the variability of UCS among different stone types. If different types of stones were tested within one test series, only sandstones were included in the current analysis. To allow different sandstone types to be meaningfully compared, multiple test data for the same stone types were represented by the average values only.

All available test data for 78 different sandstones, including the current tests for Darney stone are shown in Figure 10. The average relationship between saturated UCS (UCS_{sat}) and oven dry UCS (UCS_{dry}) is shown in Equation 18 and indicates an average reduction of 20% in UCS under saturation.

$$UCS_{sat} = 0.8017\ UCS_{dry} - 8.6108 \qquad (R^2 = 0.9138) \tag{18}$$

Three researchers have proposed correlations between UCS_{sat} and UCS_{dry} that are included in Figure 10 and listed in Table 3. Vasarhelyi (2003) based his model on a similar set of 35 British sandstone tests by Hawkins and McConnell (1992) and identified an around 25% reduction in UCS due to saturation. This is similar to the current model with 20% reduction. Majeed and Abu Bakarb (2018) tested a wider range of 34 sedimentary rocks (including limestones, sandstones, dolomites) with around 33% reduction. Rabat, Cano, and Tomas (2020) tested four porous calcarenite building stones with around 45% reduction in UCS. For sandstones, the average reduction in UCS is therefore around 20–25%, while for a wider range of stones it is notably greater.

4.2. Time-dependent strength loss

Five sets of test data have been published in the literature on the rate of saturation. For moisture gain (soaking), two tests were published by Zhou et al. (2016) and Tang (2018) on sandstones and one by Liu, Yang, and Yu (2015) on slate. On moisture loss (during drying) two tests were published by Zhou et al. (2016) and Liu et al. (2020) on sandstones. Moisture loss for the current sandstone samples was also measured. Results are however not directly comparable as Zhou et al. (2016) dried samples under laboratory conditions with very good ventilation at 25°C and Liu et al. (2020) in an electric-drying oven with forced convection at 110°C.

As part of the current test series, five sets of samples were tested for the rate of saturation for the first 24 hours and for moisture loss up to 300 hours under indoors conditions at 16°C.

The collated test data for normalized saturation levels against time are shown in Figure 11 together with the current test data. Zhou et al. (2016) and Tang (2018) provide high-resolution relationships for early saturation while Liu, Yang, and Yu (2015) only provides data after 24 hours.

For the available tests, full saturation is reached within 24–48 hours for sandstones and around 240

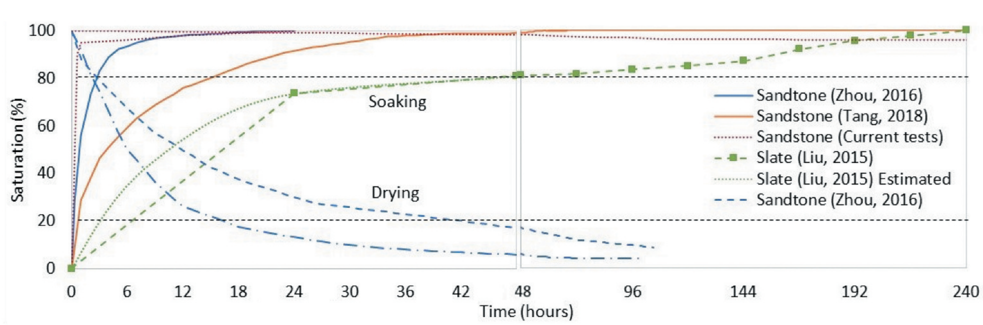

Figure 11. Saturation vs. soaking time.

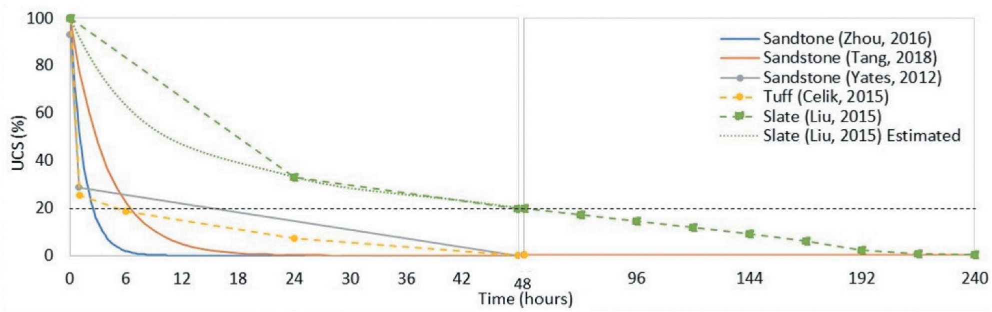

Figure 12. UCS vs. soaking time.

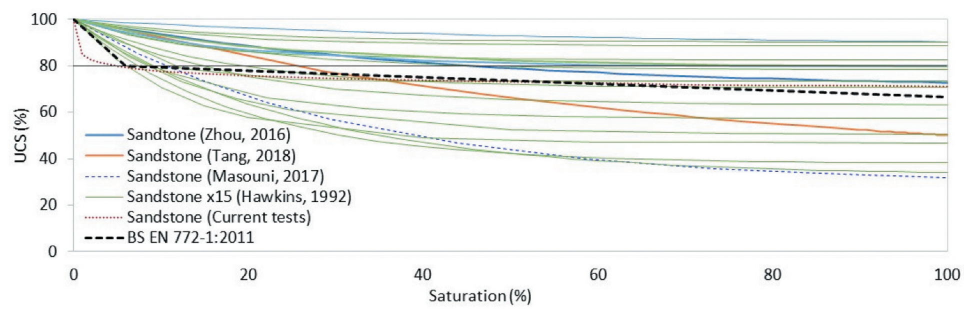

Figure 13. UCS vs. saturation.

hours for slate. During soaking, 80% of saturation is reached within 2–15 hours for sandstone and 48 hours for slate. The drying test results are not comparable as they were carried out under very different conditions.

Five sets of test data have been published in the literature on UCS against saturation time, three on sandstones by Zhou et al. (2016), Tang (2018), and Yates, Richardson, and Miglio (2012) one on tuff by Celik and Ergul (2015) and one on slate by Liu, Yang, and Yu (2015). The collated test data normalized for UCS against time is shown in Figure 12. Eighty percent of the UCS is lost within 2.5–6 hours for sandstones and tuff and 48 hours for slate, corresponding to around 20% of saturation time for the individual stones.

Finally, the relationship between UCS and saturation time identified for 19 stone types by Zhou et al. (2016), Tang (2018), Masoumi, Horne, and Timms (2017), Hawkins and McConnell (1992) and the current tests is shown in Figure 13 for the available sandstones tests. The loss of UCS under full saturation ranges widely between 10–65%. Figure 13 also includes the equivalent compressive strength as a function of saturation defined by BS EN 772–1:2011 (BSI British Standards Institution 2011). BS EN 772–1:2011 adjusts the equivalent compressive strength of air-dry units using multipliers 1.0 for air-dry and 6% moisture, 0.8 for oven-dry and 1.2 for immersed conditions. For air-dry conditions with 20% reduction in UCS, BS EN 772–1:2011 shows good agreement (lower-bound solution) for the test data. For full saturation (immersed conditions) the estimated ca. 30% reduction by BS EN 772–1:2011, however significantly overestimates many of the stone types up to 65% reduction in UCS and provides an average, rather than lower-bound solution.

The BS EN 772–1:2011 (BSI British Standards Institution 2011) estimate of ca. 30% reduction in UCS under immersed conditions is, however, similar to the average 20–25% reduction indicated by the 78 sandstones tests (Equation 5, Equation 18, Figure 10 and Table 3).

To provide a safe estimate, the adjustment factor needs to be reviewed for a wider selection of stones based on further tests. As a general figure, a lower-bound solution around 50% reduction in UCS is likely to be more a realistic (lower-bound) estimate. 50% reduction would be the equivalent of a 1.6 multiplier (instead of the current 1.2) for immersed conditions. For individual stones the adjustment factor generally can be reduced, based on test data.

5. Conclusions

The effect of moisture content was investigated on the uniaxial compressive strength (UCS) of sandstones.

From an extensive literature review, test data for 77 sandstone types was collated for the loss of UCS, together with available models. Thirty-four UK Darney stone samples were tested under six different moisture conditions. The rate of moisture-gain and loss was evaluated with respect to UCS. Findings for the reduction of UCS were compared with the equivalent compressive strength used in BS EN 772–1:2011 for oven-dry, air-dry, and saturated conditions.
Summary of findings:

- Test data for 77 different sandstone types was collated to identify the loss of UCS. Under full-saturation UCS reduced up to around 45%, with the average reduction of around 20%.
- UCS for the UK Darney sandstone was 72 N/mm^2 under oven-dry and 58 N/mm^2 under saturated conditions, with around 20% loss of UCS. About half the loss of UCS occurred within the first 0.16% moisture gain, at air-dry conditions. Findings agreed well with the test data for 77 sandstones published in the literature.
- The rate of saturation was strongly nonlinear and occurred soon after exposure to water. For sandstones 80% of saturation occurred within 2-15 hours and full saturation was typically reached within 24-48 hours. During drying, 80% of moisture loss was reached between 12-48 hours. The time required for drying was around four times longer than the saturation time.
- Significant loss of UCS occurred soon after exposure to water. For sandstones 80% of UCS loss occurred within the first 2.5-6 hours and UCS was reduced up to 45% when fully saturated.
- The BS EN 772-1:2011 estimates for the effect of moisture on UCS were compared with the available test data. Adjustment factors for the equivalent compressive strength of air-dry and oven-dry conditions showed good agreement with lower-bound solution. For immersed conditions, the BS EN 772-1:2011 estimate of 30% reduction in UCS is however significantly smaller than some of the test results up to 45% loss in UCS.
- BS EN 772-1:2011 is likely to overestimate the equivalent compressive strength under immersed conditions. The adjustment factor needs to be reviewed. A 50% reduction in UCS under saturation is proposed as a more conservative (lower-bound) estimate that would be the equivalent of a 1.6 multiplier (instead of the current 1.2) for immersed conditions. For individual stone types, the adjustment factor can generally be reduced based on test data.

The effect of moisture content on UCS is of particular importance for assessing low-strength historic masonry and for designing new masonry structures. Further work is needed to identify the variability and lower-bound estimates for the effect of moisture on UCS for sandstones.

Acknowledgments

The authors gratefully acknowledge the support of the University of Pécs, Hungary through the Thematic Excellence Programme Framework 2019 (TUDFO/51757-1/2019-ITM). The opportunity to use the Brunel University Civil Engineering laboratory facilities is gratefully acknowledged. The authors wish to thank Marcus Paine from Hutton Stone for his expert advice and providing Darney stone samples for testing. Further thanks to Sabrirajan Tamilselvam and Mihrab El-Fatih MSc students at Brunel University London for their excellent help with laboratory testing.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

The work was supported by the Thematic Excellence Programme Framework 2019 [TUDFO/51757-1/2019-ITM].

References

Agliata, R., T. Bogaard, R. Greco, L. Mollo, E. Slob, and S. Steele-Dunne. 2018. Non-invasive estimation of moisture content in tuff bricks by GPR. *Construction and Building Materials* 160:698–706. doi:10.1016/j.conbuildmat.2017.11.103.
Agustawijaya, D. 2007. The uniaxial compressive strength of soft rock. *Civil Engineering Dimension* 9 (1):9–14.
ASTM (American Society for Testing and Materials). 2016. ASTM D5731-16 Standard Test Method for Determination of the Point Load Strength Index of Rock and Application to Rock Strength Classifications.
ASTM (American Society for Testing and Materials). 2017. ASTM C170-17 Standard test method for compressive strength of dimension stone.
ASTM (American Society for Testing and Materials). 2018. ASTM C97-18 Standard test methods for absorption and bulk specific gravity of dimension stone.
ASTM (American Society for Testing and Materials). 2019. ASTM D2216-19 Standard test method for laboratory determination of water (moisture) content of soil and rock by mass.

Ballivy, G., B. Ladanyi, and D. Gill. 1976. Effect of Water Saturation History on the Strength of Low-Porosity Rocks. STP599-EB Soil Specimen Preparation for Laboratory Testing. In *ASTM International Soil Specimen Preparation for Laboratory Testing*, ed. D. Sangrey, and R. Mitchell, 4–20. West Conshohocken, PA: ASTM International.

Bell, F. 1978. The physical and mechanical properties of the fell sandstones, Northumberland, England. *Engineering Geology* 12:1–29. doi:10.1016/0013-7952(78)90002-9.

Bell, F., and M. Culshaw. 1998. Petrographic and engineering properties of sandstones from the Sneinton Formation, Nottinghamshire, England. *Quarterly Journal of Engineering Geology* 31 (1):5–19. doi:10.1144/GSL.QJEG.1998.031.P1.02.

Binda, L., G. Cardani, and L. Zanzi L. 2010. Nondestructive Testing Evaluation of Drying Process in Flooded Full-Scale Masonry Walls. *Journal of Performance of Constructed Facilities* 24 (5):473–83. doi:10.1061/(ASCE)CF.1943-5509.0000097.

BSI (British Standards Institution). 1999a. BS EN 1925: 1999 Natural stone test methods. Determination of water absorption coefficient by capillarity.

BSI (British Standards Institution). 1999b. BS EN 772-10: 1999 Methods of test for masonry units, Part 10: Determination of moisture content of calcium silicate and autoclaved aerated concrete units.

BSI (British Standards Institution). 2002. BS EN 13364: 2002 Natural stone test methods. Determination of the breaking load at dowel hole.

BSI (British Standards Institution). 2005. BS EN 1996-1-1: 2005 Eurocode 6, Design of masonry structures, Part 1-1: General rules for reinforced and unreinforced masonry structures.

BSI (British Standards Institution). 2006a. BS EN 12372: 2006 Natural stone test methods. Determination of flexural strength under concentrated load.

BSI (British Standards Institution). 2006b. BS EN 1926: 2006 Natural stone test methods - Determination of compressive strength.

BSI (British Standards Institution). 2006c. BS EN 1936: 2006 Natural stone test methods. Determination of real density and apparent density, and of total and open porosity.

BSI (British Standards Institution). 2008. BS EN 13755: 2008 Natural stone methods, Determination of water absorption at atmospheric pressure.

BSI (British Standards Institution). 2010. BS EN 12371: 2010 Natural stone test methods. Determination of frost resistance.

BSI (British Standards Institution). 2011. BS EN 772-1: 2011 Methods of test for masonry units, Part 1: Determination of compressive strength.

BSI (British Standards Institution). 2017. BS EN 16682: 2017 Conservation of cultural heritage - Methods of measurement of moisture content, or water content, in materials constituting immovable cultural heritage.

Camuffo, D. 2018. Standardization activity in the evaluation of moisture content. *Journal of Cultural Heritage* 31S:S10–14. doi:10.1016/j.culher.2018.03.021.

Celik, M., and A. Ergul. 2015. The influence of the water saturation on the strength of volcanic tuffs used as building stones. *Environmental Earth Science* 74 (4):3223–39. doi:10.1007/s12665-015-4359-x.

Di Tullio, V., N. Proietti, M. Gobbino, D. Capitani, R. Olmi, S. Priori, C. Riminesi, and E. Giani. 2010. Non-destructive mapping of dampness and salts in degraded wall paintings in hypogeous buildings: The case of St. Clement at mass fresco in St. Clement Basilica, Rome. *Analytical and Bioanalytical Chemistry* 396 (5):1885–96. doi:10.1007/s00216-009-3400-x.

Edis, E., I. Flores-Colen, and J. De Brito. 2014. Passive thermographic detection of moisture problems in façades with adhered ceramic cladding. *Construction and Building Materials* 51:187–97. doi:10.1016/j.conbuildmat.2013.10.085.

Fahimifar, A., and H. Soroush. 2007. A Moisture Index Classification System for Rocks (MiC System). *Rock Mechanics & Rock Engineering* 40 (1):63–79. doi:10.1007/s00603-005-0079-y.

Hall, C., and W. Hoff. 2001. *Water transport in brick, stone and concrete*. 3rd ed. London: CRC Press.

Hall, C., and W. Hoff. 2007. Rising damp: Capillary rise dynamics in walls. *Proceedings of the Royal Society. A, Mathematical, physical, and engineering sciences* 463:1871–84. https://www.jstor.org/stable/20209286

Hawkins, A. 1998. Aspects of rock strength. *Bulletin of Engineering Geology and the Environment* 57 (1):17–30. doi:10.1007/s100640050017.

Hawkins, A., and B. McConnell. 1992. Sensitivity of sandstone strength and deformability to changes in moisture content. *Quarterly Journal of Engineering Geology and Hydrogeology* 25 (2):115–30. doi:10.1144/GSL.QJEG.1992.025.02.05.

Jeng, F., M. Weng, M. Lin, and T. Huang. 2004. Influence of petrographic parameters on geotechnical properties of tertiary sandstones from Taiwan. *Engineering Geology* 73 (1–2):71–91. doi:10.1016/j.enggeo.2003.12.001.

Karakul, H. 2017. Investigation of saturation effect on the relationship between compressive strength and Schmidt hammer rebound. *Bulletin of Engineering Geology and the Environment* 76 (3):1143–52. doi:10.1007/s10064-016-0883-5.

Karakul, H., and R. Ulusay. 2013. Empirical Correlations for Predicting Strength Properties of Rocks from P-wave velocity under different degrees of saturation. *Rock Mechanics & Rock Engineering* 46:981–99. doi:10.1007/s00603-012-0353-8.

Khanlari, G., and Y. Abdilor. 2015. Influence of wet–dry, freeze–thaw, and heat–cool cycles on the physical and mechanical properties of Upper Red sandstones in central Iran. *Bulletin of Engineering Geology and the Environment* 74 (4):1287–300. doi:10.1007/s10064-014-0691-8.

Kim, E., M. Stine, D. De Oliveira, and H. Changani. 2017. Correlations between the physical and mechanical properties of sandstones with changes of water content and loading rates. *International Journal of Rock Mechanics and Mining Sciences* 100:255–62. doi:10.1016/j.ijrmms.2017.11.005.

Lai, J., G. Wanga, Z. Wang, J. Chen, X. Pang, S. Wang, Z. Zhou, Z. He, Z. Qin, and X. Fan. 2018. A review on pore structure characterization in tight sandstones. *Earth-*

Science Reviews 177:436–57. doi:10.1016/j.earscirev.2017.12.003.

Larsen, P. 2012. Determination of Water Content in Brick Masonry Walls using a Dielectric Probe. *Journal of Architectural Conservation* 18 (1):47–62. doi:10.1080/13556207.2012.10785103.

Lin, M., F. Jeng, L. Tsai, and T. Huang. 2005. Wetting weakening of tertiary sandstones—microscopic mechanism. *Environmental Geology* 48 (2):265–75. doi:10.1007/s00254-005-1318-y.

Liu, Y., Y. Cai, S. Huang, Y. Guo, and G. Liu. 2020. Effect of water saturation on uniaxial compressive strength and damage degree of clay-bearing sandstone under freeze-thaw. *Bulletin of Engineering Geology and the Environment* 79 (4):2021–36. doi:10.1007/s10064-019-01686-w.

Liu, X., C. Yang, and J. Yu. 2015. The Influence of Moisture Content on the time-dependent characteristics for Rocks. *Advances in Materials Science and Engineering* 2015:1–13. doi:10.1155/2015/725162.

Majeed, Y., and M. Abu Bakarb. 2018. Water saturation influences on engineering properties of selected sedimentary rocks of Pakistan. *Journal of Mining Science* 54 (6):914–93. doi:10.1134/S1062739118065060.

Masoumi, H., J. Horne, and W. Timms. 2017. Establishing Empirical Relationships for the Effects of Water Content on the Mechanical Behavior of Gosford Sandstone. *Rock Mechanics & Rock Engineering* 50 (8):2235–42. doi:10.1007/s00603-017-1243-x.

Mollo, L., and G. Greco. 2011. Moisture measurements in masonry materials by time domain reflectometry. *Journal of Materials in Civil Engineering* 23 (4):441–44. doi:10.1061/(ASCE)MT.1943-5533.0000188.

Mol, L., and H. Viles. 2013. Exposing drying patterns: Using electrical resistivity tomography to monitor capillary rise in sandstone under varying drying conditions. *Environmental Earth Sciences* 68 (6):1647–59. doi:10.1007/s12665-012-1858-x.

Orr, S., L. Fusade, M. Young, D. Stelfox, A. Lesliee, J. Currand, and H. Viles. 2020. Moisture monitoring of stone masonry - a comparison of microwave and radar on a granite and a sandstone tower. *Journal of Cultural Heritage* 41:61–73. doi:10.1016/j.culher.2019.07.011.

Phillipson, M., P. Baker, M. Davies, Z. Ye, G. Galbraitha, and R. McLeanc. 2008. Suitability of time domain reflectometry for monitoring moisture in building materials. *Building Services Engineering Research & Technology* 29 (3):261–72. doi:10.1177/0143624408092423.

Price, N. J. 1960. The compressive strength of coal measure rocks. *Colliery Engineering* 37 (437):283–92.

Priest, S., and S. Selvakumar. 1982. *The Failure Characteristics of Selected British Rocks*. Transport and Road Research Laboratory Report.

Proietti, N., P. Calicchia, F. Colao, S. De Simone, V. Di Tullio, L. Luvidi, F. Prestileo, M. Romani, and A. Tatì. 2021. Moisture damage in ancient masonry: A multidisciplinary approach for in situ diagnostics. *Minerals* 11 (4):406–29. doi:10.3390/min11040406.

Rabat, A., M. Cano, and R. Tomas. 2020. Effect of water saturation on strength and deformability of building calcarenite stones: Correlations with their physical properties. *Construction and Building Materials* 232:117259. doi:10.1016/j.conbuildmat.2019.117259.

Rirsch, E., and Z. Zhan. 2010. Rising damp in masonry walls and the importance of mortar properties. *Construction and Building Materials* 24 (10):1815–20. doi:10.1016/j.conbuildmat.2010.04.024.

Roels, S., and J. Carmeliet. 2006. Analysis of moisture flow in porous materials using microfocus X-ray radiography. *International Journal of Heat and Mass Transfer* 49 (25):4762–72. doi:10.1016/j.ijheatmasstransfer.2006.06.035.

Sandrolini, F., and E. Franzoni. 2006. An operative protocol for reliable measurements of moisture in porus materials of ancient buildings. *Building and Environment* 41 (10):1372–80. doi:10.1016/j.buildenv.2005.05.023.

Semerák, P., and R. Cerny. 1997. A capacitance method for measuring the moisture content of building materials. *Stavebnıóbzor* 6:102–03.

Tang, S. 2018. The effects of water on the strength of black sandstone in a brittle regime. *Engineering Geology* 239:167–78. doi:10.1016/j.enggeo.2018.03.025.

Van Eeckhout, E. 1976. Mechanisms of strength reduction due to moisture in coalmine shales. *International Journal of Rock Mechanics and Mining Sciences* 13 (2):61–67. doi:10.1016/0148-9062(76)90705-1.

Vasarhelyi, B. 2003. Some observations regarding the strength and deformability of sandstones in dry and saturated conditions. *Bulletin of Engineering Geology and the Environment* 62 (3):245–49. doi:10.1007/s10064-002-0186-x.

Vasarhelyi, B., and P. Ván. 2006. Influence of water content on the strength of rock. *Engineering Geology* 84 (1–2):70–74. doi:10.1016/j.enggeo.2005.11.011.

Verstrynge, E., R. Adriaens, J. Elsen, and K. Van Balen. 2014. Multi-scale analysis on the influence of moisture on the mechanical behavior of ferruginous sandstone. *Construction and Building Materials* 54:78–90. doi:10.1016/j.conbuildmat.2013.12.024.

Verstrynge, E., L. Schueremans, and D. Van Gemert. 2012. Creep and failure prediction of Diestian ferruginous sandstone: Modelling and repair options. *Construction and Building Materials* 29:149–57. doi:10.1016/j.conbuildmat.2011.10.042.

Wiid, B. 1967. The influence of moisture upon the strength behaviour of rock. PhD diss., University of Witwatersrand.

Winkler, E. 1994. *Stone in architecture: Properties, durability*. 3rd ed. Heidelburg: Springer-Verlag.

Wong, L., V. Maruvanchery, and G. Liu. 2016. Water effects on rock strength and stiffness degradation. *Acta Geotechnica* 11 (4):713–37. doi:10.1007/s11440-015-0407-7.

Xi, K., Y. Cao, Y. Wang, Q. Zhang, J. Jin, R. Zhu, S. Zhang, J. Wang, T. Yang, and L. Du. 2015. Factors influencing physical property evolution in sandstone mechanical compaction: The evidence from diagenetic simulation experiments. *Petroleum Science* 12 (3):391–405. doi:10.1007/s12182-015-0045-6.

Yao, W., C. Li, H. Zhan, J. Zhou, R. Criss, S. Xiong, and X. Jiang. 2020. Multiscale Study of Physical and Mechanical Properties of Sandstone in Three Gorges Reservoir Region Subjected to Cyclic Wetting–Drying of Yangtze River Water. *Rock Mechanics & Rock Engineering* 53 (5):2215–31. doi:10.1007/s00603-019-02037-7.

Yasar, S. 2020. Long term wetting characteristics and saturation induced strength reduction of some igneous rocks. *Environmental Earth Sciences* 79 (14):353. doi:10.1007/s12665-020-09105-0.

Yates, T., D. Richardson, and B. Miglio. 2012. Changes in engineering properties of natural stone. *Proceedings of the Institution of Civil Engineers Construction Materials* 165 (3):127–33. doi:10.1680/coma.9.00023.

Zhang, D., R. Gamage, M. Perera, C. Zhang, and W. Wanniarachchi. 2017. Influence of water saturation on the mechanical behaviour of low-permeability reservoir rocks. *Energies (Basel)* 10 (2):236–55. doi:10.3390/en10020236.

Zhao, J., E. Rivera, A. Mufti, D. Stephenson, and D. Thomson. 2012. Evaluation of dielectric based and other methods for moisture content measurement in building stones. *Journal of Civil Structural Health Monitoring* 2 (3–4):137–48. doi:10.1007/s13349-012-0024-1.

Zhou, Z., X. Cai, W. Cao, X. Li, and C. Xiong. 2016. Influence of water content on mechanical properties of rock. *Rock Mechanics & Rock Engineering* 49 (8):3009–25. doi:10.1007/s00603-016-0987-z.