Hall's Notes and Queries

NQ8

Wetting and drying strain in four English building stones

The topic of wetting/drying strain [WDS] has been strangely neglected in England. It is true that in 1927 F L Barrow[1] at the Building Research Station constructed an accurate mechanical extensometer to measure such movements. This was used by R E Stradling[2] to obtain data on a few materials, including just one stone (an unspecified Portland limestone), and all summarised in a single figure. Later Schaffer[3] devotes a few pages to "moisture expansion" as a cause of mechanical weathering and includes a compilation of data expressed as percent expansive strain on wetting.[4] Four calcitic limestones, two dolomitic limestones, and three sandstones only are included. No data source is given, so I assume the numbers come from

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[1]F L Barrow (1927) The measurement of moisture movements in building materials. J Sci Instrum **4** 475–480.

[2]R E Stradling (1928) Effects of moisture changes on building materials, Building Research Bulletin no 3, HMSO, London.

[3]R J Schaffer (1932), The weathering of natural building stones, Building Research Special Report no 18, HMSO London.

[4]The term *moisture expansion* is widely used but is not ideal: first, it is desirable to have a term which embraces both expansion on wetting and contraction/shrinkage on drying, the cyclic and largely reversible process with which I am concerned here; second, the term moisture expansion is also used to describe the slow and irreversible expansion of fired-clay brick ceramics due to rehydroxylation, a distinctly different process. I therefore use the term *wetting/drying strain* [WDS] in this NQ.

unpublished BRS files. That is more or less the extent of it for English stones. In contrast, data on European building stones are extensive: many publications from Professor Siegesmund at Göttingen[5] on stones from Germany and other countries; several solid contributions on French and Spanish materials;[6] and there is also Scherer's work[7] on N American sandstones.

In most if not all cases the existence of a significant WDS is linked to the presence of swelling clays in the mineralogy of the stone.

The purpose of this NQ is not to fill the English gap (an unrealistic ambition), but to report a few laboratory observations on English building stones and perhaps to spur interest in the topic. In addition I mention several open issues that arise.

New observations

Experimental details WDS and other measurements were carried out on 50 mm cubes of stone, except where noted. All tests were run at 25.0 ± 0.2 °C. Strain was measured with a Keyence GT-75A LVDT contact sensor, with a range of ± 5.0 mm reading to 1.0μm, and calibrated with a Moore & Wright 310 micrometer head. Displacement of the top face of the sample was measured during spontaneous imbibition of water through the base of the sample (Fig 1) and continued

[5] See for example J Ruedrich, T Bartelsen, R Dohrmann, S Siegesmund (2011) Moisture expansion as a deterioration factor for sandstone used in buildings. Environ Earth Sci **63** 1545-–1564.

[6] See for example J Berthonneau, P Bromblet, F Cherblanc, E Ferrage, J-M Vallet, O Graubya (2016), The spalling decay of building bioclastic limestones of Provence (South East of France): From clay minerals swelling to hydric dilation, J Cult Herit **17**, 53–60

[7] T Wangler & G W Scherer (2008), Clay swelling mechanism in clay-bearing sandstones, Environ Geol **56**, 529–534

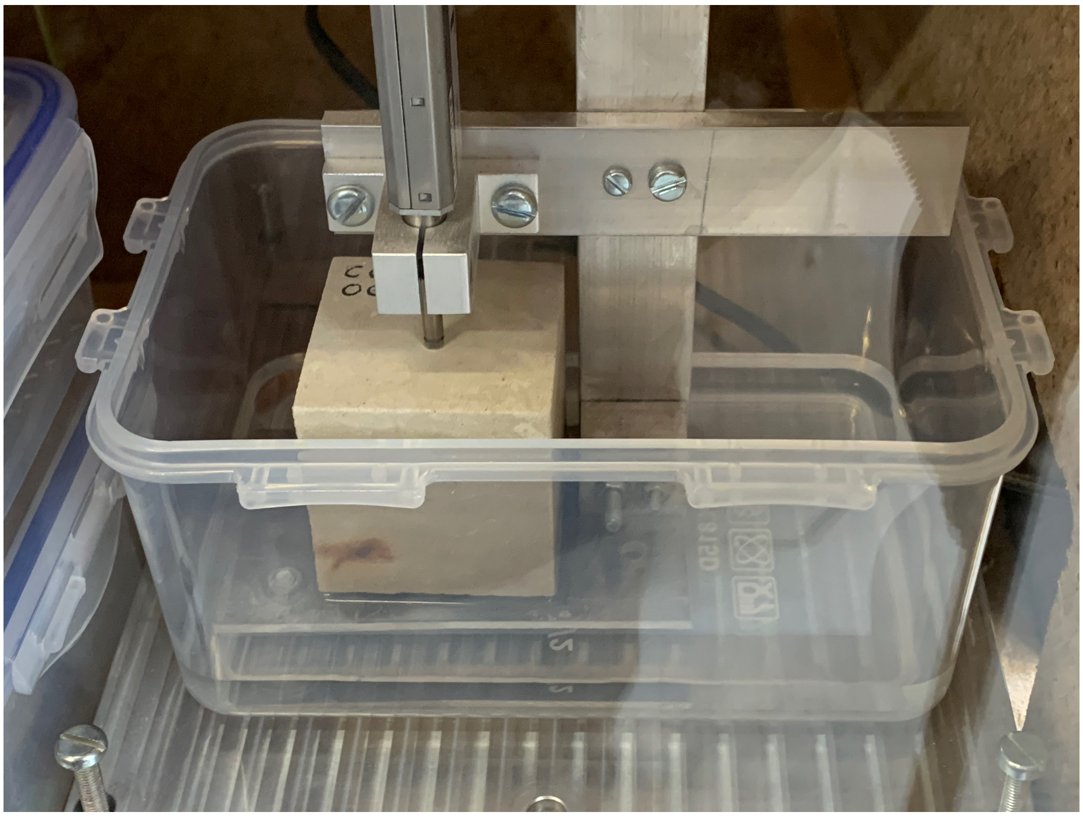

Figure 1: Experimental arrangement for WDS tests.

as the sample later dried by slow evaporation. RH was not controlled during drying but was measured and was generally in the range 25–55 percent.

Totternhoe limestone This stone, from Totternhoe in Bedfordshire, has been used locally for many centuries.[8] It comes from the cretaceous Lower Chalk formation, and generally contains some glauconite clay. Tests were carried out on several small rectangular prisms, and also on a larger irregular block with flat facets to provide contact surfaces for the LVDT sensor. Materials were provided by H G Clarke & Son. The measured porosity f is 0.262 ± 0.010; the fractional Hirschwald coefficient h 0.81; and the sorptivity 0.621 mm/min$^{1/2}$. The porosity agrees with Leary's values of 0.257 and 0.273.

Fig 2 shows the WDS measured with water over three complete wetting/drying cycles. The duration of the wetting phase is controlled by the rate of spontaneous imbibition (and the sample length), and is 1–2 h. The drying phase takes much longer as it controlled by slow evaporation processes, and here takes several days. The volume-fraction water content at the end of the wetting phase is $\theta_{\mathsf{h}} = f\mathsf{h}$: that is, the sample is in the Hirschwald state[9]. It is useful to have a simple metric for the magnitude of the WDS: for this purpose I use the *range* of the WDS in a single wetting/drying cycle. Let us call this quantity ϵ. Here ϵ for water is $\approx 8.0 \times 10^{-4}$ or about 0.08 percent or 0.8 mm/m.

Test samples of Totternhoe stone lacked a discernible bedding plane. However WDS tests carried out in three orthogonal directions showed considerable anisotropy. The ϵ values for the three directions are 8.0×10^{-4} (as in Fig 2), and 4×10^{-4} and 1.5×10^{-4} in the other two

[8] E Leary (1989) The building limestones of the British Isles, HMSO London.
[9] See NQ4

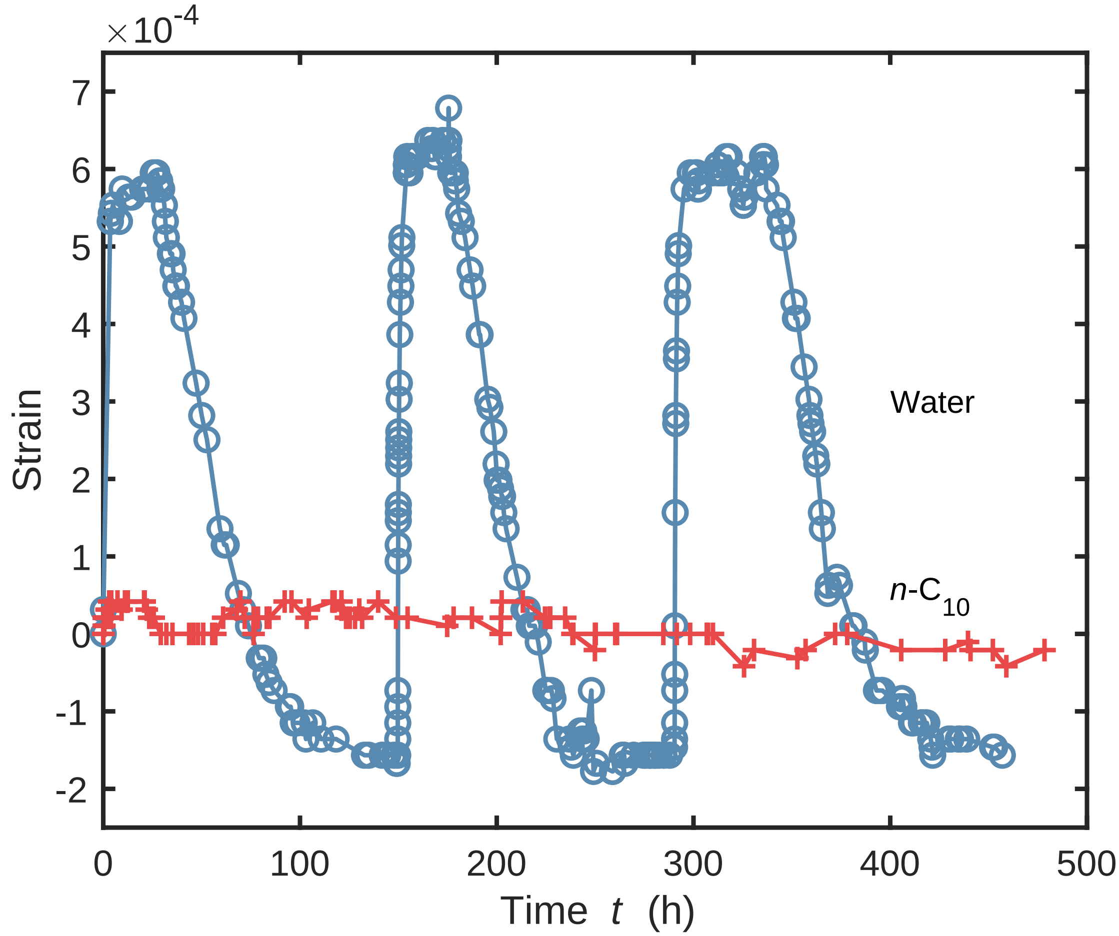

Figure 2: WDS in Totternhoe stone over three wetting/drying cycles at 25 °C; gauge length 47.9 mm; expansive strain, positive values. Blue ○, water; red +, *n*-decane.

orthogonal directions.

Fig 2 also shows data from tests in which the wetting liquid is the hydrocarbon *n*-decane, and for which the WDS is close to zero. This result is evidence that the strain observed with water is caused by physicochemical processes specific to water itself, and that simple capillarity effects are largely (and probably entirely) absent.

Greetland sandstone This stone, much used as pavers, is from within the Rough Rock sandstone formation, quarried in W Yorkshire, and known commercially as a Yorkstone.[10] Quartz and feldspars are the predominant minerals, with some clay. On samples tested, measured porosity f is 0.095, Hirschwald coefficient h 0.57, and sorptivity S 0.056 mm/min$^{1/2}$ (unusually low).

Fig 3 shows the WDS measured on a 50 mm Greetland cube over several cycles. The average ϵ value is about 7.1×10^{-4}. Also shown is the variation of RH during the drying phases. This varies in the range 21–59 percent. The strain at the end of each drying phase appears to be sensitive to the RH at that time.

Barrington limestone This is another Cambridgeshire clunch from the same Lower Chalk formation as Totternhoe; and also used locally for many centuries. Samples were supplied by Fairhaven Stone, Bottisham. The measured porosity f is 0.326 ± 0.010; the fractional Hirschwald coefficient h 0.78; and the sorptivity 0.934 mm/min$^{1/2}$.

The WDS over four cycles is shown in Fig 4. The average ϵ value is about 11.1×10^{-4}, the largest of the four stone types examined. Strain data from the wetting phases are replotted in Fig 5 to show

[10] C S Bristow (1993), Sedimentology of the Rough Rock: a Carboniferous braided river sheet sandstone in northern England. In Best & Bristow (eds), Braided rivers, Geological Society Special Publication no 75, pp 291–304.

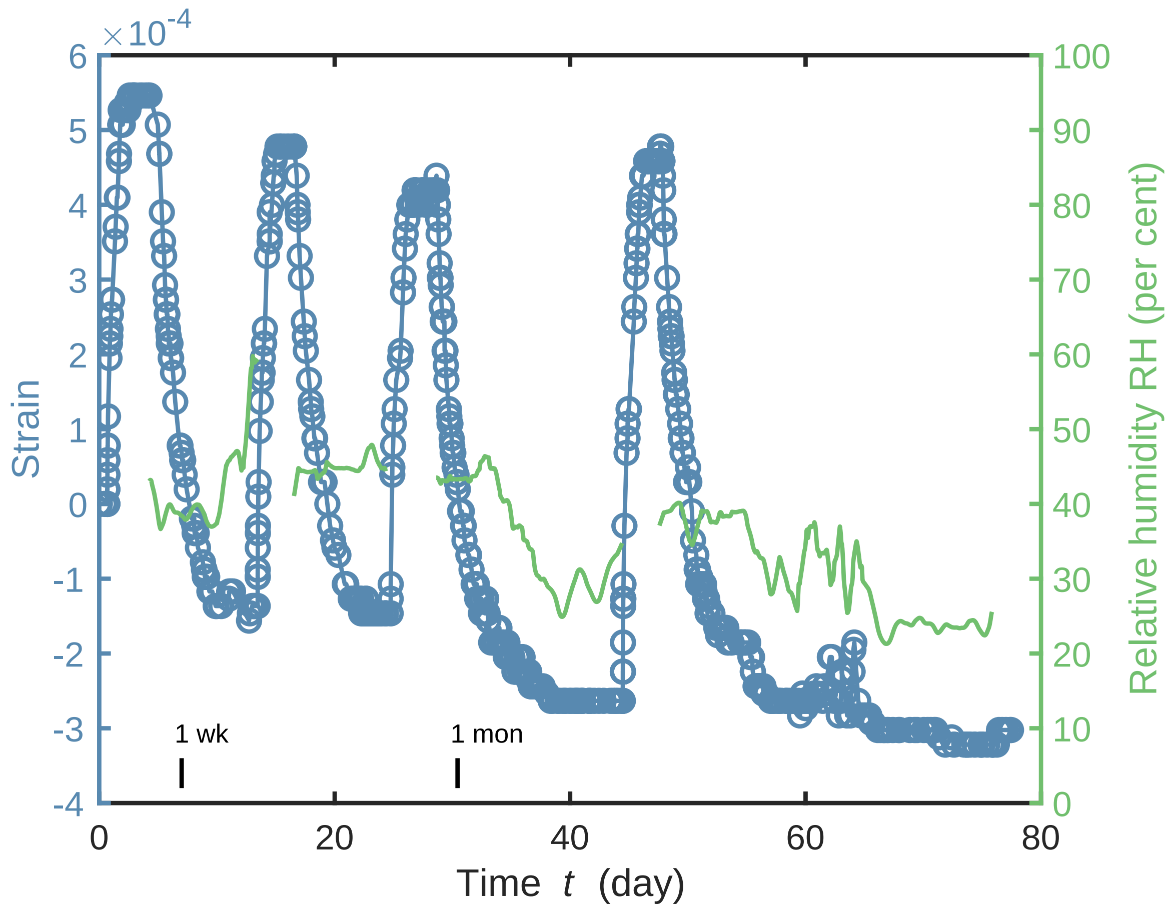

Figure 3: WDS in Greetland sandstone over four wetting/drying cycles at 25 °C; expansive strain, positive values. Blue ◯, water; green −, measured RH in sample environment

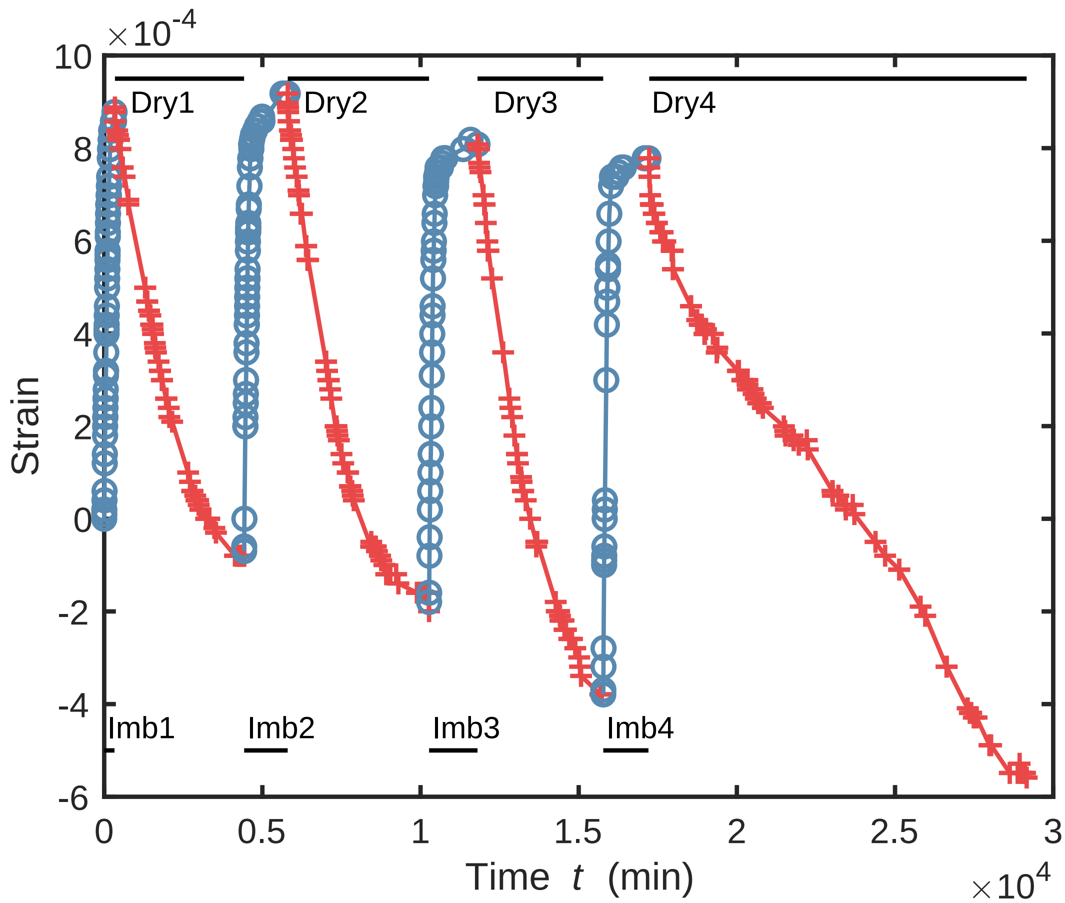

Figure 4: WDS in Barrington clunch over four wetting/drying cycles at 25 °C; expansive strain, positive values. Blue ○, water imbibition (wetting) phase; red +, drying phase

that the strain and the strain rate are more or less unchanged from cycle to cycle. Also plotted is the water absorption. The expansive strain during wetting tracks closely the water absorption, apart from a brief lag of about 5 min at the beginning of each imbibition. For practical purposes the strain and the water absorption are synchronous.

Barrington clunch is the only one of the four stones for which I have XRD data, see Fig 6.[11] The pattern confirms the presence of glauconite, together with calcite, considerable quartz and minor kaolinite.

Clipsham limestone Tests on a 50 mm cube of Clipsham stone show no measurable wetting strain on water imbibition. The sensitivity of the LVDT device is about $\pm 1\ \mu$m, so that the wetting strain (and ϵ approximately) is not greater than 0.2×10^{-4} going from dry to the Hirschwald state.

Comments

- The results reported here are incomplete and partial. They do however indicate the magnitude of the WDS. Similar values are reported elsewhere: for example the range of expansive strains in wetting is 3.7–15.3×10^{-4} in ten sandstones and tuffs from several countries;[12]; 2.3–13.2×10^{-4} in eight German sandstones;[13] 0.14–7.2×10^{-4} in seven French limestones;[14] and 10–

[11] XRD data from J Ioannou, U Cyprus

[12] S Siegesmund, C J Gross, R Dohrmann, B Marler, K Ufer, T Koch (2023), Moisture expansion of tuff stones and sandstones, Environ Earth Sci, v82, 146.

[13] Rüdrich et al. *op. cit.*

[14] Berthonneau et al. *op. cit.*

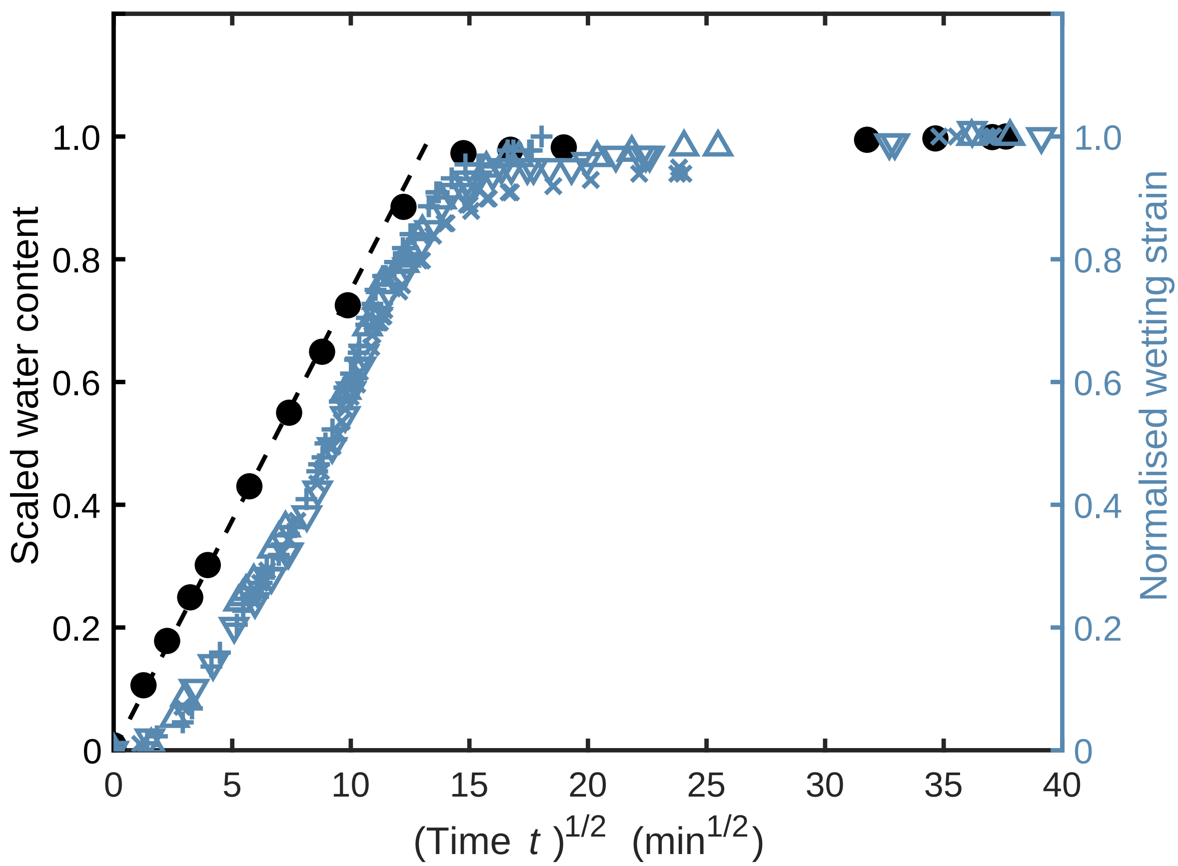

Figure 5: Expansive wetting strain in Barrington clunch (four cycles, data from Fig 4), compared with water content. Strain is normalised by its range in the wetting phase of each cycle; the water content is normalised by the quantity θ_h, and both are plotted against $t^{1/2}$, the square root of the elapsed time from the start of each wetting phase.

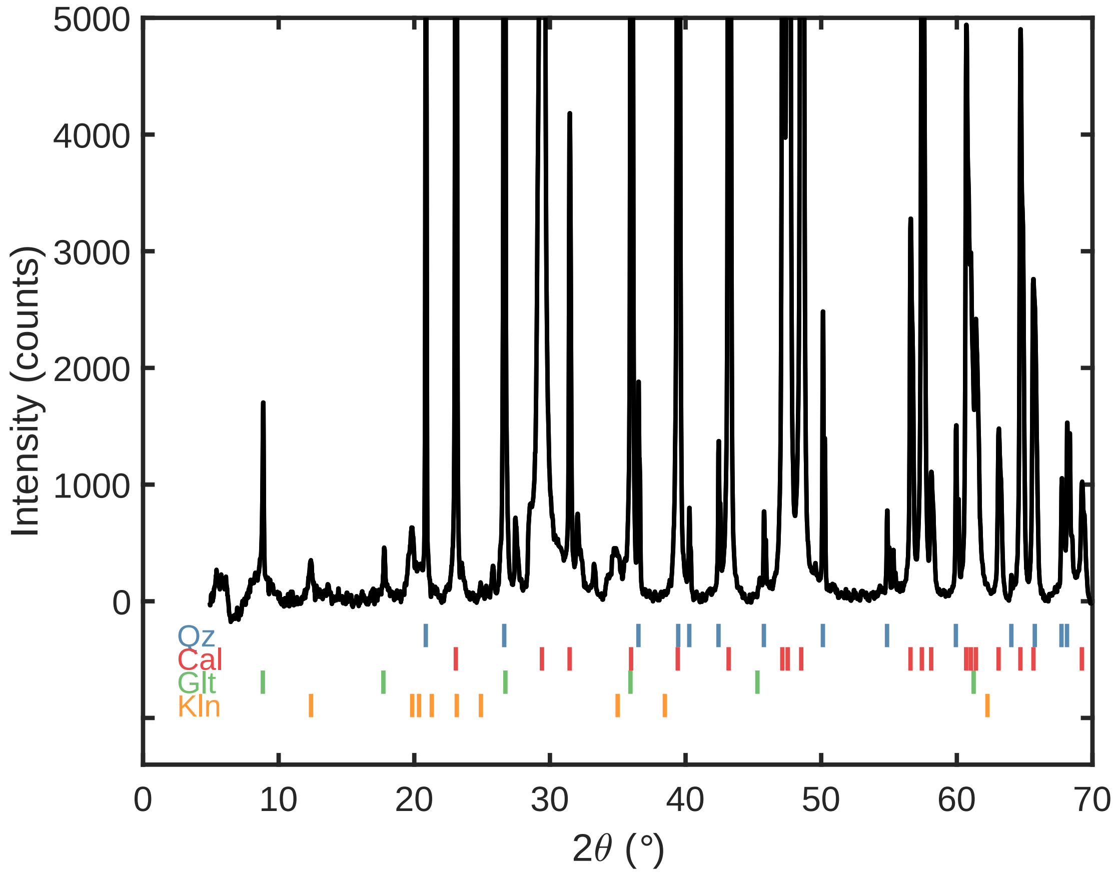

Figure 6: Powder XRD pattern of Barrington clunch: Cal calcite (ICSD 191852), Qz quartz (ICSD 100341), Glt glauconite (ICSD 166975), Kln kaolinite (G W Brindley & G Brown (1980), Crystal structures of clay minerals and their X-ray identification, Mineralogical Society, London, table 1.8)

21×10^{-4} in three N American sandstones.[15]

- Measurements of unconstrained expansion in the direction of unidirectional imbibition, and then of contraction in the same direction during evaporative drying from all cube faces, are simple and useful, but hardly adequate to characterise the mechanics of WDS. As noted by Scherer[16], the transient stresses developed during wetting and drying may include viscoelastic relaxation and buckling [17] Furthermore, the magnitude of WDS is such that in constrained situations the stress may be comparable with the local failure stress. In brittle materials such stones local stress may be amplified by Griffith flaws.

- In addition to the continuum mechanics, much remains to be understood about the micromechanics and physical chemistry of stones that exhibit WDS. In particular, the upscaling of clay swelling at the particle level in a complex hetereogeneous microstructure is only understood in a rather qualitative sense. In this NQ I have a detailed mineralogy for only one of the four stones; and properties such as sorption isotherms are lacking for all.

- The data on Totternhoe stone show the strong anisotropy of the WDS. This is hardly surprising in a sedimentary rock (and is found in all the other reports cited here). However, it means that a full characterisation requires measurements in two or preferably three directions at right angles, ideally in directions well defined in relation to the bedding plane – a lot of work. More fundamentally, the anisotropy at bulk level is the result

[15] Wangler & Scherer *op. cit.*

[16] G Scherer

[17] T P Wangler, A Stratulat, P Duffus, J H Prévost & G W Scherer (2011), Flaw propagation and buckling in clay-bearing sandstones, Environ Earth Sci v63 1565–1572

of microscopic orientations at the grain level. These are perhaps not even understood at the qualitative level.

- To the anisotropy, we must also add a further kind of heterogeneity often found parallel to the bedding plane: namely, lamellar structures or laminations. These arise from differences in microstructure on a rather small length scale as one moves through the stone at right angles to the bedding plane. The existence of these laminations suggests that the WDS may vary locally with a stone sample. This poses further experimental challenges.

I acknowledge a valuable exchange with Professor Siegesmund about whether Julius Hirschwald[18] made measurements of moisture expansion. We think he did not, although Schaffer[19] says that he did.

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18 October 2024

To cite this NQ: C Hall, Wetting and drying strain in four English building stones, *Hall's Notes and Queries* NQ8

[18] See NQ4 and NQ6 for more about Hirschwald.
[19] Schaffer, *op. cit.*