Effect of Ambient Humidity on the Elasticity and Deformation of Unweathered Granite

Y. Li¹, K. Leith¹, M. A. Perras², and S. Loew¹

¹Department of Earth Sciences, ETH Zürich, Zürich, Switzerland, ²Department of Civil Engineering, Lassonde School of Engineering, York University, Toronto, Canada

Abstract  Moisture variation has been noted as a driver of strains in both natural and anthropogenic bedrock environments. Similarly, increasing water content has been shown to reduce elastic stiffness in a variety of rock materials, though evidence for granites is limited. This study presents strains of an axially stressed (0.1 MPa) Herrnholz granite cylinder with ambient relative humidity alternating between 20% and 90% in a stepwise manner. At each ambient humidity level, the Young's modulus and Poisson’s ratio were determined by performing a series of load and unload cycles at 1–12 hr intervals. We observed that when the ambient humidity increased from 20% to 90%, Young’s modulus declined by 13% on average, and nearly returned to the initial dry value when the ambient humidity was reduced to 20%. Poisson’s ratio increased by 130% in response to the same humidity change, and approximately 60% of it was reversed when dried. These changes occurred linearly with a volumetric strain of up to $8 \times 10^{-4}$ of the tested sample, equivalent to 24.5 MPa internal stress. This stress change is attributed to the generation of nanoscale adsorption stress, which includes surface adhesion pressure along pore walls and capillary pressures within characteristic pore spaces. Using a modified adsorption model, the two contributions were estimated to be 8.5 and 16 MPa, respectively. The agreement between laboratory-derived and modeled stress change validates the proposed mechanism of adsorption-induced strains and elastic property variations in unweathered granite.

Plain Language Summary  The public is well aware that moisture variations caused by rainfall events or freeze-thaw processes have a negative impact on the stability of rock-formed infrastructures, such as stone constructions, water supplies, bridges, and natural rock slopes. However, the underlying mechanisms, such as how liquid water or vapor affects the properties and behaviors of rock, are not well understood. Granite, in particular, is generally known as a hard, low-porosity, and clay-deficient material; however, its softening and expansion under moist conditions is underappreciated. In a stepwise manner, we measured progressive deformation, and changes in Young's modulus and Poisson's ratio of a Herrnholz granite cylinder with ambient humidity alternating between 20% and 90%. Results suggest softening (Young’s modulus) and volumetric expansion of unweathered granite in wet conditions, and vice versa in dry conditions.

1. Introduction

Natural micro fractures in unweathered granitic rocks can provide specific surface areas of several m²/g (Beckingham et al., 2016; Dubois, 2011). When these surface areas come into contact with moisture (in either gas or liquid phase) from the surrounding atmosphere, fluid-solid interactions occur. Fluid-solid interactions have been shown to directly induce macroscopic strains and affect elastic and brittle properties of the whole body of the solid by adjusting crystal lattice spacing, generating internal pressures, and varying electrostatic forces between opposing crack walls (Gor & Bernstein, 2016; Gor et al., 2018; Hossain, 2017; Hossain et al., 2019; Pimiento et al., 2014; Tiennot & Fortin, 2020; Yurikov et al., 2018).

Extensive strains resulting from adsorption of liquid or gas molecules onto the solid surface of mesoporous (2 nm < pore diameter <50 nm according to the International Union of Pure and Applied Chemistry pore size classification method (Gregg & Sing, 1982)) media (e.g., carbons, silica, and glasses) have been shown to be on the order of $10^{-4}$ to $10^{-3}$ (Amberg & McIntosh, 1952; Chen, 2019; Chen et al., 2019; Gor et al., 2013, 2017; Haines & McIntosh, 1947; Jähnert et al., 2009; Lakhanpal & Flood, 1957; Schappert & Pelster, 2014b, for a useful review). Expansion of geological media was initially observed in stone building materials (e.g., sandstone and limestone) as air humidity increased (McBain & Ferguson, 1927). Since then, the addition of water has been shown to generate extensional strains ranging from 100 to 7,000 μm/m in a variety of clay-bearing sandstones.
A reduction in the elastic stiffness of geological media is commonly observed in association with relative increases in water content when performing laboratory compression tests (D. S. Yang et al., 2012; Heap et al., 2018, 2019; L. N. Y. Wong et al., 2016; Suknev, 2019; Tang et al., 2018) or ultrasonic measurements (Nakao et al., 2016; Pimenta et al., 2014, 2019; Spencer, 1981; Yurikov et al., 2018) in laboratory settings. Moisture has been shown to reduce stiffness in clay-bearing rocks by up to 90% (Erguler & Ulusay, 2009; L. N. Y. Wong et al., 2016) due to layer structure (which provide space for water) of clay minerals and their affinity for moisture. Numerous uniaxial compressive strength experiments on Buntsandstein sandstone cylinders revealed that elastic modulus of the water saturated sample was reduced by 9%–19% (Heap et al., 2018) compared to the oven-dry (>48 hr) state. Yurikov et al. (2018) observed a ~20% reduction and subsequent recovery of bulk and shear moduli associated with water adsorption (increased relative humidity [RH] from 13% to 97%) and desorption (decreased RH from 97% to 13%) onto Bentheim sandstone. This was accompanied by a 10^−4 expansion and contraction during the wetting-drying cycle. Hossain et al. (2019) discovered that the bulk and shear moduli of Bentheim sandstone are similarly dependent on RH, with the difference of up to 22.5% between the wettest (90% RH) and the driest (vacuum oven for 48 hr) states. The temporal evolution of P-wave velocity in a series of rock types (Berea sandstone, Shirahama sandstone, Kushiro sandstone, and Oshima granite) as RH increases from 50% to 90% reveals that granite has the least P-wave velocity reduction (1/6–1/3 of the reduction in sandstones) (Nakao et al., 2016). Wave velocities are known to be related to the elastic moduli of materials. One study (Labuz & Berger, 1990) previously reported that spraying the surfaces of employed specimens with tap water reduces the stiffness of granite by ~15%.

Macroscopic changes in strains and elastic properties are of practical importance for conventional geotechnical applications (e.g., underground excavations for radioactive waste disposal, and carbon capture and storage), as well as near-surface seismic studies (e.g., decrease in bulk modulus is expected to reduce wave velocities and resonance frequency). The decreasing resonance frequency of an unstable rock slope (140,000 m^3) near Preonzo (Switzerland) during a rainy period (precipitation up to 25 mm) appears to be related with precipitation-induced decrease in bulk modulus of the unstable structure (Burjánek et al., 2018). The progressive spalling and slabbing of granite from the Bedretto tunnel, a 1,500-m-deep adit off the main Furka Railway Tunnel in Switzerland, is assumed to be associated with regular fluctuations in moisture content and water condensing onto the rock walls due to humidity changes with passing trains in the main tunnel (Diederichs, 2007). Though commonly attributed to humidity-accelerated subcritical cracking (Eppes & Keanini, 2017; Nara et al., 2010), this type of failure could also be associated with strain-induced failure initiation, heterogeneity, and/or loading of stressed rock bridges as strain increases due to elastic softening of the adjacent intact rock subjected moisture content change. This effect is little recognized in practical examples, while Voigtlander et al. (2018) observed an immediate increase in notch-tip strains, and initiation of progressive failure of a 1 m-long loaded beam after adding water to the notch.

To assess the effect of ambient humidity on both strains and elasticity (termed as hygrosopic properties) within an unweathered intact granite, we conducted two uniaxial compression tests on a single Herrnholz granite cylinder (50 mm in diameter and 140 mm in length) exposed to “staged” and “continuous” humidity variation. Uniaxial compression was varied through a series of load/unload/hold sequences, while humidity was varied in a stepwise manner between 20% and 90% with air temperature maintained constant at 55°C. The strains of the specimen were measured in each load/unload/hold cycle with different RH to investigate the following key points: (a) the changes in strains and elastic properties as a function of RH, (b) the correlation between variations in strains and elastic properties, and (c) the fundamental mechanisms of humidity effect on strains and elastic properties.

2. Background

2.1. Atomic Basis of Crystalline Rock

Fundamentally, the arrangement of atoms in the interior of a crystalline solid can be represented by a unit cell of three-dimensional lattice. Two isolated atoms are stable at an equilibrium separation when their total interatomic
energy is at a minimum due to a balance of repulsive and attractive forces (Askeland, 2016). Surface atoms that have fewer neighboring atoms interact with their surroundings less than the interior atoms of the bulk material. As a result, the potential energy of a surface atom is greater than that of an interior atom (Haiss, 2001). Surface energy is defined as the difference between interatomic energy of the surface and interior atoms. Fractures within a crystalline solid are delineated by partially bonded atoms with surface energy because they represent contiguous regions of broken atomic bonds (Bitzek et al., 2015; Gumbsch & Cannon, 2000). Microcracks in typical rock-forming minerals such as biotite (T.-F. Wong & Biegel, 1985) and feldspars (Brown & Macaudière, 1984; Tullis & Yund, 1992; Willaime et al., 1979), have been shown to primarily occur along crystallographic planes that pass through the centers of atoms, resulting in dangling bonds and unfilled valencies. Atoms on the surfaces of such microcracks can interact with pore fluids as well as atoms on opposing crack walls.

2.2. Adsorption-Induced Deformation

Gas adsorption is a two-stage process in a mesopore ($2 \text{ nm} < \text{pore diameter} < 50 \text{ nm}$ based on (Gregg & Sing, 1982)), as illustrated by a typical adsorption isotherm (Thommes et al., 2015) for mesoporous solids, which shows a progressive increase in adsorbate amount at low relative pressures, followed by a sharp increase caused by the outset of capillary condensation (Figure 1a). In the first stage with low relative pressures, gas molecules accumulate on the solid pore surface, forming a liquid-like film. The confined gas molecules become thermodynamically unstable as relative pressure increases and condense to liquid, causing a proportion of the mesopore to be filled, which is known as the pore filling stage. The transition between these two stages is marked by the capillary condensation point, the relative pressure threshold at which the adsorbed gas molecules begin to condense to liquid. The capillary condensation point ($P_C$) for a sphere-like pore of radius $R$ can be determined from the Kelvin equation:

$$
\ln \left( \frac{P_C}{P_0} \right) = -\frac{2\gamma_L V_L}{R \gamma L T R}
$$

where $P_0$ is the saturated vapor pressure, that is, the boiling pressure of a liquid at a given temperature $T$, $V_L$ is the molar volume of the condensed liquid, $\gamma_L$ is the wetting liquid-vapor interface energy (also surface tension), and $R$ is the gas constant.

Adsorption-induced deformation of a porous media is a result of pore size changes (Barsotti et al., 2021), which are presumably driven by the development of “adsorption stress,” a combination of “disjoining pressure,” “surface adhesion pressure,” and “Laplace pressure” (also termed as “capillary pressure”). At relative pressures below the capillary condensation point, single to multiple layers of gas molecules adhere on a pore surface by interacting with the partially bonded surface atoms, as illustrated in Figure 1b, causing (a) a reduction in surface energy (Bentz et al., 1998; Colback & Wiid, 1965) and (b) stretching of bonds between solid atoms (Haiss, 2001). These two effects can be quantitatively described by a generation of surface adhesion pressure ($P^A$) along the adsorbent-adsorbate interface (see pore sketch and associated pressure in Figure 1a). The disjoining pressure ($P^D$) within the adsorbed film describes the intermolecular interactions (e.g., van der Waals forces) at a few nm scale (i.e., the thickness of the adsorbed film). They together determine deformation of the pore wall during the film forming stage. As relative pressure increases above the capillary condensation point, a proportion of the pore fills with condensed adsorbate, forming menisci at the pore entrance (see pore sketch in Figure 1a). Deformation of the pore throughout this pore-filling stage is governed by the pressure difference across the meniscus with curvature (Barsotti et al., 2016; Choi et al., 2001; Gor & Neimark, 2010; Neimark & Ravikovitch, 2001; Prass et al., 2009), which is termed as the Laplace pressure ($P^L$), and can be determined by:

$$
P^L = \frac{R_T}{V_L} \ln \left( \frac{P_V}{P_0} \right)
$$

where $P_V$ is the vapor pressure, $P_0$ is the saturated vapor pressure, and the ratio of $P_V$ to $P_0$ is defined as the RH in terms of water vapor. As the vapor pressure and thus the amount of adsorbed fluid increases, the magnitude of attractive Laplace pressure decreases, indicating an apparent expansion normal to the pore walls (Fisher et al., 1981; Gor & Neimark, 2010).
2.3. Adsorption-Induced Change in Elasticity

Increasing moisture content has been shown to reduce the stiffness of porous materials (Dobrzanski et al., 2021; Gor, 2014; Schappert & Pelster, 2008, 2014a), as well as a variety of geological media (D. S. Yang et al., 2012; Heap et al., 2018, 2019; Hossain et al., 2019; L. N. Y. Wong et al., 2016; Pimienta et al., 2014; Suknev, 2019; Tang et al., 2018; Tiennot & Fortin, 2020; Yurikov et al., 2018). This observation, however, has only been directly associated with the physical process of adsorption in laboratory studies involving sandstones (Hossain et al., 2019; Pimienta et al., 2014; Tiennot & Fortin, 2020; Yurikov et al., 2018). In these studies, the softening of sandstones is assumed to be caused by (a) a reduction in surface energy as gas molecules interact with partially bonded solid atoms on pore surfaces (Hossain et al., 2019; Pimienta et al., 2014), and/or (b) the generation of Laplace (or capillary) pressure within a condensed liquid layer confined between two opposing pore walls (Tiennot & Fortin, 2020; Yurikov et al., 2018).

The hypothesis of surface energy associated elasticity variation was corroborated by a comparison between experimentally determined elastic properties and simulated effective elastic moduli based on surface energy considerations (Hossain et al., 2019; Pimienta et al., 2014). Pimienta et al. (2014) applied a micromechanical model of Murphy et al. (1984), which assumes that the rock frame moduli depend on surface energy at the grain
contacts (Johnson et al., 1971), to reproduce the observed decreases in P- and S-wave velocities in Fontainebleau sandstone as RH increased. Hossain et al. (2019) derived the effective elastic properties of the Bentheimer sandstone using a linear elastic relationship between applied stress and resulting strain, where the total strain tensor is the sum of surface energy and elastic strain tensor. Their estimated elastic moduli decrease in humid conditions and agree with experimental results qualitatively.

Surface energy decreases monotonically as adsorption progresses and approaches the minimum when a capillary condensed water layer covers the entire internal surface area of the porous rock (Bentz et al., 1998). The generation of attractive Laplace (or capillary) pressure within the capillary condensed water layers at grain contacts is assumed to govern the change in elastic moduli of the overall rock with adsorption of water (Tiennot & Fortin, 2020; Yurikov et al., 2018). This assumption has recently been validated in sandstones by a broad agreement between the measured variations in the bulk and shear moduli (based on measured P- and S-wave velocities) related to the estimated change in the Laplace pressure (based on measured extensional strains) and the stress dependency of bulk and shear moduli of the tested rock material.

3. Materials and Methods

3.1. Material Description

The granite used in this study was sourced from the Herrnholz quarry (Li et al., 2021), which is located on the eastern side of the Hauzenberg pluton in the southern Bavarian Forest (Passauer Wald) of Germany. The Hauzenberg granite was formed in the middle Carboniferous period (∼320 Ma) and intruded late- to post-kinematically into high-grade metamorphic rocks at depth ranging from 16 to 18 km (Klein et al., 2008; Siebel et al., 2008), with little to no ductile tectonic overprint. Thin sections (35 mm × 22 mm, ~30 ± 5 μm thick) were prepared for petrographic analysis from a suit of 35 mm × 22 mm × 15 mm blocks (see Figure 2a as an example). Biotite grains can be distinguished from others in plane-polarized light by their brownish appearance (Figure 2b), while muscovite crystals are distinctive in crossed-polarized light by their mottled appearance with rainbow pattern (Figure 2c).

In thin section, quartz can be distinguished from feldspar because it is generally clear and lacks visible twinnage or cleavage, despite all being shades of dark gray through to white in crossed-polarized light. These observations indicate granitic mineralogical assemblage of our selected specimen, with approximately 50% quartz, 38% feldspar, and 11% mica in area fraction. We used the “Quick Trace” command in CorelDRAW™ to trace grain boundaries (white lines in Figure 2d) and averaged lengths of the longer and shorter axes of each grain to estimate grain size. The resulting sizes range from approximately 0.03 to 1 mm, with a mean of 0.23 mm and a standard deviation of 0.13 mm.

Pores and their internal surface area provide spaces for fluid-solid interactions and thus play an important role in governing the rock-fluid behavior. In this study, the pore space properties, including porosity, pore size distribution, and specific surface area of the Herrnholz granite were characterized using a combination of mercury injection porosimetry and nitrogen adsorption analysis. From measured intrusive volume of mercury under controlled pressure, mercury injection porosimetry can provide information on pore volume or porosity, as well as a wide range of pore throat size (typically from 3 to 10 nm up to microns). The nitrogen adsorption method can evaluate the size of mercury-inaccessible small pores by measuring the amount of adsorbate at a series of relative pressures.

The intrusive volume (mm³/g) of mercury in seven 20 mm × 6.5 mm × 6.5 mm samples ranges from 2.63 to 6.17 mm³/g (mean at 4.22 mm³/g) at pressures up to ~400 MPa (see the volume evolution as a function of applied pressure in Figure 3a), suggesting an average mercury-accessible porosity of 1.15%. The conversion of applied pressure to pore throat size (Washburn, 1921) provides information on pore throat size distribution over 10 nm to 100 μm, indicating that around 70% of the pore volume is composed of pores with throat diameters less than 200 nm (see Figure 3a).

To quantify the size of mercury-inaccessible small pores, nitrogen adsorption analysis was undertaken on two intact 40 × 10.5 × 10.5 mm³ samples using the automated gas sorption analyzer, Autosorb iQ™. The existing instrument software AsiQwinMT computed connected surface area and pore size distribution based on the Brunauer-Emmett-Teller (BET) (Brunauer et al., 1938) and Barret-Joyner-Hallenda (BJH) (Barrett et al., 1951) model, respectively. The details of these models have been discussed in the mentioned papers; hence, they were not explained here. In general, the BET specific surface area was obtained by fitting the relationship between...
the weight of total nitrogen molecules adsorbed and the relative pressure (i.e., the BET equation, presented as Equation S3 in Supporting Information S1) in its range of 0.05–0.35, assuming infinite layers of adsorption with no interlayer interaction (Brunauer et al., 1938). The BJH method calculated pore size distribution from the desorption isotherm (see Figure S2 in Supporting Information S1) by relating the change in desorbed volume at a given pressure to the pore radius that capillary evaporation (analogous to capillary condensation) occurs at the same pressure during desorption (Barrett et al., 1951). These measurements indicate a mean BET specific surface area of 0.46 m$^2$/g, of which 80% is composed of pores with diameters below 10 nm (see Figure 3b).

The combination of mercury injection porosimetry and nitrogen adsorption analysis provides a wide range of pore size distributions over 3 nm to 100 μm (Figure 3). The nitrogen adsorption analysis provides pore volume of ~0.5 mm$^3$/g (or porosity of 0.14%) over a pore diameter range of 3–10 nm, which, when compared to the pore volume (4.22 mm$^3$/g) or porosity (1.15%) accessible by mercury, implies that only 1/12 of the small pores are accessible to nitrogen. We found the cumulative pore volume measured from mercury injection porosimetry (~1.2 mm$^3$/g) is slightly greater than that from the nitrogen adsorption analysis (~0.8 mm$^3$/g) over the overlapped diameter range of the two techniques, that is, 10–100 nm, indicating a greater differential of pore volume with respect to pore diameter. This slight inconsistency may be due to the nonuniform pore geometry (e.g., wedge shaped pore) of the analyzed sample (Labani et al., 2013).

### 3.2. Experimental Description

We conducted two sets of uniaxial compression tests on Herrnholz granite cylinders (50 mm in diameter, 140 mm in length) subjected to (a) loading at constant displacement rate (4 mm/min) to failure, and (b) cyclic
load/unload/hold sequences within the elastic region. Failure tests were conducted on 10 cylinders to determine the elastic limit of this material, which is the upper load limit of the cyclic load/unload/hold tests performed on a single one cylinder. Every specimen was cored in the same direction and ground into two parallel end surfaces. A custom static loading frame with integrated climate chambers (Li et al., 2019) was used to conduct above experiments. Within the frame assembly, a load cell and displacement transducer directly measure the applied load and piston displacement, respectively (Figure 4a). The Dycometal Model CCK-25/85c climate chamber (400 mm × 475 mm × 430 mm) can control air temperature ranging from −20°C to +150°C (±0.1°C), and humidity ranging from 20% to 90% (±2.5%). A side port of the climate chamber allows us to monitor sample surface temperature throughout a test using a PT100 temperature probe mounted on the sample surface with adhesive tape and insulated from the surrounding air (Figure 4b).

Surface strains of a tested sample can be tracked using a range of extensometers connecting to the testing machine controller. A four-point averaging longitudinal extensometer (Epsilon Model 3442RA1) and a radial chain extensometer (Epsilon Model 3544) (Figure 4b) are commonly employed together to measure axial and radial strains, respectively, of a cylindrical sample subjected to uniaxial compression. The longitudinal extensometer has a measurement range of 100 mm. Optically clear viewport installed through side wall of the climate chamber allows the acquisition of digital photographs using a combination of Sony A7RII digital camera and Sony FE 24–105 mm F4 G OSS zoom lens. Digital image correlation (DIC) analysis of the acquired photographs provides a reference deformation measurement that is independent of temperature and humidity changes in the chamber. Compression negative convention is adopted for both extensometers and DIC measured strains.

Figure 3. Comparison of nitrogen adsorption analysis and mercury injection porosimetry results for pore size distribution. (a) Cumulative pore volume and mercury-accessible porosity as a function of pore throat diameter and applied pressure by mercury porosimetry. (b) Cumulative pore volume and surface area as a function of pore diameter during nitrogen adsorption.
3.2.1. Determination of Elastic and Brittle Properties

Uniaxial compression strength (UCS) tests were performed on 10 cylinders (50 mm in diameter, 140 mm in height) under ambient conditions to determine elastic and brittle properties of the Herrnholz granite. Axial stress-strain curves showed an average UCS of 154 (±3) MPa and a consistent linear portion between 30% and 35% UCS (see Figure S3 in Supporting Information S1). The linear stress-strain relationship in loading stages over this interval was used to calculate the Young's modulus and Poisson's ratio, providing a mean Young's modulus of 35 GPa and Poisson's ratio of 0.28 at ambient environmental conditions.

The crack initiation (CI) threshold marks the elastic limit of a brittle rock, and is typically between 30% and 50% of the UCS (Brace et al., 1966; Katz & Reches, 2004; Martin, 1993, 1997; Nicksiar & Martin, 2012). Three of the tested samples were instrumented with mechanically mounted longitudinal and circumferential extensometers, allowing the CI threshold to be determined using the crack volumetric strain reversal method (Diederichs & Martin, 2010; Martin, 1993). It indicates an average CI threshold of 54 MPa (see Figure S4 in Supporting Information S1), 35% of the average UCS, consistent with our assumed upper limit for elastic behavior.

3.2.2. Determination of Hygroscopic Properties

To derive hygroscopic properties of our selected Herrnholz granite, we performed two uniaxial compression tests on a single Herrnholz granite cylinder (50 mm in diameter and 140 mm in length) exposed to “staged” and “continuous” humidity variation. The first “staged” test employed a humidity stepping protocol, before the sample was removed, checked, oven dried, and prepared for the second test, which employed a “continuous” humidity stepping protocol (see flowchart in Figure 5a). The sample was dried in an oven under 80°C for 3 days prior to each test to ensure identical initial moisture conditions and to prevent inadvertent damage to the microstructure. The sample was then transferred to the loading frame, installed in the climate chamber, and loaded for 1 day with a constant axial stress of 0.1 MPa, 20% humidity, and 55°C to allow the sample to equilibrate. During the staged test, RH was ramped in a stepwise manner from 20% to 42%, 62%, 82%, and 90% before returning to 20%. We increased the RH from 20% to 90% in the continuous test before returning to 20%. The continuous test was designed to (a) evaluate the reproducibility of hygroscopic properties determined from the staged test; (b) create a full wetting—drying cycle, which was interrupted in the staged test due to a malfunction, and (c) gain insight into the sample condition (e.g., if damaged) after removal from the staged test.

In both tests, the axial stress increased at a rate of 1 MPa/s from 0.1 to 54 MPa (the predetermined CI threshold), then decreased at the same rate and remained constant at 0.1 MPa for 1 and 48 hr (Figures 5b and 5c). Throughout the hold stages, cumulative strains were observed while axial stress was held constant at 0.1 MPa. During the loading stages, axial stress-strain relationships were used to derive elastic properties at each humidity level.
For the staged test, longitudinal and circumferential extensometers were mechanically mounted at the mid-height of the specimen (see Figure 4b), allowing contact measurement of axial and radial strains (so-called extensometer-based strains) at a sampling rate of two samples per second. A (reference) uniaxial compression test was performed on an EN AW-6082 T651 aluminum cylinder (Ø 55 × 114 mm, diameter: length) exposed to continuous humidity variation between 20% and 90% for approximately 5 days to estimate the response of extensometers to RH. The results (see Figure S5 in Supporting Information S1) shown that moisture expansion of the extensometer itself causes a shift in axial and radial strain by $4 \times 10^{-5}$ and $9 \times 10^{-5}$, respectively, as RH increases from 20% to 90%. These shifts were removed from the observed (nominal) strains of the granite specimen (see Equation S11 in Supporting Information S1).

DIC was employed in parallel with longitudinal extensometer measurements during the continuous test to validate the extensometer-based strains. The circumferential extensometer could not be mounted in this case, as its placement would interfere with the digital image acquisition region. Full-length images were acquired at a resolution of approximately 0.02 mm/pixel. The open-source MATLAB program Ncorr was used for 2D DIC analysis (Blaber et al., 2015). It tracks surface deformation by correlating the best fit between pixel values within a defined search window in images taken during hold steps to those in the reference image acquired immediately prior to the first load step (i.e., the end of climate equilibrating stage, see Figure 5a). The search window was set to 50 pixels or 1 mm in radius, resulting in a measured displacement accuracy of 0.001 mm. Due to the distortion in cylindrical projection, we focused on measuring displacement and strain within a 1 mm (i.e., size of the moving window for DIC analysis) wide region in the middle of the projected surface (see Figure S10 in Supporting Information S1), where the distortion is pale. Imaging intervals were not synchronized with the loading sequence, and as such we did not have sufficient temporal coverage to track strains with DIC during load/unload cycles. We

Figure 5. Flowchart of the “staged” and “continuous” uniaxial compression tests (a), with panels (b and c) illustrating the 10 load/unload/hold cycles and 5 load/unload/hold cycles, respectively.
analyzed 425 images acquired during hold steps within the first 173 hr and tracked the DIC-based axial strain by averaging the vertical strain within a 1 × 100 mm or 50 × 5,000 pixel window (width: height), which corresponds to the position of the longitudinal extensometer. The DIC-based radial strain was estimated by averaging the horizontal strain within a 1 × 1 mm (50 × 50 pixel) window at the midpoint of the specimen, corresponding to the position of a circumferential extensometer if one had been mounted.

A system failure during the staged test led to data loss from 322 to 336 hr. Loading and environmental conditions were maintained until 335 hr, when re-starting the test resulted in the specimen being unloaded, air and sample temperatures dropping to 33°C and 40°C, respectively, and humidity dropping to 43%. The test was resumed manually at 336 hr, and the sample was re-loaded to 0.1 MPa without disturbance. Immediately after restarting the test, condensation was observed on the sample surface.

4. Results

We present results from the staged and continuous tests in terms of the response of three key variables to changes in ambient humidity. These include:

1. strain evolution during hold periods,
2. strain accumulation during load—unload cycles, and,
3. Young's modulus and Poisson's ratio calculated from loading steps.

In reporting strain data, we adopt a compression negative convention. The reported strains have been corrected by subtracting the shifts caused by climate from the nominal extensometer readings (see Equation S11 in Supporting Information S1).

4.1. Strain Evolution During Hold Periods

In both tests, axial and radial strains during 0.1 MPa hold periods increased with each stepwise increase in ambient humidity (Figures 6 and 7). The axial strain response was consistently larger, and more rapid than that of the radial strain (max. ∼4 × 10⁻⁴ vs. ∼2 × 10⁻⁴, see Figure 6), and typically stabilized after approximately 37 hr (or the seventh load—unload cycles), whereas radial strains continued to progress throughout each humidity interval. Reducing ambient humidity levels back to 20% reduced axial strains in both tests, and although DIC data acquisition ceased after 173 hr in the continuous test, the reduction in radial strain observed at 20% humidity in the staged test indicates we may expect a similar reduction in the continuous test.

Calculated volumetric strain, assumed to be axial strain +2 × radial strain, during the staged test consistently increased with increasing humidity, up to ∼3.5 × 10⁻⁴ at 322 hr. Following the re-start of the test at 336 hr, we observe a significant (∼2 × 10⁻⁴) initial increase in volumetric strain, followed by a gradual linear accumulation up to ∼6 × 10⁻⁴ at the end of the 90% humidity stage. Condensation on the sample surface following the test restart suggests that the sample surface moisture condition temporarily exceeded 90% humidity, possibly contributing to the aforementioned increase in volumetric strain. Though progressively increasing throughout the 72-hr 90% humidity interval, the maximum volumetric strain in the staged test compares favorably with that in the continuous test, which reached a more-or-less stable peak of 8 × 10⁻⁴ after 173 hr. Over the first 173 hr of the continuous test, the overall consistency between extensometer-based and DIC-based axial strain suggests the reliability of DIC data. Although DIC results show a slight decrease from 160 to 173 hr (the source of the DIC variability is unknown), the mechanical extensometer data shows a stable axial strain for the following 3 days, which we believe reflects the equilibrium condition for 90% humidity.

During the final 144 hr of the staged test, the volumetric strain returned to a similar value as observed at the end of the initial 20% humidity period (approximately 98 hr), while the axial extensometer indicated a net compaction (∼2 × 10⁻⁴), and radial expansion (1 × 10⁻⁴) at the end of the test. The lack of a radial extensometer or DIC data after 173 hr of the continuous test prevents us from determining volumetric strains during the latter stages, however, we do observe a similar (though slightly less) net axial compaction (∼1 × 10⁻⁴) from approximately 74–394 hr of the test, which (similar to the staged test) stabilized approximately 144 hr after the final transition to 20% humidity.
Throughout both tests, the sample surface temperature remained stable at around 52°C, 3°C cooler than the surrounding air. We attribute this to heat transfer through the steel loading rams to the outside air of the climate chamber. This is evidenced by a 3D heat transfer model (see Figure S11 in Supporting Information S1) where surface temperature of a cylindrical specimen heated via ambient air temperature is lower (magnitude depends on the heat transfer properties) than the air temperature. The 0.5°C–1°C variation in sample surface temperature observed at 82% and 90% relative humidities (Figures 6 and 7) might be associated with an increase in specific heat capacity of the high humidity air (Tsilingiris, 2018). These small temperature increases stabilized in up to 1.3 hr (depending on the humidifying rate) and likely generated a thermal expansion in the order of $10^{-6}$ (based on a linear thermal expansion coefficient of $8.1 \times 10^{-6}$ m/m°C for granite based on Dwivedi et al. (2008)), which is two orders of magnitude less than that of axial strain we observed in association with humidity variations.

### 4.2. Strain Accumulation During Load-Unload Cycles

Each loading stage generated axial contraction and radial extension (Figure 8), most of which was recovered elastically during the subsequent unloading stage. Gradual recovery of a proportion of the remaining axial contraction typically occurred within hours after unloading (e.g., Figure 6b). In general, higher ambient humidity levels
resulted in greater strain accumulation during loading stages, while lower humidity levels resulted in greater preservation of induced strains following load-unload events (Figure S12 and S13 in Supporting Information S1).

During loading stages, axial stiffness increased as loads approached 30 MPa (60% of CI), remaining constant with generally linear behavior between this point and the target load (Figures 8a and 9). Radial strains were increasingly responsive as loads increased to 30 MPa, above which, they demonstrated a linear increase with axial stress, indicating a stable Poisson’s ratio (Figure 8b). Although these stress-strain relationships are consistent across the humidity ranges, with non-linear behavior below 60% CI and linear behavior above, the magnitude of axial contraction (∼−15 × 10⁻⁴ to ∼−20 × 10⁻⁴), and radial extension (∼1 × 10⁻⁴ to ∼3 × 10⁻⁴) increased as humidity increased (Figures 8a and 8b). Induced volumetric strains during loading cycles (∼−12.5 × 10⁻⁴, Figure 8c) were nearly identical (±0.5 × 10⁻⁴) for all humidity levels. The specimen expanded with increasing humidity during hold periods at 0.1 MPa, resulting in a rightward shift in the starting strain for load cycles. This was reversed on drying, and volumetric strain development during the final load cycle of the staged test is similar to that of the same 20% humidity condition at the beginning of the test, with strains differing by less than 0.5 × 10⁻⁴ throughout the load range (Figure 8c).

**Figure 7.** Temporal evolution of strains (axial, radial, and volumetric) during the 0.1 MPa hold period for the continuous test. Inserted is the strain evolution during the first 6 hr of the test.

**Figure 8.** Stress-strain curves from the last loading phase of the staged test at each humidity level. (a) Axial stress-axial strain curves at each humidity, with the subplot showing the determination of Young’s modulus ($E$) at 90% relative humidity, as an example, by linear regression of the portion from 46 to 54 MPa axial stress; (b) axial stress-radial strain curves at each humidity; and (c) Axial stress-volumetric strain curves at each humidity. RH: relative humidity.
As is often observed (Heap et al., 2010; Martin & Chandler, 1994; S. Q. Yang et al., 2015), a component of axial strain remained following each load-unload cycle (Text S8 in Supporting Information S1). During the wetting phases of both tests, we observed discrete axial strain decreases of approximately $0.2 \times 10^{-4}$ to $0.6 \times 10^{-4}$ persisting after each cycle (see Figure 6b as some examples). These strains typically recovered non-linearly over the next 1–9 hr, with expansion rates gradually decreasing to background for the remainder of the hold phase (see Figure 6b some examples). During the drying stages, load-unload cycles produced similar discrete decreases in axial strain, for example, at 456 hr in the staged test (Figures 6a and 265 hr in the continuous test (Figure 7), but without the subsequent recovery evident during wetting stages. The magnitudes of these strain decreases were much greater in the staged test than in the continuous test, although in both cases the magnitudes of decreases appear to be similar to that of contraction during the preceding hold phase. This apparent discrepancy may be due to the inconsistent timing of the load-unload events across the two tests, with the staged test, for example, having a 48 hr hold interval prior to the first 20% humidity load-unload cycle, and the continuous test having just 1 hr interval.

4.3. Variation of Elastic Properties Derived From Loading Steps

Elastic properties were derived from axial stress-strain relationships during loading steps. The Young's modulus ($E$) was determined for each axial stress-axial strain curve by linear regression of the portion from 46 to 54 MPa (i.e., 30%–35% UCS) axial stress, as illustrated by the subplot in Figure 8a, which shows the determination of Young's modulus at 90% humidity as an example. Poisson's ratio was determined by linear regression of the radial strain-axial strain curve over the same stress interval (illustrated by Figure S14 in Supporting Information S1).

Calculated Young's modulus and Poisson's ratio from each loading step are listed in Tables S4 and S5 in Supporting Information S1.

Overall, Young's modulus in the staged and continuous tests decreased from ~43 to ~44 GPa, respectively, down to ~38 GPa in response to ambient humidity increasing from 20% to 90% (Figures 10 and 11). Returning humidity to 20% resulted in a recovery of Young's modulus, with a persistent 0.5 GPa increase in stiffness on completion of the staged test, and a similar decrease in stiffness on completion of the continuous test. Poisson's
ratio (calculated from the staged test) increased from 0.12 to 0.26 across the humidity range, with a 60% recovery when humidity level was reduced to 20% (Figure 10).

Combining Young's modulus \(E\) and Poisson's ratio \(\nu\) with the assumption of an isotropic medium, we find the bulk modulus \(K = E / (3(1 − 2\nu))\) from axial stress-strain measurement increased from 18.8 GPa up to 26 GPa, before decreasing to 22 GPa at the completion of the staged test (Figure 10). Similar to the recovery of strains during drying phases, we observe a progressive recovery of Young's modulus and Poisson's ratio throughout the final 20% humidity interval of the staged test. The bulk modulus, however, stabilizes in 48 hr (or one load-unload cycle) after humidity was reduced (456 hr, Figure 10). This is comparable to the time required to reduce strains accumulated over hold phase following wetting events to background levels, and it may reflect the time required for humidity equilibration within the sample.

5. Discussion

5.1. Cyclic Loading and Hysteresis

5.1.1. Initial Loading Step in Each Test

The first loading step in each test generated a persistent increase in Young's modulus (staged: 35.8 to 41.8 GPa, continuous: 41.7 to 44.1 GPa, see Figures 10 and 11), as well as decrease in axial strain (staged: \(3 \times 10^{-4}\) to 0, continuous: \(0.7 \times 10^{-4}\) to 0, see Figures 6 and 7). We suggest this may be associated with mineral compaction, closure of pre-existing microcracks (as observed in thin section by Li et al. (2021)), and sliding on discontinuities which were perhaps expanded by elevated ambient humidity levels entering the crystalline matrix prior to the testing period. A combination of friction and electrostatic effects is likely to facilitate the preservation of some contractional strains, as well as elevated stiffness on unloading. This appears to have been preserved while the sample rested between the two tests under ambient laboratory conditions (~45% humidity), as the Young's modulus at the end of the staged test is only slightly lower (0.4 GPa) than that during the 20% humidity equilibration phase of the following continuous test (cf., Figures 10 and 11). Given the general increasing trend in Young's modulus during the final 20% humidity stage of the staged test, we consider it is reasonable to assume that there was essentially no change in stiffness, and thereby no release of stored frictional strain energy, between the two tests.

5.1.2. Load-Unload Cycles at Each Humidity Stage

Each load-unload cycle was associated with a distinct decrease in axial strain (see Figure 6b as some examples), the majority of which was recovered during the next hold period in wetting phases (e.g., reversible axial strain in Figure 6b), while little was recovered during the drying phases (e.g., irreversible axial strain at ~456 hr of the staged test (Figure 6a), and ~265 hr of the continuous test (Figure 7)). Although the apparently irreversible nature of strains during the drying phases may typically be highlighted as evidence for cyclic fatigue (Cerfontaine & Collin, 2018; David et al., 2012; Scholz & Kranz, 1974; Zoback & Byerlee, 1975), the fact that we observe a
recovery of this deformation during wetting phases, and no apparent reduction in stiffness or increase in volumetric strain throughout each test suggests that this is more likely due to closure of expanded microcracks and sliding on discontinuities, an effect similar to that observed after the first load-unload cycle. This hypothesis is supported by stress-strain behaviors during loading cycles (Figures 8 and 9), which indicate a progressive stiffening of the specimen over loading, with the majority of nonlinear deformation occurring at lower loads. Unloading phases are consistently stiffer than the loading as loads drop from the peak, and maintain a stronger linearity down to the “hold” load level (see Figures S12 and S13 in Supporting Information S1). These characteristics suggest little, if any damage accumulation has occurred during load-unload cycles.

5.1.3. Residual Changes in Elasticity and Strain at the End of Each Test

The reducing rates of both strain, and elasticity recovery during the final 20% humidity phases make it challenging to determine if, or when the specimen achieved equilibrium at the end of each test. From the end of the initial 20% humidity phase at 98 hr of the staged test to the test termination at 555 hr, we observe a net axial contraction of $2 \times 10^{-4}$, and radial expansion of $1 \times 10^{-4}$ (Figure 6a). The net volumetric strain over the same period is, however, null. This may be considered an indication that, while the specimen has changed shape, no additional volume has been generated through the creation of new pore space (i.e., damage), or infilling of pores with moisture. Together with a net stiffening of the specimen, reflected in increases in both Young's modulus and Poisson's ratio over the same interval, it seems likely that (yet again) the net changes at the end of the staged test reflect an accumulation of strain energy on existing frictional contacts (e.g., within microcracks), rather than induced damage (which would more likely result in a reduction in stiffness). Though 0.5 GPa decrease in Young's modulus over the course of the continuous test was observed (Figure 11), we assume there was essentially no change in stiffness given the increasing trend in Young's modulus during the final hours of this test.

5.1.4. Re-loading During Staged Test

The staged test was manually restarted after a malfunction at 322 hr, and condensation was observed on the sample, with its base in contact with liquid water that had accumulated on the lower loading platen. These observations suggest that condensing conditions with 100% humidity most likely developed within the sample during this time. After restarting the subsequent 90% humidity period, the sample could then be expected to have dried. This could explain the decrease of axial strains during this 90% humidity hold period (Figure 6), as well as increase in Young's modulus (Figure 10).

5.2. Evolution of Strain and Elastic Properties

5.2.1. Physical Versus Mechanical Effects

We suppose that at least three mechanisms are involved in the evolution of strain and elastic properties during these tests. These include adhesion of water vapor molecules on internal surfaces, generation of capillary pressure, and loading-induced sliding on discontinuities. Though it may be tempting to include damage evolution through crack propagation in this list, we are confident that this does not play a significant role in our test results as we:

1. do not load the specimen above a predetermined CI threshold,
2. do not observe dilatant behavior in volumetric strain accumulation during loading,
3. do not observe any persistent change in volumetric strain on completion of the staged test, and,
4. do observe a recovery of Young's modulus on completion of both tests.

Although numerous studies have shown a reduction in compressive strength of granite by approximately 3%–5% with increasing water content (Lajtai et al., 1987; Okubo et al., 1992), it is currently unclear whether this effect translates to a similar reduction in the CI threshold. In the case that increasing humidity did lead to a reduction in the CI threshold, as observed in sandstones (Dyke & Dobereiner, 1991) and Opalinus clay (Wild et al., 2015), cracking may be expected during loading stages at humidities greater than 45% (the humidity level at which CI was determined), and be limited to periods of increasing moisture content during the staged test. This latter consideration is a result of the Kaiser effect (e.g., Holcomb, 1981; Kurita & Fujii, 1979; Lavrov, 2003), a widely observed phenomenon in which new cracking in cyclically loaded specimens is not observed until the previous load threshold is exceeded.
5.2.2. Wetting Versus Drying Process

Insight into relative rates of wetting and drying can be determined by comparing rates of strain response, and Young’s modulus change in the continuous test. In this test, the decrease in Young’s modulus and increase in axial strain after the onset of wetting stabilized at approximately 120 hr, just 48 hr after the increase in humidity. In contrast, the sample took a full 144 hr to recover both strain and elasticity once humidity was reduced to 20%. This was characterized by an initially rapid recovery, followed by a gradual decay in the rate through time. This is consistent with typical observations of an exponential decrease in water content through evaporation (e.g., Franzen & Mirwald, 2004), and supports our inference of this as the driving mechanism for both effects.

5.2.3. Relations Among Volumetric Strain, Elastic Properties, and Relative Humidity

The stabilized volumetric strain, Young’s modulus, Poisson’s ratio, and combined bulk modulus (calculated from Young’s modulus and Poisson’s ratio) at each humidity level are summarized in Figure 12. We find that increases in bulk modulus appear to vary linearly with volumetric strain, indicating the same physical driver for each. It is likely that volumetric deformation and variation in bulk modulus are the direct results of adsorption, although we have direct measurements of axial/radial strains, Young’s modulus, and Poisson’s ratio. We extend the apparent variations of Young’s modulus and Poisson’s ratio to that of the bulk modulus, and propose a linear relationship between bulk modulus variations and volumetric strain for intact Herrnholz granite (Figure 13a):

\[ \Delta K_{ax}(\text{GPa}) = K_{ax} - K_{ax0} = (1.13 \times 10^4 \pm 7.14 \times 10^2) \varepsilon_v \]  

Figure 12. Demonstration of Young’s modulus, Poisson’s ratio, bulk modulus (calculated from axial stress-strain measurement), and volumetric strain (in reference to 20% humidity) as a function of relative humidity.

where \( \Delta K_{ax} \) and \( \varepsilon_v \) are the change in bulk modulus, and volumetric strain in reference to the 20% humidity state where the initial bulk modulus \( K_{ax0} \) is defined, with the subscript “ax” denoting axial stress-strain measurement based. \( 7.14 \times 10^2 \) is the standard error of estimated slope of \( 1.13 \times 10^4 \). This can be extrapolated into bulk modulus estimation from volumetric strain, which is easier to measure in both laboratory and field studies. Similarly, increases in Poisson’s ratio appear to vary linearly with Young’s modulus variation, indicating the same physical driver for each. As such, we adopt a linear regression between the changes in Poisson’s ratio (\( \Delta \nu \)) and Young’s modulus (\( \Delta E \)) (Figure 13b), and obtain:

\[ \Delta \nu = (-2.73 \times 10^{-2} \pm 1.30 \times 10^{-3}) \Delta E(\text{GPa}) \]  

where \( 1.30 \times 10^{-3} \) is the standard error of estimated slope of \( -2.73 \times 10^{-2} \). Notable is that Equation 3 and Equation 4 provide empirical fits of five data points from this study. Elastic moduli of a rock solid are largely related to its mineral composition and crystal structure; hence, it is unknown how derived coefficients in Equations 3 and 4
are expected to vary with respect to rock composition and microcrack population. We therefore encourage similar investigations on different types of rock in the future to develop a broader correlation.

Together with the combined relation between elastic moduli:

$$K_{\text{ax}} = E \left( 1 - 2\nu \right)$$

Equations 3 and 4 allow us to estimate Young’s modulus ($E$) or Poisson’s ratio ($\nu$) from bulk modulus ($K_{\text{ax}}$) or observed volumetric strain ($\varepsilon_v$) by:

$$E = K_{\text{ax}} \left( -18.315 + E_0 + 36.63\nu_0 \right) \frac{\nu}{K_{\text{ax}} - 6.10501}$$

$$\nu = \frac{0.5 K_{\text{ax}} - 6.1051 v_0 - 0.16667 E_0}{K_{\text{ax}} - 6.10501}$$

where $E_0$ and $\nu_0$ are the Young’s modulus and Poisson’s ratio at the reference humidity (here, 20%) state. The standard error of the coefficient $1.13 \times 10^4$ in Equation 3 results in an uncertainty of 4.77% for the parameters $6.10501, 18.315,$ and $36.63$ in Equations 6 and 7. These predictions are essential for the application of rock physics theories and numerical models in which an input of Young’s modulus and Poisson’s ratio is always necessary and has to be taken into account in wet (e.g., unsaturated) conditions.

5.3. Adsorption Stress

To gain insights into the mechanisms of variations in strains and elastic properties of Herrnholz granite as ambient humidity increases, we compare laboratory observations with theoretical predictions. To this end, we estimate the change in equivalent internal stress, also referred to as adsorption stress, in two ways:

1. adsorption stress change from laboratory-observed macroscopic strains and elastic properties of the tested material, and
2. adsorption stress change based on environmental conditions, adsorbate and adsorbent parameters, and their interaction.

5.3.1. Laboratory-Derived Adsorption Stress Change

The volumetric strain ($\Delta \varepsilon_v$) of a rock material under hydrostatic stress of $\sigma_v$ and exposed to a change in water content is governed by the bulk modulus $K_v$ and change in solvation pressure, which is defined as the difference between the internal stress (i.e., adsorption stress) $\sigma_a$ and the external stress $\sigma_v$ (Gor & Neimark, 2010):

$$\Delta (\sigma_a - \sigma_v) = K \Delta \varepsilon_v$$

![Figure 13. Demonstration of (a) change in bulk modulus (calculated from axial stress-strain measurement) as a function of humidity-induced volumetric strain in reference to the 20% humidity state, and (b) change in Poisson's ratio as a function of Young's modulus change. Linear regression with a confidence level of 95% for each function falls inside the red solid lines, while the black line represents linear regression without an intercept for each function. RH denotes the relative humidity.](image-url)
This is based on the assumption of a linear Hooke law. For constant external stress conditions ($\Delta \sigma = 0$), the change in adsorption stress ($\Delta \sigma_a$) is the product of bulk modulus and volumetric strain change. Assuming our sample is subjected to a constant external stress condition during the wetting period, we find the calculated adsorption stress change increases with RH, as is indicated by circles in Figure 14, based on the laboratory observed volumetric strain and calculated bulk modulus from axial stress-strain measurement at each humidity level (Figure 12).

### 5.3.2. Modeled Adsorption Stress Change

To model the theoretical adsorption stress due to an increase in RH, we adopt the approach of Gor and Neimark (2010) who predict the adsorption stress based on air temperature, RH, adsorbate and adsorbent parameters, and their interaction. At relative humidities below the capillary condensation point, the interaction between the adsorbate molecules and the adsorbent surface can be described by the Frenkel-Halsey-Hill adsorption theory in terms of the adsorbed film thickness $h$:

$$h = h_0 \left( \frac{\ln(P_v/P_0)}{-k} \right)^{-1/m}$$

where $h_0$ is the monolayer adsorbate thickness, $P_v$ is the vapor pressure, and $P_0$ is the saturated vapor pressure. $k$ describes the interaction of the first adsorbed layer with the adsorbent surface, and $m$ is associated with the decaying interaction as the film thickness increases (Laaksonen et al., 2016). Assuming a cylindrical pore with radius $R$, the adsorption stress before capillary condensation (i.e., non-condensing conditions) ($\sigma_{\Delta a}^{\text{nc}}$) can be described as follows (corresponding derivation can be found in Gor and Neimark (2010)):

$$\sigma_{\Delta a}^{\text{nc}} = -\gamma_{sl} - \frac{\gamma_l}{R - h} - \frac{R_g T}{V_L} k \frac{m}{m - 1} \frac{h_0}{R} \left( \frac{h}{h_0} \right)^{1/m}$$

where $\gamma_{sl}$ is the solid-liquid interface energy, $\gamma_l$ is the liquid-air interface energy (also surface tension), $R_g$ is the gas constant, $T$ is the absolute temperature, and $V_L$ is the molar volume of the liquid phase. As RH exceeds the capillary condensation point (i.e., condensing conditions), the pore fills with fluid, forming menisci at its open entrance, and the adsorption stress ($\sigma_{\Delta a}^{\text{c}}$) is described as (corresponding derivation can be found in Gor and Neimark (2010)):

$$\sigma_{\Delta a}^{\text{c}} = -\gamma_{sl} \frac{R_g T}{V_L} \ln \left( \frac{P_v}{P_0} \right)$$

Figure 14. Demonstration of laboratory-derived adsorption stress change based on observed bulk modulus and volumetric strains (Equation 8), represented by hollow circles; and modeled adsorption stress change in cylindrical pores for non-condensing (Equation 10) and condensing (Equation 11) conditions based on the Gor and Neimark approach, represented by curves. “R” denotes the radius of a cylindrical pore, and RH denotes the relative humidity.
The last term in Equation 11 is the Laplace pressure (Equation 2). This Gor and Neimark approach (i.e., Equations 10 and 11) has been verified by comparing it to laboratory-derived stress change caused by adsorption-induced deformation of mesoporous media such as glass (Amberg & McIntosh, 1952) and SBA-15 silica (Jähnert et al., 2009). Regarding the change in adsorption stress as a result of increasing moisture content within a given solid, $\gamma_d$ and $R$ are both constants, the first term of Equations 10 and 11 can therefore be canceled out. The remaining input parameters are listed in Table 1, and we can calculate the theoretical adsorption stress change with respect to the 20% humidity state by applying pore radii ($R$) of 2.5, 5, and 7.5 nm, as demonstrated by the red (in non-condensing conditions) and blue (in condensing conditions) solid curves in Figure 14. The inflection points indicate the critical RH (capillary condensation point) at which water vapor begins to condense to liquid.

### 5.4. Surface Energy

The Gibbs adsorption equation (Bangham, 1937) is used to calculate surface energy change with adsorption. As relative pressure (or RH) increases from $P_1/R_s$ to $P_2/R_s$ ($P_2/P_0 < P_1/P_0$), the adsorption-induced surface energy change ($\Delta \gamma_s$) can be calculated in the form (Bangham, 1937):

$$\Delta \gamma_s = \gamma_s\left(\frac{P_2}{P_0}\right) - \gamma_s\left(\frac{P_1}{P_0}\right) = \frac{R_sT}{V_L} \int_{P_1/P_0}^{P_2/P_0} h d\left(\ln\left(\frac{P}{P_0}\right)\right)$$  \hspace{3cm} (12)

where $\gamma_s\left(\frac{P_1}{P_0}\right)$ and $\gamma_s\left(\frac{P_2}{P_0}\right)$ are the solid-air interface energies at pressure of $P_1$ and $P_2$ respectively, $R_s$ is the gas constant, $T$ is the absolute temperature, $V_L$ is the molar volume of the condensed phase, and $h$ is the adsorbed film thickness (Equation 9). Assuming no surface energy consumption under condensing conditions, the surface energy reduction under the non-condensing conditions can therefore be calculated by:

$$\gamma_s\left(\frac{P}{P_0}\right) = \gamma_s\left(\frac{P_c}{P_0}\right) = \frac{R_sT}{V_L} - \frac{m}{m-1} h_0(-k)^{1/m} \left\{ \ln\left(\frac{P_c}{P_0}\right) \right\}^{(m-1)/m} - \left\{ \ln\left(\frac{P}{P_0}\right) \right\}^{(m-1)/m}$$  \hspace{3cm} (13)

where the relative pressure $P_c/P_0$ is the condensation point at which the adsorbate begins to condense, can be determined by the Kelvin equation or Equation 1.

Using adsorption parameters in Table 1, and pore radius ($R$) of 5 nm (as characterized by nitrogen adsorption analysis in Section 3.1), the surface energy determined by Equation 13 decreases monotonically as adsorption progresses with increasing film thickness, and approaches the minimum at 82% humidity (i.e., the condensation point determined by Equation 1, also indicated by the inflection point in Figure 14). The surface energy change from completely dry (0% RH) to condensation point is approximately 0.15 J m$^{-2}$ (Figure 15), consistent with the 0.13 J m$^{-2}$ change from dehydroxylated to hydroxylated quartz (Iler, 1979). The average free energy of

### Table 1: Input Parameters for Adsorption Stress Calculation Using Equations 10 and 11

| Parameter  | Value |
|------------|-------|
| $T$ (K)    | 328   |
| $R_s$ (J K$^{-1}$) | 8.31  |
| $V_L$ (m$^3$) | 0.072 |
| $\gamma_1$ (J/m$^2$) | 2.95  |
| $m$        | 1.36  |
| $h_0$ (m)  | 1 x 10$^{-10}$ |

*Note. $T$ is the air temperature, $R_s$ is the gas constant, $V_L$ is the molar volume of liquid water, $\gamma_1$ is the water-air interface energy (Schön, 2011), $h_0$ is the monolayer adsorbed film thickness (Gor & Neimark, 2010), $k$ and $m$ are Frenkel-Halsey-Hill parameters derived from water adsorption on quartz at room temperature (Kumar et al., 2011)."
feldspar surface, which includes “adsorption sites with both the highest and the lowest energy of interactions”, is 0.16 J m$^{-2}$, as documented by Staszczuk et al. (1996). Despite the lack of feldspar moisture content, the average surface energy change would be around 0.16 J m$^{-2}$. This again suggests our calculation is reasonable. Note that the reduction in surface energy of Fontainebleau sandstone as RH increases from 0% to 100% is estimated to be 0.33 J/m$^2$ (Pimienta et al., 2014), twice our prediction for Herrnholz granite (0.15 J m$^{-2}$). This could be due to the different pore sizes of the rock samples involved. For example, Gibbs’s theory (Equation 12) predicts a greater surface energy change for a larger pore. Pimienta et al.’s estimation, on the other hand, assumes that elastic weakening is solely caused by surface energy variation, while in our study, the elastic variation is caused by surface energy reduction in non-condensing conditions and capillary effect in condensing conditions. According to the calculated results in Figure 15, as RH increases from 20% to 82%, surface energy of the tested material decreases by 0.06 J m$^{-2}$, contributing to a volumetric expansion of $3.7 \times 10^{-4}$ (46% of the total strain), and a Young’s modulus reduction from 43 to 39 GPa (67% of the total reduction).

5.5. Elastic Properties Estimation From Relative Humidity

We can predict elastic properties of the tested material as a function of RH by combining our observation of an apparently linear relationship between humidity-induced variations in bulk modulus and volumetric strain (Equation 3) with the existing relationship between volumetric strain and adsorption stress (Equation 8). Initial (reference) elastic properties, correlation coefficients, pore radius, and environmental conditions such as temperature and humidity are all input parameters.

Combination of Equation 8 with Equation 3 gives (assuming $K = K_{0}$): $K^2 - K_0 K = 1.14 \times 10^4 \Delta (\sigma_a - \sigma_c)$, which can be solved, and we get $K$ as:

$$K = \frac{K_0 + \sqrt{K_0^2 + 4 \times 1.13 \times 10^4 \times \Delta (\sigma_a - \sigma_c)}}{2} \quad (14)$$

where the initial bulk modulus $K_0$ and change in external stress $\Delta \sigma_e$ are known, 1.13 $\times$ $10^4$ is the correlation coefficient between variations in bulk modulus (from axial stress-strain measurement) and volumetric strain (Figure 12), and $\Delta \sigma_e$ is a function of RH (Equations 10 and 11) for a given porous media. Equation 14 predicts changing bulk modulus of a sample exposed to various RH conditions with a constant external stress ($\Delta \sigma_e = 0$), as presented in Figure 16a. Predicted results are consistent with laboratory calculated values at RH levels above 20%. We can estimate the evolution of Young’s modulus and Poisson’s ratio as RH increases by substituting

---

**Figure 15.** Calculated surface energy change (in reference to the condensation point, here 82% relative humidity based on Equation 1) as a function of relative humidity during adsorption with increasing film thickness, based on the Gibbs adsorption equation (Equation 13). RH denotes the relative humidity.
Equations 6 and 7 into Equation 14, as shown in Figures 16b and 16c. We predict negative Poisson's ratios for humidity less than 3%, indicating that Equation 10 may be inappropriate for describing adsorption behavior at such low humidity levels.

5.6. Relative Effect of Expansion and Softening

Alongside the apparent decrease in axial stiffness as ambient humidity increases, we observe an increase in non-linear axial strain accumulation during each load cycle (Figure 8a). Assuming that adhesion causes a consistent reduction in the axial stiffness of backbone minerals (i.e., linear-elasticity), non-linear axial strains during loading phases may reflect contributions from capillary-induced expansion of connected pore spaces. We can gain insight into the relative effect of adhesion and capillary action by evaluating the linear and non-linear portions of the axial stress-strain relationship during loading steps. To this end, we calculate the accumulated linear strain by dividing the estimated Young’s modulus for each load cycle by the change in applied stress. We can then quantify the non-linear strain component by subtracting the estimated linear strain from the total accumulated strain during the loading step. Figure 17 compares axial strain accumulated during hold stages to linear-elastic, non-linear, and total axial strains accumulated during loading cycles. Below we expand on these comparisons.

Overall, we observe that linear-elastic strains in the staged test (Figure 17a) respond relatively quickly (when compared to the non-linear strains) and stabilize soon after each of the first two humidity steps (i.e., 20% and 42% RH). In contrast, the non-linear strains show a progressive accumulation over each humidity interval. Increasing humidity from 62% to 82% generates a similar, initially rapid accumulation of linear-elastic strain, followed by a stabilization, while the non-linear component somewhat matches the initial rate of linear-elastic strains accumulation, and continues to accumulate throughout the 82% humidity interval. Following re-start of the staged test, linear-elastic strains are relatively stable, decaying slightly throughout the 90% humidity interval. Non-linear strains, however, demonstrate the greatest increase during the test, and continue to accumulate throughout the 90% RH hold period. The continuous test (Figure 17b) exhibits a similar behavior, with an initially rapid accumulation of linear-elastic strains that stabilizes after approximately 48 hr, after which cumulative non-linear strains become dominant and continue to increase progressively. These results are consistent with the Gor and Neimark model (Figure 14), in which relatively rapid adhesion dominates at humidity levels below 60%, and more progressive capillary-driven reduction in stiffness and pore expansion dominates above the 82% humidity level. The increasing nonlinear response with adsorption, especially through the 82% and 90% humidity stages in this study, has also been observed in sandstone and limestone (Van Den Abeele, 2002), and is assumed to be associated with an increase in micro-heterogeneities caused by capillary condensation in characterized pores, and thus an increase of nonlinear elastic effects.

Axial strain during hold periods associated with increasing humidity appears to develop in a manner most similar to that of linear-elastic strains (Figures 17a and 17b), with initially rapid expansion, followed by a gradual reduction in strain rate until the specimen achieves dimensional stability. Axial strains appear to mirror the reduction in total loading-induced strain during the drying phase, though data for this phase is limited. We note that the apparently similar magnitudes of compressional and extensional strain during load and hold periods are primarily a result of our selected load levels and are therefore somewhat coincidental. Though further analysis is
likely required, our results indicate that the evolution of axial expansion during the hold periods with increasing humidity may primarily be driven by adhesion of water onto free surfaces of minerals (i.e., linear-elastic behavior), while capillary effects within the pores (and possibly pumping of fluid during load-unload cycles) contribute primarily to changes in elasticity.

5.7. Equivalent Stress Change With Increase in Ambient Humidity

To extend our observations in laboratory to in-situ settings (e.g., tunnels, wellbores, and rock slopes) under varied stress conditions, we estimate the stress change as a result of competition between adsorption-induced expansion and softening (Young’s modulus) in wet conditions. We adopt the Hooke’s law for isotropic linear elastic materials:

\[
\Delta \sigma_X = \frac{E_0 + \Delta E}{1 + (\nu_0 + \Delta \nu)} \left( \Delta \varepsilon_X + \frac{\nu_0 + \Delta \nu}{1 - 2(\nu_0 + \Delta \nu)} (\Delta \varepsilon_X + \Delta \varepsilon_Y + \Delta \varepsilon_Z) \right) 
\]

(15)

\[
\Delta \sigma_Y = \frac{E_0 + \Delta E}{1 + (\nu_0 + \Delta \nu)} \left( \Delta \varepsilon_Y + \frac{\nu_0 + \Delta \nu}{1 - 2(\nu_0 + \Delta \nu)} (\Delta \varepsilon_X + \Delta \varepsilon_Y + \Delta \varepsilon_Z) \right) 
\]

(16)

\[
\Delta \sigma_Z = \frac{E_0 + \Delta E}{1 + (\nu_0 + \Delta \nu)} \left( \Delta \varepsilon_Z + \frac{\nu_0 + \Delta \nu}{1 - 2(\nu_0 + \Delta \nu)} (\Delta \varepsilon_X + \Delta \varepsilon_Y + \Delta \varepsilon_Z) \right) 
\]

(17)

where \( \Delta \sigma \) is the moisture-induced variation in stress (i.e., the equivalent stress change), \( \Delta \varepsilon \) is the moisture-induced variation in strain, with the subscripts \( X, Y, \) and \( Z \) indicating the vertical, maximum horizontal, and minimum

Figure 17. Comparison of axial strain accumulated during hold stages to linear-elastic, non-linear, and total axial strains accumulated during loading cycles for the (a) staged and (b) continuous test.
horizontal values, $\Delta E$ and $\Delta \nu$ are moisture-induced variations in Young's modulus and Poisson's ratio, respectively. $E_0$ and $\nu_0$ are the Young's modulus and Poisson's ratio, respectively, at the reference humidity state.

By substituting our observed changes in Young's modulus, Poisson's ratio, and volumetric strains in response to changing humidity (Figure 12) into Equations 15–17, we estimate the equivalent stress change as a result of increasing humidity from 20% under three stress conditions (Figure 18):

1. For an unconfined uniaxial compression state, mechanical stress $\sigma_X \neq 0, \sigma_Y = \sigma_Z = 0$, mechanical strain $\varepsilon_Y / \varepsilon_X = -\nu$, Equation 15 can be reduced to $\Delta \sigma_X = \frac{E_0 + \Delta E}{1 + \nu_0 + \Delta \nu} \Delta \varepsilon_X$, giving an equivalent vertical (or axial) stress change of 17 MPa as humidity increases from 20% to 90%.

2. For confined biaxial compression state, mechanical stress $\sigma_Y \neq 0, \sigma_X = \sigma_Z \neq 0$, mechanical strain $\varepsilon_Y = \varepsilon_Z$, Equations 15–17 give the equivalent changes in vertical stress up to 30 MPa, and horizontal stress up to 22 MPa under 90% humidity.

3. For triaxial compression state, Equations 15–17 calculate the average stress change as $\frac{\Delta \sigma (\varepsilon_Y + \varepsilon_Z + \varepsilon_X)}{3} = \frac{E_0 + \Delta E}{1 + 2
\nu_0 + 3 \Delta \nu} \frac{\Delta \varepsilon (\varepsilon_Y + \varepsilon_Z + \varepsilon_X)}{3}$. Applying observed elastic properties and strains to this equation, we assess that the average stress change required to maintain a constant volumetric strain under 90% humidity would be 25 MPa.

6. Conclusions

This study set out to investigate the effect of RH on the deformation and elastic properties of unweathered granite. To this end, uniaxial load/unload/hold sequences were applied to a Herrnholz granite cylinder exposed to stepwise humidity variation, allowing us to measure strains, Young's modulus, and Poisson's ratio at the reference humidity state. Young's modulus and Poisson's ratio, respectively, at the reference humidity state. Young's modulus and Poisson's ratio, respectively, at the reference humidity state. Young's modulus and Poisson's ratio, respectively, at the reference humidity state.

Adsorption stress of 8.5 MPa is generated as RH increases from 20% to 82%, and 16 MPa as humidity continues to increase from 82% to 90%, based on variations in bulk modulus and volumetric strain. We suggest the former is caused by water vapor molecules adhering on solid surfaces such as grain contacts and/or cleavages, while the latter results from capillary condensation of water vapor within pores with apertures around 5 nm. This assumption is based on comparisons of laboratory-derived and modeled adsorption stresses in characteristic pores of the tested granite under testing humidity conditions. Note that the adsorption model we used in this study predicts monotonic expansion of the media as ambient humidity increases from zero to 20%, while we do not have experimental data below 20% humidity due to the control limit of our climate chamber. Further investigation into deformation of unweathered granite with varying relative humidities below 20% is encouraged, given that Haines & McIntosh (1947), and Lakhanpal & Flood (1957) observed an initial contraction of activated charcoal as relative pressures increased from zero, which gradually transitioned to expansion as relative pressures increased beyond ~10%.

We propose a linear relationship between humidity-induced variations in bulk modulus and volumetric strain for intact Herrnholz granite. This finding, together with the Gor and Neimark (2010) approach, allows us to predict elastic properties of the rock as a function of RH. This prediction is important in the application of rock physics theories and numerical models where an input of material elastic properties is always required and has to be taken into account in wet (e.g., unsaturated) conditions. Whereas the proposed relationships are empirical fits...
of five data points from this study at ambient humidity levels of 20%, 42%, 62%, 82%, and 90%, we encourage repeat experiments on the same material with more humidity levels to consolidate our conclusion. Moreover, the elastic moduli of a rock material are likely to vary with rock composition and micro crack population. We therefore encourage similar future experiments on other rock types to develop a broader correlation between ambient humidity and elastic properties.

The calculated generation of adsorption stress at 90% RH is 24.5 MPa, equivalent to 2–3 km of hydrostatic head. The physics of adhesion and capillary condensation indicated in this study may contribute to deformation and stiffness variation of fine-grained granitic rock in geotechnical settings as the moisture content alters under natural conditions, for example, slab failures associated with ventilation of the tunnels, and variation of resonance frequency of rock slopes with precipitation events.

Data Availability Statement

Data sets for this research are available in the data repository https://doi.org/10.3929/ethz-b-000554796, including: (a) data from the mercury intrusion test on Herrnholz granite; (b) data from the nitrogen adsorption test on Herrnholz granite; (c) machine data from the uniaxial compression test on Herrnholz granite exposed to humidity variation; (d) machine data from the uniaxial compression test on aluminum specimen exposed to humidity variation; (e) digital images taken during hold period of the “continuous” compression test on Herrnholz granite; (f) digital image correlation analysis results in Ncorr; (g) heat transfer model of a cylindrical specimen; and (h) machine data from the uniaxial compression strength (failure) test on Herrnholz granite under laboratory environmental conditions.

References

Amberg, C. H., & McIntosh, R. (1952). A study of adsorption hysteresis by means of length changes of a rod of porous glass. Canadian Journal of Chemistry, 30(12), 1012–1032. https://doi.org/10.1139/v52-121
Ashkelon, D. R. (2016). The science and engineering of materials. Retrieved from https://digitalcommons.bucknell.edu/books/105/
Bangham, D. H. (1937). The Gibbs adsorption equation and adsorption on solids. Transactions of the Faraday Society, 33, 805–811. https://doi.org/10.1039/TF3733000805
Barrett, E. P., Joyner, L. G., & Halenda, P. P. (1951). The determination of pore volume and area distributions in porous substances. I. Computations from nitrogen isotherms. Journal of the American Chemical Society, 73(1), 373–380. https://doi.org/10.1021/ja01145a126
Barsotti, E., Tan, S. P., Saraji, S., Piri, M., & Chen, J. H. (2016). A review on capillary condensation in nanoporous media: Implications for hydrocarbon recovery from tight reservoirs. Fuel, 184, 344–361. https://doi.org/10.1016/j.fuel.2016.06.123
Beckingham, L. E., Mimitnick, E. H., Steelcl, C. I., Zhang, S., Voltolini, M., Swift, A. M., et al. (2016). Evaluation of mineral reactive surface area estimates for prediction of reactivity of a multi-mineral sediment. Geochimica et Cosmochimica Acta, 188, 310–329. https://doi.org/10.1016/j.gca.2016.05.040
Bentz, D. P., Garboczi, E. J., & Quenard, D. A. (1998). Modelling drying shrinkage in reconstructed porous materials: Application to porous Vycor glass. Modelling and Simulation in Materials Science and Engineering, 6(2), 211–236. https://doi.org/10.1088/0965-0393/6/2/002
Bitzek, E., Kermode, J. R., & Gumbsch, P. (2015). Atomic aspects of fracture. International Journal of Fracture, 191(1), 13–30. https://doi.org/10.1007/s10704-015-9988-2
Blaber, J., Adair, B., & Antoniou, A. (2015). Ncorr: Open-source 2D digital image correlation MATLAB software. Experimental Mechanics, 55(6), 1105–1122. https://doi.org/10.1007/s11340-015-0009-1
Brace, W. F., Paulding, B. W., Jr., & Scholz, C. (1966). Dilatancy in the fracture of crystalline rocks. Journal of Geophysical Research, 71(16), 3939–3953. https://doi.org/10.1029/JZ071i016p03939
Brown, S. L., & Macaëduire, J. (1984). Microfracturing in relation to atomic structure of plagioclase from a deformed meta-anorthosite. Journal of Structural Geology, 6(5), 579–586. https://doi.org/10.1016/0191-8141(84)90067-1
Brunauer, S., Emmett, P. H., & Teller, E. (1938). Adsorption of gases in multimolecular layers. Journal of the American Chemical Society, 60(2), 309–319. https://doi.org/10.1021/ja01269a023
Burjánek, J., Gischig, V., Moore, J. R., & Fäh, D. (2018). Ambient vibration characterization and monitoring of a rock slope close to collapse. Geophysical Journal International, 212(2), 297–310. https://doi.org/10.1093/gji/ggy424
Cerfontaine, B., & Collin, F. (2018). Cyclic and fatigue behaviour of rock materials: Review, interpretation and research perspectives. Rock Mechanics and Rock Engineering, 51(2), 391–414. https://doi.org/10.1007/s00603-017-1337-5
Chen, M. (2019). Sorption-induced deformation of nanoporous materials. ETH Zurich. Retrieved from https://www.research-collection.ethz.ch/handle/243 of 27
Chen, M., Coasne, B., Guyer, R., Derome, D., & Carmeliet, J. (2019). Molecular simulation of sorption-induced deformation in atomistic nanoporous materials. Langmuir: The ACS Journal of Surfaces and Colloids, 35(24), 7751–7758. https://doi.org/10.1021/acs.langmuir.9b00839
Choi, J.-G., Do, D. D., & Do, H. D. (2001). Surface diffusion of adsorbed molecules in porous media: Monolayer, multilayer, and capillary condensation regimes. Industrial & Engineering Chemistry Research, 40(19), 4005–4031. https://doi.org/10.1021/ie0103952
Colback, P. S. B., & Wib, B. L. (1965). The influence of moisture content on the compressive strength of rocks. Geophysics, 65–83. [Preprint]. Retrieved from https://trid.trb.org/view/139969
David, E. C., Brantut, N., Schubnel, A., & Zimmerman, R. W. (2012). Sliding crack model for nonlinearity and hysteresis in the uniaxial stress-strain curve of rock. International Journal of Rock Mechanics and Mining Sciences, 52, 9–17. https://doi.org/10.1016/j.ijrmms.2012.02.001
Swanson, P. L. (1984). Subcritical crack growth and other time-and environment-dependent behavior in crustal rocks. *Journal of Geophysical Research, 89*(B6), 4137–4152. Retrieved from https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JB089iB06p04137@10.1002/ISSN2169-9356.CHEMDEF1

Tang, S. B., Yu, C. Y., Heap, M. J., Chen, P. Z., & Ren, Y. G. (2018). The influence of water saturation on the short- and long-term mechanical behavior of red sandstone. *Rock Mechanics and Rock Engineering, 51*(9), 2669–2687. https://doi.org/10.1007/s00603-018-1492-3

Thommes, M., Kaneko, K., Neimark, A. V., Olivier, J. P., Rodriguez-Reinovo, F., Rougier, J., & Sing, K. S. (2015). Physisorption of gases, with special reference to the evaluation of surface area and pore size distribution (IUPAC Technical Report). *Journal of Macromolecular Science, Part A: Pure and Applied Chemistry*, 87(9–10), 1051–1069. https://doi.org/10.1515/pac-2014-1117

Tiennot, M., & Fortin, J. (2020). Moisture-induced elastic weakening and wave propagation in a clay-bearing sandstone. *Geotechnique Letters*, 10(3), 424–428. https://doi.org/10.1680/gele.19.00052

Tsaligramis, P. T. (2018). Review and critical comparative evaluation of moist air thermophysical properties at the temperature range between 0 and 100°C for Engineering Calculations. *Renewable and Sustainable Energy Reviews, 83*, 50–63. https://doi.org/10.1016/j.rser.2017.10.072

Tullis, J., & Yund, R. (1992). Chapter 4 the brittle-ductile transition in feldspar aggregates: An experimental study. In B. Evans & T.-F. Wong (Eds.), *International geophysics* (pp. 89–117). Academic Press. https://doi.org/10.1016/S0074-6142(08)62816-8

Van Den Abeele, K. E.-A. (2002). Influence of water saturation on the nonlinear elastic mesoscopic response in Earth materials and the implications to the mechanism of nonlinearity. *Journal of Geophysical Research*, 107*(B6), 2121. https://doi.org/10.1029/2001JB000368

Voigtländer, A., Leith, K., & Kraublatter, M. (2018). Subcritical crack growth and progressive failure in Carrara marble under wet and dry conditions. *Journal of Geophysical Research: Solid Earth, 123*(5), 3780–3798. https://doi.org/10.1002/2017JB014956

Wangler, T. P., Stratulat, A., Duffus, P., Prévost, J. H., & Scherer, G. W. (2011). Flaw propagation and buckling in clay-bearing sandstones. *Environmental Earth Sciences*, 63(7), 1565–1572. https://doi.org/10.1007/s12665-010-0732-y

Wangler, T., & Scherer, G. W. (2008). Clay swelling mechanism in clay-bearing sandstones. *Environmental Geology*, 56(3), 529–534. https://doi.org/10.1007/s00254-008-1380-3

Washburn, E. W. (1921). Note on a method of determining the distribution of pore sizes in a porous material. *Proceedings of the National Academy of Sciences of the United States of America, 7*(4), 115–116. https://doi.org/10.1073/pnas.7.4.115

Wild, K. M., Wymann, L. P., Zimmer, S., Thoeny, R., & Amann, F. (2015). Water retention characteristics and state-dependent mechanical and petro-physical properties of a clay shale. *Rock Mechanics and Rock Engineering, 48*(2), 427–439. https://doi.org/10.1007/s00603-014-0565-1

Willaime, C., Christie, J., & Kovačs, M.-P. (1979). Experimental deformation of K-feldspar single crystals. *Bulletin de Mineralogie*, 102(2), 168–177. https://doi.org/10.1680/ijrmms.1979.7272

Wong, L. N. Y., Maruvanchery, V., & Liu, G. (2016). Water effects on rock strength and stiffness degradation. *Acta Geotechnica*, 11(4), 713–737. https://doi.org/10.1007/s11440-015-0407-7

Wong, T.-F., & Biegel, R. (1985). Effects of pressure on the micromechanics of faulting in San Marcos gabbro. *Journal of Structural Geology, 7*(6), 737–749. https://doi.org/10.1016/0191-8141(85)90049-X

Yang, D. S., Bornert, M., Chanchole, S., Gharbi, H., Valli, P., & Gatmiri, B. (2012). Dependence of elastic properties of argillaceous rocks on moisture content investigated with optical full-field strain measurement techniques. *International Journal of Rock Mechanics and Mining Sciences, 53*, 45–55. https://doi.org/10.1016/j.ijrmms.2012.04.004

Yang, S. Q., Ranjith, P. G., Huang, Y. H., Yiu, P. F., Jing, H. W., Gui, Y. L., & Yu, Q. L. (2015). Experimental investigation on mechanical damage characteristics of sandstone under triaxial cyclic loading. *Geophysical Journal International*, 201(2), 662–682. https://doi.org/10.1093/gji/ggv023

Yurikov, A., Lebedev, M., Gor, G. Y., & Gurevich, B. (2018). Sorption-induced deformation and elastic weakening of Bentheim sandstone. *Journal of Geophysical Research: Solid Earth, 123*(10), 8589–8601. https://doi.org/10.1029/2018JB016003

Zoback, M. D., & Byerlee, J. D. (1975). The effect of cyclic differential stress on dilatancy in Westerly granite under uniaxial and triaxial conditions. *Journal of Geophysical Research, 80*(11), 1526–1530. [Preprint]. https://doi.org/10.1029/JB080i11p01526

References From the Supporting Information

Junghans, K., Peter, N., & Fritz, B. (2005). Untersuchungen Zum Einfluss Der Thermischen Vergüttung Auf Die Porosität von Fichtenholz. *Holz Als Roh-Und Werkstoff, 63*(3), 243–244. https://doi.org/10.1007/s00107-004-0553-3