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SWELLING PRESSURE AND STRESS DEVELOPMENT IN CLAY-BEARING SANDSTONES

Timothy Wangler,[1,2] Elaine Ngo[3] and George W. Scherer[4]

[1] *Princeton University Department of Chemical Engineering, Princeton, NJ, 08544*
[2] *Now: ETH Zürich Institute for Building Materials, Zürich, Switzerland 8093*
3 University of Notre Dame, Department of Chemistry, South Bend, IN, USA 46556
[4] *Princeton University Department of Civil & Environmental Engineering, Princeton, NJ 08544*

Abstract

Many stones used in buildings, monuments, and other objects of cultural importance contain clays in the matrix that can swell when exposed to water. This swelling can lead to damaging stresses, and an understanding of how these stresses develop during wetting and drying cycles can help to mitigate this problem. An important variable to consider when analyzing stress development is the swelling pressure, which is defined as the stress exerted by a constrained stone sample after wetting. In this study, the swelling pressure of Portland brownstone, a commonly used building stone in historic buildings in the northeastern United States, is measured at varying overburden stresses. The results indicate a hysteresis in the swelling process, and the impact on the stress during a wetting cycle is discussed.

Keywords: clays. swelling, swelling pressure

1. Introduction

Swelling clays can exist in the cementing phase of many types of sandstone used in buildings and monuments that are important for cultural heritage. When subjected to wetting and drying cycles, differential strains can develop that lead to stresses comparable to the strength of the stone. This phenomenon has been studied by researchers in conservation (Wendler et al. 1990), and especially in recent times (Gonzalez and Scherer 2004; Sebastian et al. 2008; Franzini et al. 2007; Rüdrich et al. 2011), as well as civil engineering (Dunn and Hudec 1966; Brattli and Broch 1995). Damage in the field can arise during wetting, where a thin wet layer buckles due to compression by the rest of the dry stone, or during drying, where a thin dry layer cracks in tension (Gonzalez and Scherer 2004). Damage during wetting requires a preexisting flaw to detach part of the surface from the stone, and a recent experimental study explored the possibility of how wetting patterns can lead to flaw propagation and ultimately buckling (Wangler and Scherer 2011). Most damage observed in the field is presumed to come from wetting, though some drying damage has been observed on protruding elements (Gonzalez et al. 2008). The characterization of how stresses evolve in swelling sandstone during a wetting cycle is therefore of great interest in understanding how swelling leads to damage. Traditionally, the stress evolved by swelling clays in stone has been measured by an experiment in which a stone sample is restricted, then wetted, and the force it generates is measured (Madsen and Müller-moos 1989). Stress and pressure obey opposite sign conventions. Since the stone expands, it can be said to experience a positive internal pressure. To suppress the expansion, it is necessary to exert a compressive (negative) stress on the body. This external stress is what we call swelling stress; it is equal and opposite in sign to the internal swelling pressure.

When an initially dry stone is restricted uniaxially, the swelling stress expected to evolve will be the quantity:

$$\sigma_S = -p_S = -E_w \epsilon_s \qquad (1)$$

where σ_S is the swelling stress, p_S is the swelling pressure, E_w is Young's modulus of the wet stone, and ε_s is the free swelling strain of the stone. The swelling stress is compressive (negative). Scherer and Gonzalez performed measurements of this type on Portland brownstone and found values of the swelling pressure of 0.74 MPa, or about 50-75% less than expected (2005). This was attributed to potentially poor contact with the platens of the testing device and the lower resolution of the testing device.

In the same study, Scherer and Gonzalez presented an alternative method of demonstrating and indirectly measuring the developed stresses during wetting by using a novel warping experiment. In this experiment, a thin plate of stone of length *L* and thickness *h* is wetted from one side. As the water penetrates the thin stone plate, the wet portion expands, while the dry portion resists the expansion, and the stone plate bends as a compromise, as seen in Figure 1.

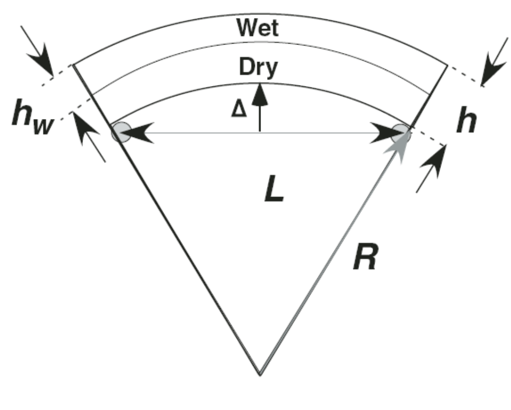

Figure 1. Geometry of warping experiment. Wet stone attempting to expand is compressed by dry stone, inducing deflection.

The deflection Δ is easily measured as a function of time. After the water has penetrated a certain depth, the bottom portion of the stone begins to swell relative to the already swollen top portion, and the deflection reaches a maximum and begins to decrease. Building upon the analysis by Timoshenko of a bimaterial strip (1925), Scherer and Gonzalez showed that the fit of the Δ versus time curve can yield several useful parameters, such as the swelling strain ε_s, the sorptivity *S*, and the ratio of the wet to the dry modulus *f*. Fits to warping data of a Portland brownstone plate showed a good fit to the early part of the curve, but the later portion of the curve shows that the plate does not relax as quickly as expected, as seen in Figure 2.

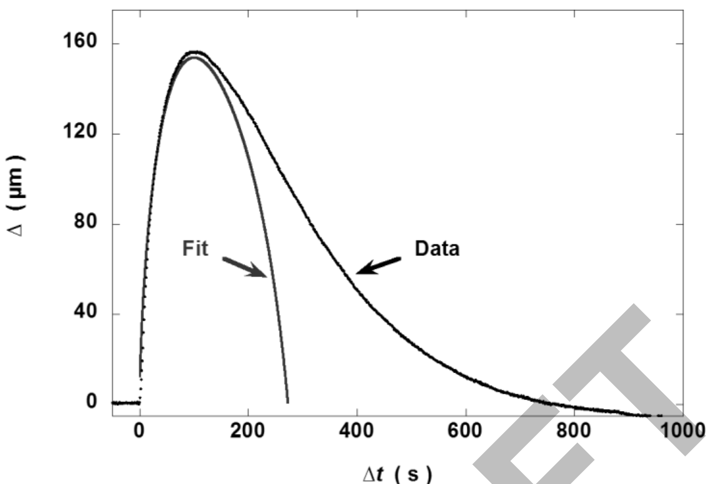

Figure 2. Warping curve of Portland brownstone (solid) compared to theory (dashed), showing persistent deflection at longer times.

The slow relaxation of the plate can be due to a number of reasons, including a delay in either the swelling or the softening of the stone after invasion of the water. An additional possibility is that there is a dependence of the swelling strain on the stress state of the stone. That is, if the stone is placed under an external compressive stress (also termed overburden pressure), it may not swell as much as in the free state. In this study, the swelling pressure is measured when imposing an overburden stress before wetting, and the relationship between the swelling pressure and the compressive state of the stone is then explored.

2. Materials and Methods

For this study, small prismatic samples of stone were cut and mounted in a mechanical testing device, placed under a specific overburden stress, and wetted. The evolution of the load versus time was monitored until the wetting process was completed.

2.1 Portland brownstone

Portland brownstone, a widely used and well characterized building stone from the northeastern United States, was used for this study (Gonzalez and Scherer 2004). Prismatic samples approximately 1 x 1 x 5 cm were cut with the bedding perpendicular to the long dimension to maximize swelling. The free swelling strain in this direction was measured via dilatometry to be 0.9 mm/m. Larger pieces of Portland brownstone, approximately 20 x 10 x 2 cm, were cut to measure the elastic modulus under compression.

2.2 Elastic modulus under compression

The compressive elastic modulus was measured in the wet and the dry state using an Instron® 600DX testing device. This device had a lower measuring resolution and required the larger samples, but it was used because it had an extensometer (Epsilon Technologies) for accurate strain measurements.

2.3 Swelling pressure measurement

The swelling pressure was measured on a smaller Instron® 5567 testing machine with a higher resolution, necessary for accurate determination of loads on the smaller samples. Samples were placed as shown in Figure 3, with a spherical washer assembly on the top of the sample to adjust to the sample irregularities. The platens were brought into contact with the sample, then a prescribed dry overburden stress σ_D between 0.25 to 9 MPa was imposed. After an initial relaxation period of approximately 10 minutes, the sample was wetted and the load monitored, with the stress at saturation recorded. The difference between the initial dry stress and the final stress at saturation, $\Delta\sigma$, was recorded.

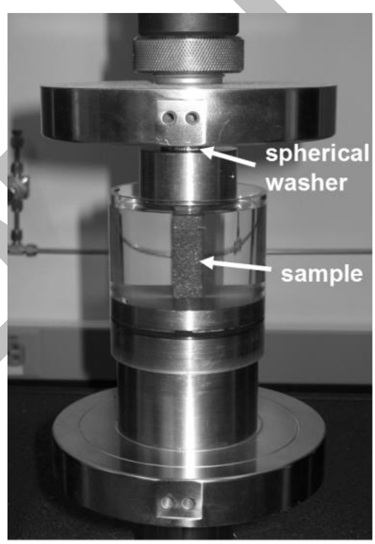

Figure 3. Experimental setup for swelling pressure experiments.

3. Results

3.1 Elastic modulus under compression

The elastic modulus measurements were performed over a range corresponding to the range of compressive stress applied in this experiment. The results can be seen in Figure 4. While linear elasticity fits in the dry state, the stress-strain curve is clearly nonlinear for the stone in the wet state. A second order fit was applied and the following expression was adopted to describe the stress-strain behavior of the wet stone.

$$|\sigma_x| = 2.891|\epsilon_x|^2 + 2.5268|\epsilon_x| \qquad (2)$$

The stresses and strains are negative, as the stone is in compression.

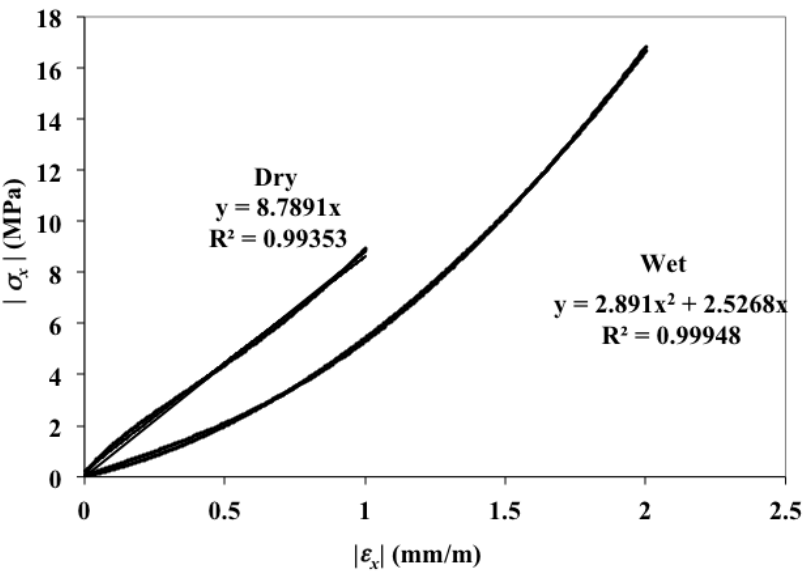

Figure 4. Stress-strain curves for Portland brownstone under compression in the wet and dry state.

3.2 Swelling pressure

The results of the swelling pressure experiments in Figure 5 show a decrease in the evolved wetting stress as the overburden pressure increases. Above 8 MPa overburden stress, the curve drops below zero due to viscoelastic relaxation during the experiment. Even at the smallest imposed stress, the swelling pressure is less than 1 MPa.

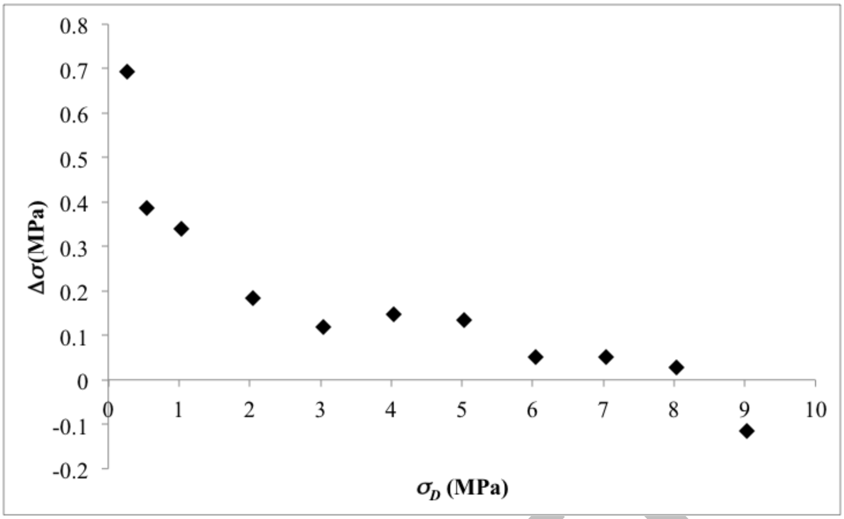

Figure 5. Change in pressure of stone upon saturation versus initial overburden stress σ_D.

4. Discussion

The behavior of the wet stone in compression is nonlinear, with an increasing stiffness as the compressive strain increases. This behavior arises from squeezing the water out of the clay layers, and one would expect then that the water would be fully removed from the clay layers when the wet stone is compressed by a strain of ε_s, back to its original length in the dry state. With the measured swelling strain of 0.9 mm/m and the expression describing the stiffness in (2), this means one would expect this pressure to be 4.6 MPa. Therefore, a dry stone under an overburden pressure of 4.6 MPa should not swell when wetted. When one examines Figure 5, however, it is clear that swelling is still occurring, even at overburden pressures above this. Madsen and Müller-Vonmoos measured the swelling pressure for opalinum shales and found them to be in the range of 1-2 MPa (1989). This range was expected for osmotic swelling, which was the attributed swelling mechanism in their swelling rock. In the case of the Portland brownstone, an earlier study confirmed that swelling occurs almost exclusively in the intracrystalline range (Wangler and Scherer 2008), where swelling pressures have been calculated to be on the order of 400 MPa to prevent the first layer of water from entering the clay, and down to 20-30 MPa to prevent the third and fourth layers from entry (Madsen and Müller-Vonmoos 1989).

Because the overburden pressures are not close to this, one would expect some intracrystalline swelling to occur. Looking at Figure 5, one might say that an overburden pressure of approximately 8 MPa is sufficient to suppress swelling, but consideration of viscoelastic relaxation would be necessary to get a more accurate estimate. In any case, these overburden pressures are still very low compared to the 400 MPa required for suppression of swelling. The clays, however, are concentrated between the larger grains that make up the stone, and the smaller areas they occupy will act to magnify the external stress. The fact that the modulus only changes by about a factor of two between the dry and saturated states indicates that many of the grain boundaries do not contain swelling clay, and those boundaries constrain the expansion and impose stress on the clay. Both of these factors can act in concert to raise the stress that the clay layer actually feels, compared to the external stress imposed on the whole system.

The present results confirm the earlier swelling pressure measurements of Scherer and Gonzalez, where the swelling pressures at no initial overburden pressure were much lower than expected (2005). In this study, the same experiment yielded about 0.7 MPa, about the same as in the earlier study. With increasing overburden pressure to obtain better contact to the platens, the stress after wetting remains low. The time scale of the saturation (in all cases, approximately 20 minutes) does not allow enough viscoelastic relaxation to occur to explain the low stresses measured. The low swelling stress is most likely an indication of hysteresis.

Hysteresis in intracrystalline swelling has been demonstrated experimentally by Fu et al. (1990) and with molecular dynamics studies by Boek et al. (1995). A more recent molecular dynamics study performed by Tambach et al. (2006) demonstrates that there is a free energy barrier in going from the monolayer to the bilayer hydrate, meaning the external pressure required to keep water from entering the interlayer is not as high as that required to force it from the interlayer. In the present experimental study, only about 0.7 MPa is necessary to maintain an initially dry stone's linear dimension, but to return an already saturated stone to this same dimension required 4.6 MPa. As mentioned earlier, this low external stress can be magnified at the actual clays located at the grain boundaries by stress concentration due to area reduction and also the additional stress supplied by the stone's nonswelling components.

The overburden pressures for this experiment were selected based on the stresses calculated to evolve during the warping experiment. The stresses in the stone plate calculated from the analysis of Timoshenko are illustrated schematically in Figure 6 and are shown as they evolve in both the wet and dry layers as a function of wetted depth in Figure 7. For much of the experiment, the majority of the wet portion of the stone is under compressive stress, and at levels that could be sufficient to inhibit the swelling process until compressive stress is reduced to the point where swelling can occur. In all likelihood, the persistent deflection in the warping experiment can be explained by the hysteresis in expansion, as the portions of the plate subjected to compressive stresses are inhibited from expanding. This may be a kinetic effect, where an external stress on the stone merely delays swelling and softening rather than inhibiting it, but Boek et al. (1995) conclude that in the case of intracrystalline swelling, this is highly unlikely. Additionally, the behavior of the wet stone under compression could be strain rate dependent, owing to the kinetics of forcing the water out of the interlayer. Future studies can address these issues, while also focusing on more fully quantifying the hysteretic relationship between swelling and the stress state of the stone, for example by monitoring the strain of the sample through a loading, wetting, unloading, and reloading cycle.

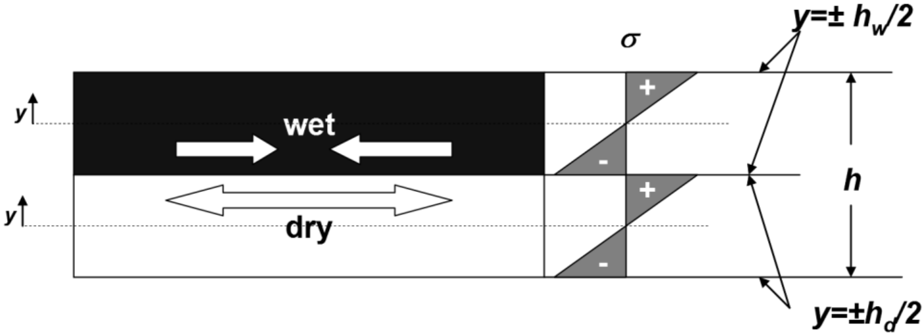

Figure 6. Schematic of stress in a plate of stone during the warping experiment, assuming linear elasticity.

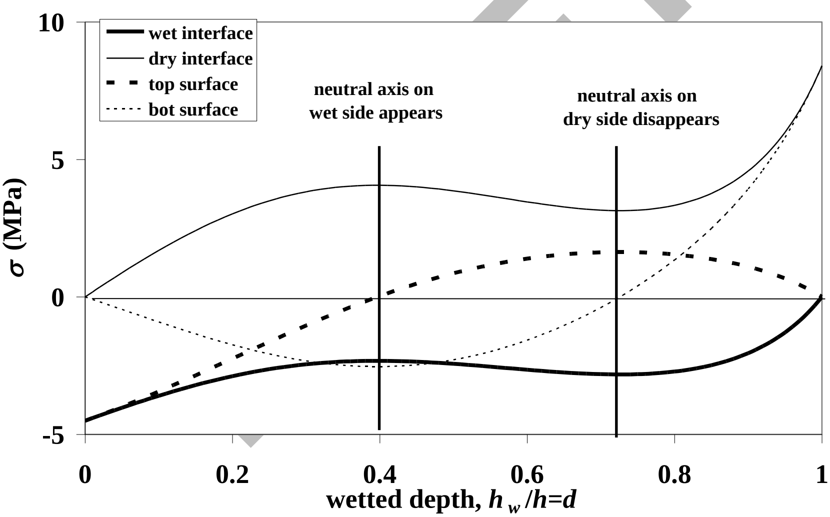

Figure 7. Stress in the wet and dry portions of the stone plate during a warping experiment as a function of wetted depth. The majority of the stress in the wet part of the stone is compressive for the duration of the experiment.

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