Internal Curing: Discussion of the Role of Pore Solution on Relative Humidity Measurements and Desorption of Lightweight Aggregate (LWA)

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Synopsis: Internal curing can be used to counteract the effects of self-desiccation in low water-cement ratio mixtures. Internal curing uses prewetted lightweight aggregate (LWA) as a reservoir that can release water as it is needed to keep the hydrating cement paste structure saturated. While many developments have been made in advancing the field of internal curing, this work examines the composition of the early-age pore solution. The effect of the pore solution composition on the relative humidity is also discussed. The paper performs desorption measurements of the lightweight aggregate to better understand how fluid is released from the lightweight aggregate. An approach is suggested to use solutions rather than pure distilled water to improve the relevance of the measurement of desorption at high relative humidities.

Keywords: autogenous shrinkage; chemical shrinkage; desorption; drying shrinkage; internal curing; lightweight aggregate; relative humidity.
**RESEARCH MOTIVATION**

Internal curing has emerged over the last decade as a method to improve the performance of low water-cement ratio (w/c) mixtures [1-3]. Specifically, internal curing refers to the use of water filled inclusions (for example, prewetted lightweight aggregate) that can provide curing water throughout the cross section of the concrete. This differs from conventional curing where water is only provided at the surface of the concrete. Internal curing can be much more efficient than conventional curing, as conventional water curing may not penetrate more than a few mm in low w/c mixtures after approximately one day of hydration.

Internal curing has been promoted to reduce the effects of self-desiccation. Internal curing was first used as a method to reduce autogenous shrinkage and autogenous shrinkage cracking [1,4-7]. More recent work has demonstrated benefits of internal curing for reducing drying shrinkage, drying shrinkage cracking [8], and plastic shrinkage cracking [9]. Internal curing can also improve the freeze-thaw resistance, resistance to fluid absorption [10,11] and ion diffusion [10,12] of concrete. It is becoming increasingly clear that internal curing has great potential for the concrete industry, however several aspects of internal curing still require closer examination. Specifically, widespread adoption of internal curing could be aided by additional information on mixture proportioning approaches that enable the use of supplementary cementitious materials. Further, additional research is needed to better understand the role of the initial moisture condition of aggregates on the potential benefits of internal curing. Additional research is also needed to better understand how to proportion mixtures with different design goals (for example, reducing drying shrinkage, reducing plastic shrinkage, reducing fluid transport) especially as it may relate to more moderate w/c (0.36 to 0.46) [13,14].

Fundamental to several of these questions is the desorption-absorption properties of the aggregate and its interaction with the pore solution from the cement paste. Several of these questions are listed below:

1. How can the saturated surface dry (SSD) condition of a lightweight aggregate be determined more accurately?
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2. How much “prewetting” is required for the aggregate to be effective in acting as an internal curing agent?
3. How does, and how quickly does, the fluid contained in the lightweight aggregate mix with the pore solution?
4. Does the pore fluid and water in the lightweight aggregate dilute the pore solution?

Research is currently being performed by the authors to answer each of the aforementioned questions [14, 15]. Specifically, however, the research described in this paper is aimed at providing fundamental information to answer these questions. Toward this end, this paper will begin by reviewing the changes that occur in the cement paste during hydration specifically as it relates to pore solution volume and ionic concentration. This is vital for answering questions 3 and 4. In addition, the paper will then discuss the concept behind internal curing specifically as it relates to evaluating the solution volume and the transfer of solution between the LWA and the pore solution which is essential for answering questions 2 and 3. Finally, the paper will discuss the results of desorption measurements of the lightweight aggregate which are important for understanding how the aggregate releases its water. This can be related in part to question 1 for the determination of SSD conditions but is also related to the development of mixture proportioning approaches to determine the correct volume of LWA for a mixture.

A REVIEW OF EARLY AGE CEMENT HYDRATION, INTERNAL CURING, AND RAOULT’S LAW

Before examining the desorption behavior of the lightweight aggregate (LWA), it is important to review the basic concepts behind self-desiccation. It is also important to review how the water that is mixed in the paste ceases to be pure water as the cement reaction progresses and is referred to as the pore solution. To better understand the changes that occur in the pore solution the basic reactions that occur during the first 24 h are discussed. Finally, the interaction between solution chemistry and meniscus geometry is discussed for measurements in a porous system like cement paste, focusing on a review of Raoult’s Law.

The hydration of cement paste causes a volume reduction called chemical shrinkage. Chemical shrinkage occurs since the volume of the hydration products is smaller than that of the reactants [16]. While chemical shrinkage starts at the time the water comes in contact with the cement, it affects the system before and after the paste sets in different ways. Before set, the chemical shrinkage causes bulk shrinkage of the cement paste. This chemical shrinkage is equal to the total external volume change. After set, however, the cement paste becomes stiff enough to resist a portion of the volume change caused by chemical shrinkage [17], causing vapor-filled cavities to form inside the cement paste [6]. In low w/c mixtures, these cavities form in relatively small pores with a small radius of curvature [18, 19]; this is known as self-desiccation. Formation of menisci with small radius of curvature induces high tensile stresses in the pore fluid and substantial shrinkage of the cementitious mixture [18].

Lightweight aggregate can be used to supply water during the hydration/curing process to mitigate the effects of self-desiccation in low w/c concrete mixtures. LWA acts as a water reservoir that can provide water to replenish the empty pore volume that is created by the chemical shrinkage occurring during hydration. The basic principle of using LWA is that the largest pores in concrete will lose water first. As a result, it is important to understand the pore sizes and pore volumes that exist in the LWA as well as how water is released from the LWA. The loss of water from the LWA pores during drying can be described through a desorption isotherm (a plot of mass loss as a function of relative humidity at a constant temperature).

The hydration of cement also causes significant changes in the chemistry of the pore solution. Previous research [20-23] has shown that immediately after the addition of water to the cement and due to the mixing action, substantial quantities of K⁺, Na⁺, Ca²⁺, OH⁻, and SO₄²⁻ are released by the cement particles into the pore fluid. As the hydration continues, the concentration of K⁺, Na⁺, and OH⁻ increases (on the order of several 100 mmol/lit), partly due to further release from cement grains and partly due to the consumption of water in hydration reactions which results in a higher concentration of the remaining pore solution. Meanwhile, the Ca²⁺ concentration is relatively steady and close to the saturation limit (on the order of 10–20 mmol/lit) due to the abundance of solid sources of calcium (calcium hydroxide, tricalcium silicate, gypsum, etc.) in equilibrium with the pore solution. The SO₄²⁻ concentration is often the highest shortly after the mixing (on the order of 10’s to 100 mmol/lit) but will sharply decrease as soon as the solid gypsum is depleted by the hydration of aluminate and ferrite compounds. Other
species such as dissolved SiO$_2$ and Al$_2$O$_3$ exist at sub-milli-molar concentrations. Beyond 24 h, the pore fluid typically contains only K$^+$, Na$^+$, and OH$^-$ in significant concentrations [20-22].

Even in a saturated cement paste, the internal RH is lower than 100% due to the presence of dissolved salts in the pore fluid. This initial RH depression can be estimated and can vary depending on the pore solution chemistry. Changes in the composition of the pore solution can consequently influence moisture loss and shrinkage of cement pastes, especially at high RH.

The partial pressure of vapor in a body of air which is in equilibrium with pure water is higher than the partial pressure of vapor in air which is in equilibrium with an aqueous solution (that is, pore solution). This can be explained by the fact that the amount of water molecules that are present at any time in the gas phase is proportional to their amount in the liquid phase. This concept is expressed in Raoult’s Law, Eq. (1)

$$RH_s = \frac{p_g}{p_{sat}} = X_l$$

where $X_l$ is the molar ratio of water in the pore solution, $p_g$ is the partial vapor pressure of water and $p_{sat}$ is the partial vapor pressure at saturation.

It should be remembered, however, that Raoult’s Law is only strictly valid for dilute solutions. As the solution becomes more concentrated, the interaction between the ions in the solution starts to play a role and the RH drop should be calculated based on the activity of the water in the solution.

When a water-saturated porous medium is in contact with air at RH<100%, it loses moisture until the RH in the pores equilibrates with the external RH. In this process, the pores of the medium partially empty and air-water menisci are formed that cause a tensile stress in the pore fluid (Kelvin’s equation). The tensile stress in the pore water is accompanied by shrinkage of the whole medium [24, 25]. However, when the porous medium is saturated with a salt solution, the internal RH at equilibrium is equal to the external one, but the tensile stress that is developed is also influenced by the composition of the pore solution, as explained by Eq. (2) and (3) below. The decomposition of the RH in the pores into a term due to pore fluid composition and a term due to pressure in the pore fluid is expressed in Eq. (2). For the derivation of this equation, refer, for example, to References 24 and 25.

$$RH_{ext} = \frac{p_g}{p_{sat}} = RH_s \cdot \exp\left(\frac{p_l V_l}{RT}\right)$$

where $RH_f$ is the contribution to the RH due to salts in the pore fluid (for ideal solutions, $RH_f = X_l$), $p_l$ is the pressure (that is, tensile stress) in the pore fluid, $V_l$ is the molar volume of the fluid, $R$ is the gas constant and $T$ is the absolute temperature.

Since at equilibrium the total RH in a porous medium filled with a salt solution will be equal to the external one, Eq. (2) can be rearranged into Eq. (3) [26]

$$p_l = \frac{RT}{V_l} \ln\left(\frac{RH_{ext}}{RH_s}\right)$$

Equation (3) allows the changes in the liquid pressure to be calculated in a partially saturated porous medium as a function of the external RH ($RH_{ext}$) and of the composition of the pore fluid. In practical applications, the molar volume of the fluid is taken equal to that of water.

**EXPERIMENTAL PROGRAM**

This paper describes a series of experiments that were performed to determine how the chemical composition of the fluid in prewetted LWA influences the desorption behavior of the LWA. Toward this end, tests are conducted that evaluate:

- The composition of the pore solution of a hydrating cement paste with a w/c of 0.30.
- The internal relative humidity of a hydrating cement paste with a w/c of 0.30.
• The internal relative humidity of a hydrating cement paste with internal curing and a \( w/c \) of 0.30.
• The relative humidity of simulated pore solutions that correspond with what may be expected in a paste with a \( w/c \) of 0.30 during the first several days of hydration.
• Desorption response (RH versus mass change) for prewetted LWA containing pore solutions with different chemical composition

The experimental methods and experimental results are described in the following two sections.

**EXPERIMENTAL METHODS**

**Pore Solution Extraction and Analysis**

To analyze the composition of pore fluid, cylindrical cement paste specimens (made using ordinary portland cement) (22 mm [0.87 in] diameter and 50 mm [1.97 in] height) were cast and cured in plastic vials. The curing temperature was controlled at 23 ± 0.5°C (73.4 ± 0.9°F) using a water bath. The specimens were demolded at specific ages (1 h, 3 h, 6 h, 10 h, 14 h, 19 h, 24 h, 33 h, and 48 h after water addition). Pore fluid extraction was performed immediately after demolding using pressure filtration for plastic pastes or a high pressure extraction die [27] for hardened pastes. The ionic composition of extracted pore solutions was measured using atomic absorption (for \( \text{Na}^+ \), \( \text{K}^+ \), \( \text{Ca}^{2+} \)), ion chromatography (for \( \text{SO}_4^{2–} \)), and acid titration (for \( \text{OH}^– \)). Details of these experimental methods and measurements are provided in References 21, 23, and 27.

**Relative Humidity**

Relative humidity measurements were performed on crushed mortar samples and solutions using sensors (±0.8% RH and ±0.1°C [0.2°F] at 23°C [73.4°F]) which were connected with a transmitter. After conditioning the signal, the data was transmitted to a computer where it was recorded at 5 minute intervals. The probes were mounted in a 75 x 68 mm (2.95 x 2.68 in) stainless steel cylinder that was placed over a water jacketed sample cup holder. The water jacket was connected with a programmable water bath, however, for this study the samples were maintained at a constant temperature (23.0 ± 0.1°C [73.4 ± 0.2°F]). The 10 g (0.35 oz) samples were placed in 12 mm (0.47 in) deep cups with a 43 mm (1.69 in) diameter. The sensor was compared with reference salts (potassium sulfate, potassium chloride, sodium chloride) between measurements to provide a point of calibration.

Figure 1 shows typical relative humidity measurements over a simulated pore solution corresponding to a cement paste at an age of 24 h. Care needs to be exercised to insure that the sample temperature is properly accounted for (in this case, maintained constant using the water jacket and water bath described above). Also, the sensor requires time to equilibrate with the solution. Figure 1 shows the effect of using sensors preconditioned at different relative humidities before the test. A time of 2 h to 3 h is needed for equilibrium when sensors were preconditioned for 4 h prior to the test at a relative humidity that is similar to what is expected from the test (that is, 97.5 ± 0.6% RH using potassium sulfate at 23 ± 0.1°C [73.4 ± 0.2°F]). When the sensors were preconditioned at 50 ± 0.5% RH (to simulate room RH) it was observed that the sensors could take much longer to equilibrate with their surroundings (8 h to 10 h). As a result, a period of preconditioning is recommended for RH measurements where rapid equilibrium may be needed. It can also be observed that when properly conditioned and calibrated the repeatability between samples is high (less than 0.8% RH for an average of four samples).

**Desorption**

Moisture desorption is an established technique for evaluating the effect of moisture loss at a given humidity for a material. A moisture sorption analyzer was used in this investigation. The system enables the sorption behavior to be evaluated under carefully controlled conditions of temperature and humidity.

The desorption response was also measured for LWA after it was oven dried for 24 ± 1 h, cooled and placed in deionized water for 24 ± 1 h prior to testing, to prewet the aggregate. The prewetted LWA was
removed from water and “patted to SSD” using absorbent towels. A 70 mg (3 × 10⁻³ oz) to 100 mg (4 × 10⁻³ oz) sample was placed in a tared quartz pan. The pan containing the sample was then suspended from the balance (± 0.001 mg [3 x 10⁻⁸ oz] accuracy) and placed in the relative humidity chamber to equilibrate at 23.0 ± 0.1°C (73.4 ± 0.2 °F) and 98 ± 1% RH for up to 48 h or until the sample had achieved a stable mass (less than an 0.001% mass change/15 minutes). After the sample equilibrated, the RH in the chamber was changed in 1% RH steps to 80% RH, allowing the sample to equilibrate at the new humidity (less than an 0.001% mass change/15 minutes or 12 h of exposure, unless noted otherwise). After equilibrating at 80% RH, the samples were dried to 0% RH at 23 ± 0.05°C (73.4 ± 0.9°F) for up to 48 h or until the sample had achieved a stable mass.

Figure 2 shows a plot of a typical mass change as a function of time (23.0 ± 0.1°C [73.4 ± 0.2°F]) for a LWA pre-wetted in a synthetic pore solution with composition 0.15 mol/lit KOH and 0.05 mol/lit NaOH. As the relative humidity is changed, the sample undergoes a rapid change in mass. The mass change decreases as the sample approaches equilibrium. It can be seen that this general behavior is observed at each change in the relative humidity, however, the magnitude of the mass change is different at each relative humidity and would be consistent with the volume of pores from which water is being lost at each step.
Figure 3 shows a typical desorption plot created using the data shown in Fig. 2. One of the points that needs to be evaluated in conducting this test is the mass-loss criterion that is used, to assume that a sample has achieved ‘equilibrium’. Three different weight loss criteria were evaluated consisting of less than a 0.1%, 0.01%, and 0.001% mass loss over a 15 minute time interval. The finest criteria is not shown since it is very similar to the 0.01% case with the exception of the 98% RH test point which is approximately 0.1 % lower that the measured value. The remainder of the tests used the 0.001% mass loss /15 minute criteria for the aggregate shown.

Unlike many desorption studies, Fig. 3 is not normalized to the weight of the SSD sample but rather it is normalized to the weight of the 0% RH (oven dry) sample. This was done since it believed that this value is more easily reproduced and is more useful for concrete mixture proportioning purposes.

EXPERIMENTAL RESULTS

The following section provides experimental results for pore solution measured from a hydrating cement paste as well as the relative humidity for the hydrating cement paste. The drying behavior of two synthetic pore solutions is also presented. Finally, the desorption behavior of LWA containing synthetic pore solution is presented. The following section provides the experimental results while subsequent sections discuss the results and their implications for future studies and implementation.

Pore Solution Composition

The concentrations of the five major ions in the extracted pore solutions are shown in Fig. 4, which agrees well with the patterns reported by previous studies [20, 22, 26]. At each age, a charge balance calculation was performed to ensure the accuracy of results. The measurement error was determined to be less than 50 mmol/lit based on an equivalent single valance ion. These results are used to prepare larger volumes of synthetic pore fluids to pre-soak LWA and to measure the equilibrium RH values.

Relative Humidity of Synthetic Pore Solutions

Six different salts (NaOH, KOH, Ca(OH)$_2$, Na$_2$SO$_4$, K$_2$SO$_4$ and CaSO$_4$) were mixed to prepare a synthetic pore solution that match the measured ion concentrations at 24 h from Fig. 4. The difference on the total ion concentrations between the measured and the synthetic solution is less than 0.1 %. To evaluate the effect of drying, the concentration of the 24 h synthetic pore solution was increased by two and four times. This simple assumption is valid when ion concentrations are well below the saturation limit of the solution and the effect of potential carbonation of pore solution during the drying process is minor. Both assumptions are reasonable for the case of LWA desorbing inside an early-age concrete. The measured 24 h pore solution concentrations and the concentrations of the synthetic pore solution are presented in Table 1. The relative humidity of the synthetic pore solutions was measured. Figure 5a shows the effect of molar concentration on the equilibrium relative humidity measured over
synthetic pore solutions. Figure 5(b) shows the effect of drying or concentrating the pore solution, as the Y-axis describes the amount of water lost from the original solution (100% is the original solution) due to drying (external or self desiccation).

Table 1—Composition (mol/L) of synthetic pore solutions

<table>
<thead>
<tr>
<th>Ions</th>
<th>Measured 24h concentration</th>
<th>Synthetic 24h concentration</th>
<th>2 times Synthetic 24h concentration</th>
<th>4 times Synthetic 24h concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>K+</td>
<td>0.670</td>
<td>0.684</td>
<td>1.340</td>
<td>2.680</td>
</tr>
<tr>
<td>Na+</td>
<td>0.117</td>
<td>0.117</td>
<td>0.234</td>
<td>0.468</td>
</tr>
<tr>
<td>Ca++</td>
<td>0.002</td>
<td>0.002</td>
<td>0.004</td>
<td>0.008</td>
</tr>
<tr>
<td>OH-</td>
<td>0.644</td>
<td>0.632</td>
<td>1.288</td>
<td>2.576</td>
</tr>
<tr>
<td>SO4---</td>
<td>0.086</td>
<td>0.086</td>
<td>0.173</td>
<td>0.345</td>
</tr>
<tr>
<td>Total Ion Concentration</td>
<td>1.519</td>
<td>1.521</td>
<td>3.039</td>
<td>6.077</td>
</tr>
</tbody>
</table>

Fig. 5—Increasing concentration of synthetic pore solution and influence on measured RH.
Relative Humidity of an Aging Mortar

Three different mixtures were prepared with different volumes of sand replaced by saturated LWA and a w/c of 0.30. These mixtures were designated as 0.0%, 11.9% and 23.7%, where the number represents the total volume of the mixture occupied by the LWA (in percentage). It is important to note that though the designations are based on a total volume basis and the volume of aggregate (LWA and sand) remained constant at 55%, since only the sand was replaced with LWA. The 23.7% volume replacement corresponds to the amount of LWA necessary to eliminate self-desiccation according to the approach described in Reference 28.

Figure 6 show the results from the first 7 days of testing. It can be observed that the inclusion of LWA produces an increase in the relative humidity of the mortar. The addition of 23.7% LWA increases the relative humidity of a plain mortar from 85% to 92.5% at an age of 7 days.

In Fig. 6, the Plain Mortar Raoult’s Law data set was obtained by calculating the equilibrium RH using Raoult’s Law based on the measured pore solution composition from Fig. 4. This data set shows the internal RH that would develop inside the plain mortar if there was absolutely no self-desiccation and the pore structure would remain fully saturated. In this case, the reduction in the internal RH is solely due to the increase in ion concentrations of the pore solution as the mortar hydrates. The data in Fig. 6 shows that the variation in relative humidity from sample to sample is highest for the sample with 11.9% LWA at relatively early ages. This may be due in part to the fact that at this time water is being most rapidly extracted from the aggregate and the spacing between the particles is relatively large in this mixture. As a result variation may be obtained due to sampling location. Further work is needed to understand the implications that this may have on local stress variation.

Desorption of Lightweight Aggregate with Different Pore Solutions

Figure 7 shows the desorption response of LWA that were prewetted with deionized water or with a synthetic pore solution. It can be noticed that as the solution concentration increases, the mass of the LWA and solution at a given relative humidity increases. It can also be noticed that the aggregate with the solution that is more concentrated remains saturated until humidity of the environment decreases to a point where it is less than the measured equilibrium RH for the solution itself.

SUMMARY AND POTENTIAL FUTURE IMPLICATIONS

This research draws attention to the fact that the chemistry of the pore solution changes during the hydration process. This is due in part to dissolution of ionic species from cement and in part due to the reduction in pore fluid during hydration (that is, an increase in concentration). The pore solution chemistry influences the relative humidity that is measured in a cement paste. To determine the ‘equivalent
capillary radius’ from relative humidity measurements, the pore solution chemistry needs to be taken into account.

This paper described the use of desorption behavior of LWA to determine the volume of water that is removed from a prewetted lightweight aggregate at a specific external relative humidity. The chemical composition of the pore solution ($RH_s$) and the geometry of the pore that the fluid is in $RH_g$ (equal to the second term on Eq. (2)) are related to the ambient relative humidity. For solutions of low ionic concentration, $RH_s$ can be predicted using Raoult’s Law. The product of $RH_s$ and $RH_g$ are then equal to the ambient relative humidity (Eq. (2)).

The fluid volume that is desorbed from the LWA at a specific relative humidity depends on the chemical composition of the fluid. This is only of primary concern when external relative humidity is the driving force for the desorption. This would be the case for conditions where external drying takes place at early ages [29]. In fact, in the first minutes to hours of hydration, ions from the cement paste pore solution will diffuse into the LWA and soon there will be little concentration gradient between the pore solution in the paste and the fluid in the LWA. In this condition, the sorption isotherm of the cement paste containing the LWA will depend on the composition of the pore solution.

On the contrary, for sealed systems (for example, systems undergoing self desiccation), the concentration gradient between the fluid in the LWA and in the paste will soon be equalized. In this condition, the volume of water that is desorbed from the LWA should depend only on the volume of chemical shrinkage and on the relative size of the pores in the paste and aggregate [29, 30]. In sealed systems, fluid will be drawn out of the lightweight aggregate provided that the pores in the paste are smaller than the pores in the lightweight aggregate. The volume of the fluid drawn out of the LWA will simply compensate for the volume of smaller pores in the paste that are emptied due to chemical shrinkage.

The use of a solution that contains salts may enable improved characterization of the desorption behavior of the lightweight aggregate at the highest relative humidities. It can be noticed that many of the most efficient LWA for internal curing lose a majority of their fluid between saturated surface dry conditions and a high relative humidity (that is, above approximately 95 % for the LWA shown in this paper). By using a solution containing salts, the desorption behavior is shifted to begin at a lower humidity (from 100 % to 98 % for the 0.35 KOH+0.05NaOH+0.50NaCl shown here) and spread out over a wider range of humidities. In addition, this can be used to calculate the RHs from desorption isotherms using the same LWA but different solutions. This enables the LWA to be characterized more easily. This work suggests that there may be a potential to develop a test that provides some additional clarity on the determination of the desorption behavior of a LWA at higher relative humidities. One could conceive of a test where a known mass of oven dry aggregate is placed in water and a known mass of oven dry aggregate is placed in a liquid solution of a carefully determined concentration. If the specimens were then removed from the solutions and placed in an environment of a known relative humidity the
difference in sample mass may provide an indication of the pore volume in a given range of pore sizes. However, in this test the concentration of the pore solution need to be considered as water is removed. At very high concentrations even precipitation might occur; therefore, salts that have a very high solubility should be used for this test.

To understand the humidity difference that is the most critical, one would want to consider the size of pores where shrinkage and the capillary stresses start to become significant. For example, for plain water in a porous medium, a relative humidity of 95% corresponds to a Kelvin pore radius of 20.5 nm and a capillary pressure of 7 MPa (1015 psi) (Fig. 8). It can be seen that for pores larger than 20 nm the capillary stresses are low. However, as pores smaller than 20 nm are evacuated, the capillary stresses (and corresponding shrinkage) begin to increase rapidly. One could then design a solution to be used that provides the best measure of pores in this range.

![Graph showing relative humidity vs. Kelvin pore radius and capillary stress vs. Kelvin pore radius.](image)

**Fig. 8—Effect of relative humidity on capillary stress. (Note: 1 in. = 2.54 x 10^7 nm.)**

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