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Thermal Dilation and Internal Relative Humidity in Hardened Cement Paste

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Motivation & Theory

Thermal stresses may initiate crack development

- Restrained drying shrinkage and thermal dilation (or gradients) can initiate cracking in reinforced concrete pavements and structures
  - Cracking significantly reduces durability and life expectancy of concrete

Thermal dilation of cement paste dependent on RH

- Coefficient of thermal dilation (CTD) varies with internal RH (see Figure 3)
  - $CTD = CTD_{solid} + CTD_{capillary\ pressure} + CTD_{time\text{-}dependent}$
- Up to 100% additional dilation may be caused by capillary pressure component
- Time dependent component not considered since dilation was allowed to equilibrate
- Component of thermal dilation linked to RH is caused by same mechanism as early-age drying shrinkage (i.e. changes in capillary pressure)
- Shrinkage is primarily caused by differential pressures associated with the development of curved capillary menisci in small pores as concrete dries
- Pore fluid pressure differential that causes shrinkage is linked to internal RH through the Kelvin-Laplace equation

Objective:

- Investigate the relationship between thermal dilation & internal RH
- Verify the existence of an internal RH-dependent component of thermal dilation
- Accurately model thermal dilation using measured internal RH as a primary component in the model

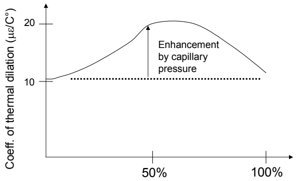


Figure 1. Illustration of the dependence of thermal dilation on RH

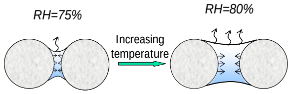


Figure 2. Increasing temperature causes decrease in surface tension resulting in reduced capillary pressure and increased thermal expansion

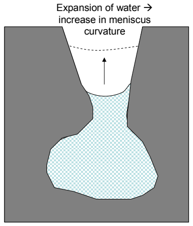


Figure 2. Additional dilation could be induced by expansion of water in ink-bottle pores causing further reduction in meniscus curvature

Experimental

- To investigate the link between internal RH and thermal dilation, three variables were measured
  - Linear dilation
  - Internal RH
  - Internal temperature
- The temperature and internal RH were measured using an embeddable sensor measurement system developed at the University of Illinois at Urbana-Champaign
- Length-change was measured using a standard comparator
- Experimental procedure:
  - Cast packaged sensors directly into fresh paste using standard mortar bar molds
  - Allow to dry to specified internal RH in an environment of 23° C
  - Seal specimens with adhesive-backed Al foil, allow sensors to equilibrate. Measure length.
  - Place sensors in refrigerator (~3° C) and allow temperature and RH to equilibrate. Measure length.
  - Place sensors back in 23° C environment. Allow to equilibrate. Measure length.
  - Remove foil seal and allow to dry to new specified RH. Repeat process at several initial internal RH from ~90%→~20%

Figure 3. Commercially available digital RH and temperature sensor

Figure 4. Sensor packaged in plastic tubing with GoreTex cap for casting in fresh paste

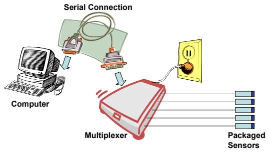


Figure 5. UIUC internal RH and temperature measurement system

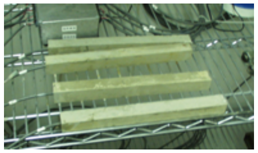


Figure 6. RH-temperature sensors cast into 1"x1"x11" hardened cement paste prisms

Results

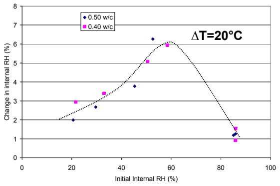


Figure 7. Measured ΔRH at varying initial RH

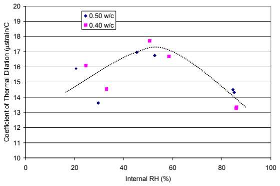
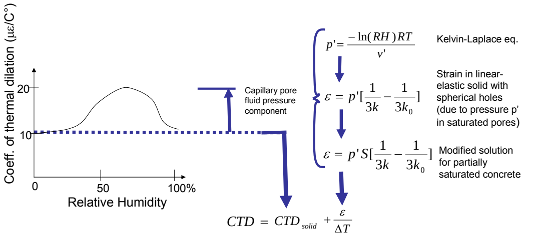


Figure 8. Measured CTD at varying initial RH

Modeling

- The experimental RH data can be used in the Kelvin-Laplace equation to determine the change in the pore fluid pressure
- The pore fluid pressure can be used in Mackenzie's solution for the linear strain in a linear-elastic solid with spherical holes (with pressure p' acting within the spherical holes
- Mackenzie's solution is only applicable for fully saturated material, so Bentz et al modified the equation to include a saturation factor S
- The strain from the modified equation represents the capillary pressure component of thermal dilation
- The dilation of hardened cement paste in absence of capillary pressure is approximately 10 με/C°

k=bulk modulus of porous solid
k_0=bulk modulus of solid
RH=internal relative humidity
R=universal gas constant
T=temperature in kelvins
v'=molar volume of water
p'=pore fluid pressure
S=saturation factor
ε=capillary pressure induced thermal strain
ΔT=temperature change



$$p' = \frac{-\ln(RH)RT}{v'}$$

Kelvin-Laplace eq.

$$\varepsilon = p'\left[\frac{1}{3k} - \frac{1}{3k_0}\right]$$

Strain in linear-elastic solid with spherical holes (due to pressure p' in saturated pores)

$$\varepsilon = p'S\left[\frac{1}{3k} - \frac{1}{3k_0}\right]$$

Modified solution for partially saturated concrete

$$CTD = CTD_{solid} + \frac{\varepsilon}{\Delta T}$$

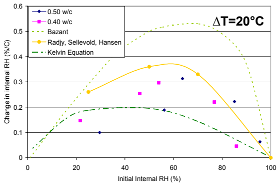


Figure 8. Measured and modeled (Kelvin equation) ΔRH at varying initial RH

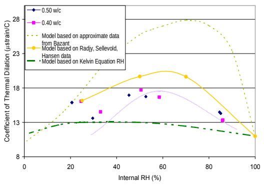


Figure 9. Modeled CTD at varying initial RH using ΔRH values from Fig. 8 in model

Conclusions

- Capillary pressure influences CTD
- Discrepancy between "Kelvin" model predicted ΔRH and measured ΔRH from expansion of water and inkbottle pores that the Kelvin model cannot account for
- To accurately model thermal dilation of hardened cement paste, the additional dilation linked to internal RH must be accounted for
  - Up to ~100% increase in thermal dilation may be caused by RH-dependent component
- The proposed model accounts for internal RH dependence in predicting thermal dilation