CONCRETE DRYING SHRINKAGE SIMULATIONS IN ABAQUS

Joshua Hogancamp[1] and Christopher Jones[2]
SAND2022-3447 C

[1]Senior Member of Technical Staff, Sandia National Laboratories, Albuquerque, NM (jhoganc@sandia.gov)
[2]Associate Professor, Kansas State University, Manhattan, KS (jonesca@k-state.edu)

INTRODUCTION

Accurately predicting the long-term structural response of post tensioned nuclear reactor containment vessels requires treatment of creep and shrinkage of the concrete. The ongoing VeRCoRs benchmark exercise demonstrates the importance of such predictive efforts. The uniquely high aspect ratio of the VeRCoRs mockup promotes significant drying shrinkage of the concrete. This research compares two approaches, both of which utilize the finite element software ABAQUS, to model drying shrinkage in concrete specimens and structures in conjunction with time dependent deformation from the applied loads. The model predictions are compared in accuracy to material test observations, fidelity to system-level experimental data, and ease of implementation.

CAPILLARY ACTION IN POROUS MATERIALS

The volumetric strain response of a porous material (such as soil or concrete) to moisture content is based on capillary action effects between the solid material and pore fluids—the fluids are usually water and air. The size of the pores in the material is one variable that dictates the magnitude of the capillary action. Capillary action is generally defined by Jurin's Law in Equation 1:

$$h = \frac{2\gamma cos\theta}{\rho g r} \tag{1}$$

where h is the height of a liquid column in a tube (or the magnitude of capillary action), γ is the liquid-air surface tension, θ is the contact angle, ρ is the density of the liquid, g is the acceleration due to gravity, and r is the radius of the tube. In porous materials, r is the intergranular pore size. The variables h and r in Equation 1 are inversely proportional, indicating that smaller radii result in larger capillary actions.

The effect of capillary action in porous materials requires both fluid (usually water) and air in the pores. A fully dried or a fully saturated sample will have zero capillary action. As a fully saturated sample begins to dry, its larger pores will evaporate first due to the wetting action of water. As the porous body continues to dry, smaller and smaller pores will begin to have their water evaporated. As indicated by Equation 1, capillary action in smaller pores is of greater magnitude than in larger pores. Therefore, the magnitude of the capillary action will grow as the sample continues to dry until the point that the growing number of emptied, and thus stress free pores, outpaces the growth in pressure. The growing capillary action in the pore network of the sample results in an overall reduction in sample volume. Conversely, if water is introduced into the system, the capillary action will subside, and the overall sample volume will increase.

The most common test performed to determine the moisture content, or saturation, of porous materials is time consuming. A fully saturated sample is subjected to various humidity levels at a constant temperature, and the sample's steady-state mass is recorded at each humidity level. Significant time can be required for the sample to reach a steady-state mass since the water must first evaporate and then diffuse out of the pore network of the sample. The saturation level of the material at each ambient relative humidity is called is sorption isotherm—"isotherm" is used to articulate that the property is temperature dependent. The test gives different results if the sample is originally fully saturated or fully dry (desorption or adsorption, respectively).

The sorption isotherms provide a relationship between saturation and relative humidity. Kelvin's Law (Equation 2) in combination with the Young-Laplace Equation (Equation 3) can be used to directly correlate relative humidity and the pore pressure inside the pore network of the sample (Equation 4).

$$\ln(H) = \frac{2\gamma}{r}\frac{\nu}{RT} \quad (2)$$

$$\Delta p = \frac{2\gamma}{r} \quad (3)$$

$$\Delta p = \frac{\ln(H)RT}{\nu} \quad (4)$$

where ν is the molar volume of water, R is the universal gas constant, T is the temperature in Kelvin, H is the relative humidity, and Δp is the pore pressure.

DATA USED IN SIMULATIONS

The concrete material data used for the simulations in this research is provided by Électricité de France (EDF) in support of the VeRCoRs project. Concrete drying shrinkage specimens were subjected to 50% relative humidity at 20°C for ~762 days and their strains recorded. The material properties provided by EDF and used in the simulations are listed in Table 1. The concrete permeability was not provided, and a value was taken from literature (Wang & Xi, 2017). Moisture flow through concrete is a well-documented phenomenon, though measurement can be problematic due to the extremely slow permeability of moisture through concrete. Note that the sorption values must be converted to Saturation vs Pore Pressure using Equation 4 for use in ABAQUS.

Table 1: Concrete material properties.

Single-Value Properties	
Elastic Modulus	34.62 GPa
Density	2390 kg/m^3
Poisson's Ratio	0.2
Void Ratio	0.147
Moisture Swelling Values	
Strain	**Saturation**
-0.000468	0.3
0	1
Sorption	

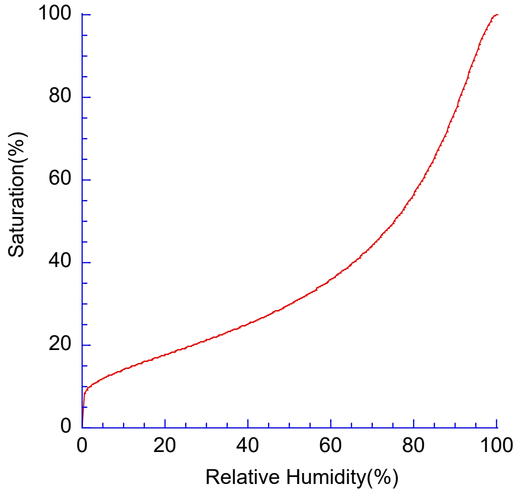

Figure 1: Concrete desorption data provided by EDF.

From Literature	
Permeability	$1 \cdot 10^{-10}$ m/s (Wang & Xi, 2017)

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

ABAQUS Moisture Transport Model

ABAQUS includes a soils analysis package that is commonly used to simulate moisture or pore fluid diffusion through soils and the soils' response such as shrinking or swelling. The same equations can be utilized to predict similar phenomena in concrete (or any porous material). Several material properties are required to define an ABAQUS fluid-filled porous material analysis:

- Elastic modulus, density, Poisson's ratio, and void ratio of the bulk material
- Permeability of the pore network inside the solids
- Sorption (optionally both adsorption and desorption) isotherm(s) that relate pore pressure with saturation
- Volumetric response of the solids to moisture content (i.e. strain vs. saturation)
- (Optional) Material properties of the solids (sans pores) and the fluids

ABAQUS's governing equations for partially saturated flow through a porous material are complex due to the many simultaneous relationships occurring between the solids, liquids, and gases. The reader is directed to the ABAQUS user's manual, particularly Coupled Pore Fluid Diffusion and Stress Analysis, for the full description of the constitutive equations (1). The bulk material is compressible, which can result in changing pore sizes and pore size distributions. The liquids are nearly, but not completely, incompressible, and the gases are compressible. The system becomes even more difficult to define mathematically if the porous material is susceptible to viscous properties (e.g. creep effects) or phase changes (e.g. solids dissolution into pore fluid). Concrete is a material that is susceptible to both, and modeling the full thermodynamic system in cement and concrete is a constantly evolving field.

A finite element simulation in ABAQUS was conducted wherein a pore pressure boundary condition equivalent to 50% relative humidity was applied to the surface of a concrete specimen with an assumed initial internal saturation rate of 90%. The material data from EDF was utilized where possible. The initial saturation was assumed equivalent to 90% relative humidity as related in Figure 1. The "predictive" results (i.e. using only experimental material data) from the simulation are compared to EDF's experimental results in Figure 2. The somewhat jagged orange line is EDF's experimental results. The blue line that approaches ~2500 μs are the predictive results using EDF's material data input into ABAQUS's moisture transport models. As can be seen, ABAQUS's moisture transport model did not accurately predict the axial strain in the concrete specimen and overestimated the results by over 400%. The ABAQUS simulation results were brought closer to accurate by reducing the permeability parameter from 10^{-10} m/s to 10^{-21} m/s.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

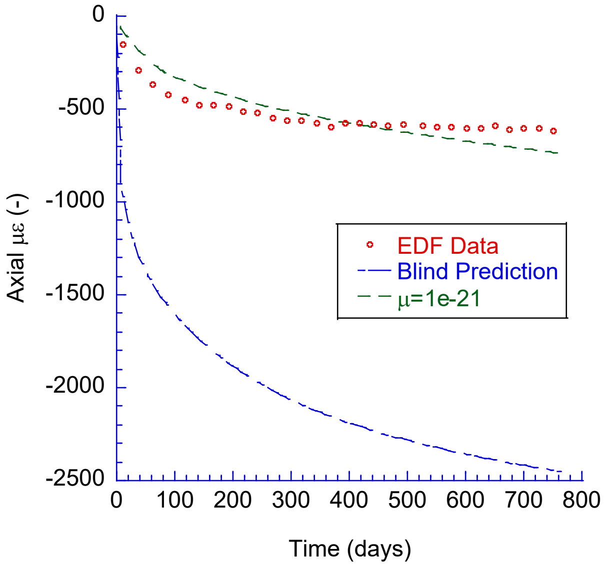

Figure 2: Moisture transport model vs. EDF experimental results.

Using only the modified permeability of 10^{-21} m/s, other variables were modified to inspect the effect on results as shown in Figure 3. The following parameter changes had little effect on the simulation results:

- Increasing the concrete void ratio by 50%.
- Increasing the swelling strain by 20%.
- Decreasing the swelling strain by 20%.

A notable change in the magnitude of overall strain, though not in the shape of the curve, was implemented by modifying the sorption data as shown in Figure 4. The sorption curves were modified by either increasing or decreasing the saturation rate at a given relative humidity by 50% at the lowest humidities decreasing to 0% change at full saturation. The results of these parameter changes are shown in Figure 3.

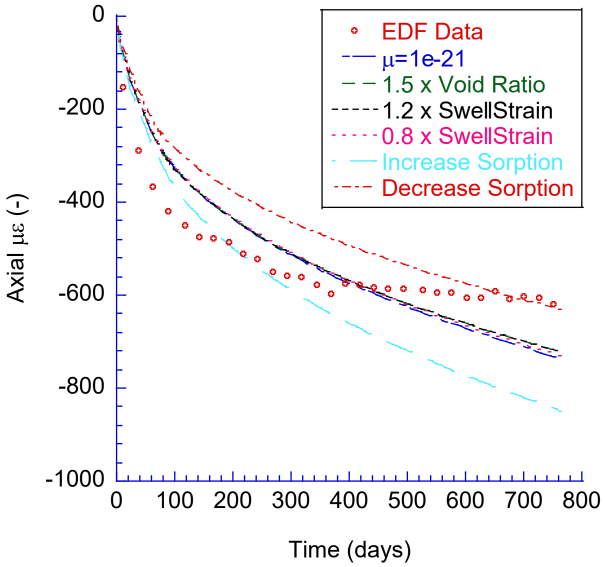

Figure 3: Moisture transport model parameter study vs. EDF experimental.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

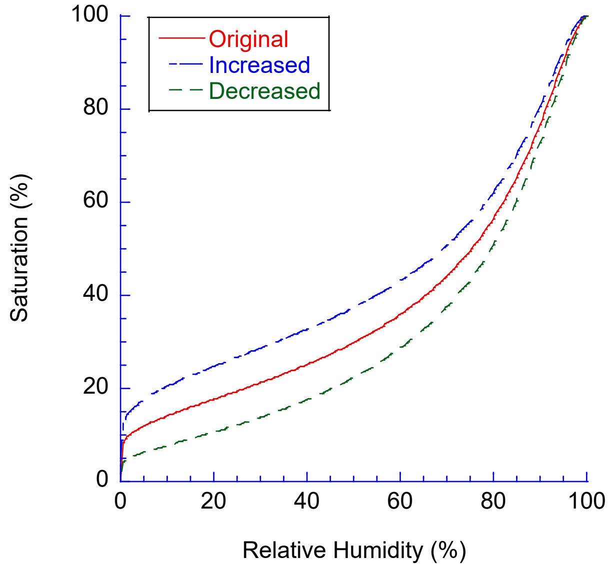

Figure 4: Modified EDF sorption data.

ABAQUS FICKIAN DIFFUSION—HEAT EQUATION

An alternative approach to modeling diffusion in concrete is Fick's 2nd Law of Diffusion (see Equation 5) wherein ψ is the concentration per volume, t is time, D is the diffusion coefficient in dimensions [length^{2}time^{-1}], and x is position.

$$\frac{\partial \psi}{\partial t} = D\frac{\partial^2 \psi}{\partial x^2} \tag{5}$$

Fickian diffusion is useful in modeling moisture transport via diffusion in concrete because only one variable is required (D). In addition, drying shrinkage in concrete is a result of moisture diffusion out of the specimen and evaporating. An important note about using Fickain diffusion to model moisture transport in concrete is that there is no forcing function in the equations. Any applied pressure or forcing function (e.g. water pressure on one surface of a concrete wall) cannot be applied solely using Fick's 2nd Law. However, when modeling moisture transport due solely to changes in relative humidity, Fick's 2nd Law is applicable.

Fickian diffusion is also commonly used to model heat flow through materials, including ABAQUS. In ABAQUS's heat equation, the variable D from Equation 5 is implemented as Equation 6 wherein k is the thermal conductivity, c_p is the specific heat capacity, and ρ is the mass density. These terms can be converted from thermal transport to moisture transport by assigning k as the moisture diffusivity and c_p as the specific moisture capacity.

$$D = \frac{k}{c_p \rho} \tag{6}$$

Finally, the coefficient of thermal expansion α is instead used as a coefficient of drying shrinkage (or coefficient of moisture swelling, either definition is equally applicable). The specific input parameters in the ABAQUS heat transfer model were iteratively adjusted to fit the EDF provided drying shrinkage data. This best-fit simulation is represented in Figure 5, Figure 6, and Figure 7 as "Thermal Fit."

A brief parameter study was performed on the thermal equation variables to analyze curve shape and magnitude changes. First, the permeability (i.e. conductivity) was altered by $\pm$50% as shown in Figure 5. The final axial microstrain is similar for all three curves, though the speed at which

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

the curves approach the asymptote varies. However, the permeability of standard concrete is a generally known number, and therefore this variable can be researched via literature and applied to the equation without modification. The permeability is henceforth fixed at 10^{-10} m/s as originally indicated in Table 1.

The coefficient of drying shrinkage (i.e. coefficient of thermal expansion) was altered by $\pm 50\%$ as shown in Figure 6 and resulted in the same general curve shape but changes in the axial strain asymptote. The specific humidity capacity (i.e. specific heat capacity) was altered by $\pm 50\%$ as shown in Figure 7 and resulted in the same axial strain asymptote but changes in the speed at which the asymptote is reached. Comparing Figure 5 with Figure 7 reveals that the permeability and the specific humidity capacity have similar effects on the shape of the curve and no effects on the axial strain asymptote; however, as mentioned prior, the permeability of concrete can be found in literature, and therefore only two variables are available for fitting the equation to experimental data: coefficient of drying shrinkage and specific humidity capacity.

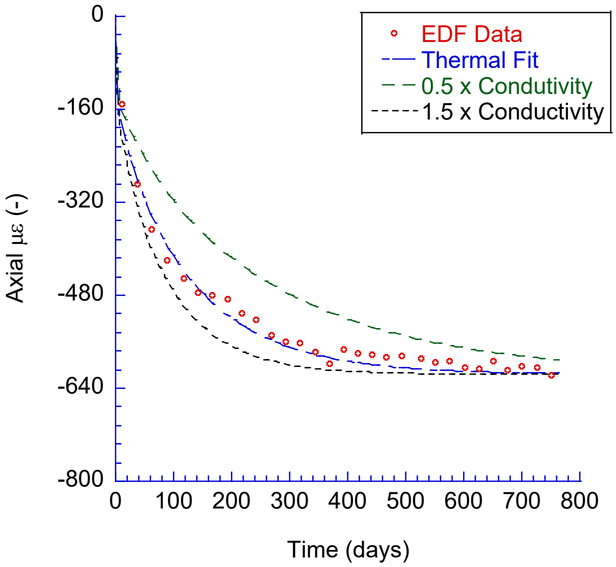

Figure 5: Modifying permeability (i.e. conductivity) by ±50%.

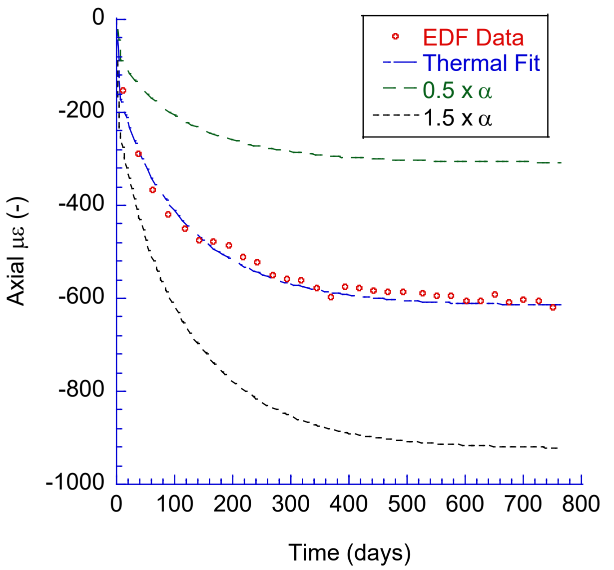

Figure 6: Modifying coefficient of drying shrinkage (i.e. coefficient of thermal expansion) by ±50%.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

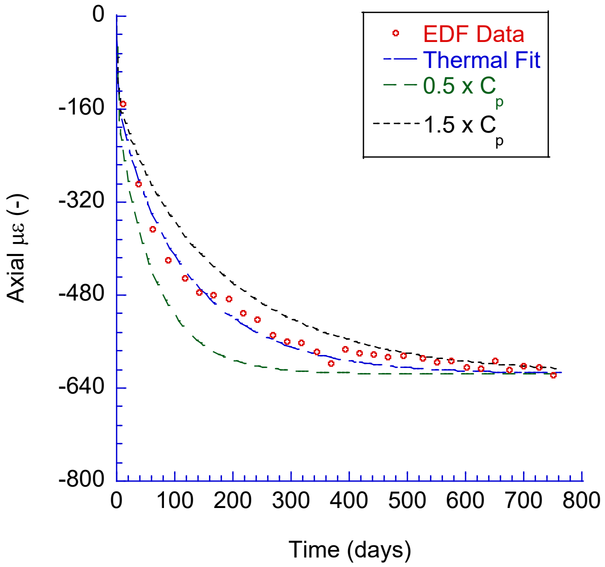

Figure 7: Modifying specific humidity capacity (i.e. specific heat capacity) by ±50%.

CONCLUSIONS

This document compares two drying shrinkage modeling approaches (Poromechanical shrinkage and Fickian diffusion), both in ABAQUS. The first modeling approach utilizes ABAQUS's pore fluid flow equations to concrete drying shrinkage modeling. The second modeling approach utilizes ABAQUS's thermal equations—which are Fick's laws of diffusion—to apply Fickian diffusion to the same model. The Fickian diffusion approach has the advantage of simplicity of implementation with good capability to match experimental data. The poromechanics approach is more difficult to implement (e.g. requires more material test data) and theoretically provides improved physical fidelity; however, results indicate that the predictive capabilities of this approach are questionable. Parameter studies on both approaches indicate that the poromechanical approach has less flexibility than the Fickian diffusion approach. A drawback of using the Fickian diffusion approach in ABAQUS is that thermal expansion and contraction effects are not available since the moisture diffusion is implemented via the ABAQUS thermal interface.

REFERENCES

Z.P.Bažant and L. J. Najjar (1972). "Nonlinear water diffusion in nonsaturated concrete," *Material and Construction*, 5(1), 3–20.

Xiao Zhang and Hongduo Zhao (2015). "Characterization of Moisture Diffusion in Cured Concrete Slabs at Early Ages," *Advances in Materials Science and Engineering*, 2015(1), 11.

Yao Wang and Yunping Xi (2017). "The Effect of Temperature on Moisture Transport in Concrete," *Materials.* 10(8).

Laurent Charpin et. al. (2021) "Ageing and air leakage assessment of a nuclear reactor containment mock-up: VERCORS 2nd benchmark." *Nuclear Engineering and Design*. 337(1).

G.K. Batchelor. "An Introduction to Fluid Dynamics." Cambridge University Press, 1967.

Dassault Systemes. ABAQUS User's Manual. 2021.

Xiaodan Li. "Computational Modeling of the Time-dependent Behavior of Cementitious Materials." Dissertation. Texas A&M University, 2017.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.