

Chemical – Mechanical – Transport Model for Wellbore Permeability for CO₂ Storage

30 March 2017

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Cover Illustration: Model of fracture deformation: a) asperities maintain the fracture aperture between the cement and caprock; b) during reaction, the portlandite depleted and amorphous alteration layers penetrate and eventually comprise the propping asperities; and c) the stress on the fracture compresses the now weakened asperities, collapsing the aperture space and reducing the permeability.

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Chemical – Mechanical – Transport Model for Wellbore Permeability for CO₂ Storage

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Acronyms, Abbreviations, and Symbols

Term	Description
σ_{eff}	Effective Stress
η	Hydraulic strain
CO ₂	Carbon dioxide
DOE	U.S. Department of Energy
NETL	National Energy Technology Laboratory
NRAP	National Risk Assessment Partnership
LLNL	Lawrence Livermore National Laboratory

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1. INTRODUCTION

Wellbores are considered to be a primary pathway of concern for potential carbon dioxide (CO₂) and brine leakage from storage reservoirs to drinking water aquifers and the atmosphere. This study investigated how chemical alteration of wellbore cement affects the mechanical and hydraulic properties of wellbore fractures and interfaces to better assess the risk for CO₂ leakage from storage reservoirs.

The observed trends are explained in hydraulic aperture in these experiments by proposing that *chemical alteration weakens the asperities that hold open pathways at cement-caprock interfaces, thereby causing the fracture to close in response to pressure placed on the sample.* Figure 1 illustrates this hypothesis by separating the concurrent chemical and mechanical processes into three schematic drawings showing the initial fracture aperture (a), chemical alteration (b), and the smaller fracture (c) aperture as a result of mechanical deformation of the altered layers.

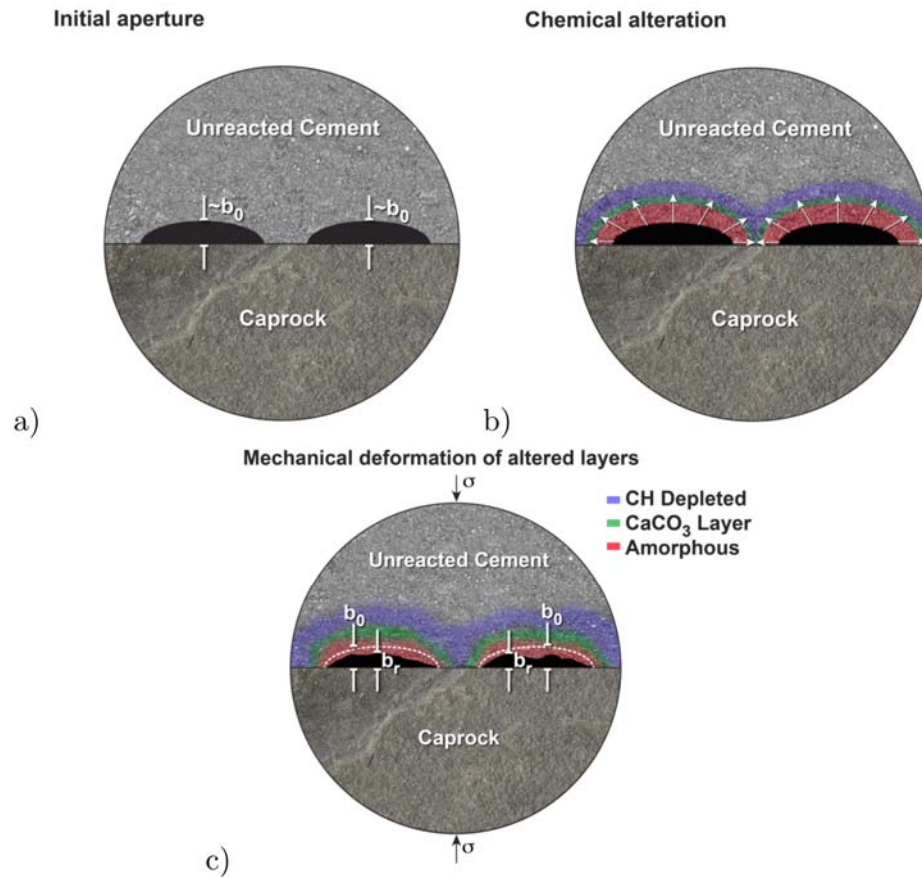


Figure 1: Model of fracture deformation: a) asperities maintain the fracture aperture between the cement and caprock; during reaction, the portlandite depleted and amorphous silica alteration layers penetrate and eventually comprise the propping asperities; and c) the stress on the fracture compresses the now weakened asperities, collapsing the aperture space and reducing the permeability. The diameter is 1.5 cm.

2. RESULTS

This study created the first-ever empirically-based model that accounts for the mechanical deformation of chemically-altered wellbore cement in carbon storage environments. This summary provides a brief description of the chemical and mechanical components of this model, some of the experimental evidence to support the model, and an example application of the model to a wellbore leakage scenario. The reader is referred to the publications (see Appendix for some examples) for more information on the chemical and mechanical components of the model and experimental analysis of the core-flood experiments on which the model was based (Walsh et al., 2012; Walsh et al., 2013a,b,c; 2014a,b; Mason et al., 2013).

There is concern that chemical alteration of the cements used to seal deep saline or depleted oil reservoirs employed for geologic CO₂ storage can create gas and brine leakage pathways to shallow water resources and back to the atmosphere. This concern exists (despite the utilization of CO₂ for enhanced oil recovery) because the Portland cements commonly used in primary cementing operations in wellbores undergo a series of reactions that can weaken the cement and alter its permeability (Carey et al., 2007, 2009; Duguid et al., 2005; Huerta et al., 2012; Kutchko et al., 2007, 2008, 2009; Mason et al., 2013; Scherer et al., 2011; Walsh et al., 2013a). Contact between carbonated brine and Portland cement produces a series of reaction fronts that divide the cement into distinctive zones. From the interior of the cement outward to the cement/brine interface (Figure 2), these zones consist of the unreacted cement, a portlandite depleted (CH-depleted) zone, a zone of calcium-carbonate precipitation, and an outer amorphous zeolite layer in direct contact with the carbonated brine (Carey et al., 2007; Kutchko et al., 2007, 2008; Rimmele et al., 2008; Mason et al., 2013).

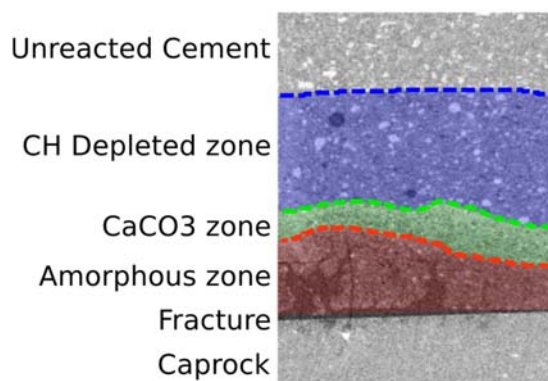


Figure 2: Reaction fronts produced by flowing carbonated brine along the cement-caprock interface in a core-flood sample.

The chemical component of this model simulates the propagation of the reaction fronts using a method similar to that proposed by Ulm and co-workers (Ulm et al., 2003; Heukamp, 2003) for simulating calcium leaching from cements. Rather than use an explicit discretization of the reaction regions, the model instead represents the fronts as a series of coupled moving boundary problems. Front movement is controlled by jump conditions that enforce conservation of mass between the dissolving and precipitating minerals and the pore-fluid concentrations. Ulm's model was extended to account for diffusive transport of multiple chemical species, changes to

chemical equilibrium at the fronts, and the effect of tortuosity on the effective diffusivity within each alteration layer. Equilibrium controls are portlandite solubility at unreacted/depleted interface, calcite solubility at both the depleted/carbonate interface and the carbonate/amorphous interface, and analcime solubility at amorphous silicate/brine interface. In addition to the solid phases, the reduced chemistry model also considers equilibrium between relevant aqueous species at each of the reaction fronts (Walsh et al., 2014a).

An empirical mechanical model is employed to describe the relationship between deformation and chemical alteration that is shown in Figure 3. In this model, the fracture is represented by a set of three spring slider sub-models, such that the overall stiffness for the fracture equals the stiffness of each alteration layer weighted by their relative contact areas. The unreacted cement is represented by a simple linear spring, because it is assumed its stiffness is independent of the loading history. However, simple strain-hardening was applied to the amorphous and depleted layers, represented by a spring arranged in series with a parallel spring/frictional slider system, because both of these regions have significantly lower yield strengths than the unreacted cement. The effect of the parallel spring/slider system is to change the slope of the hydraulic strain—effective stress relationship during loading when a given stress is exceeded—and recover the original slope as the system is unloaded. The mechanical response is coupled to the extent of the reaction by virtue of the contact areas (Walsh et al., 2014b).

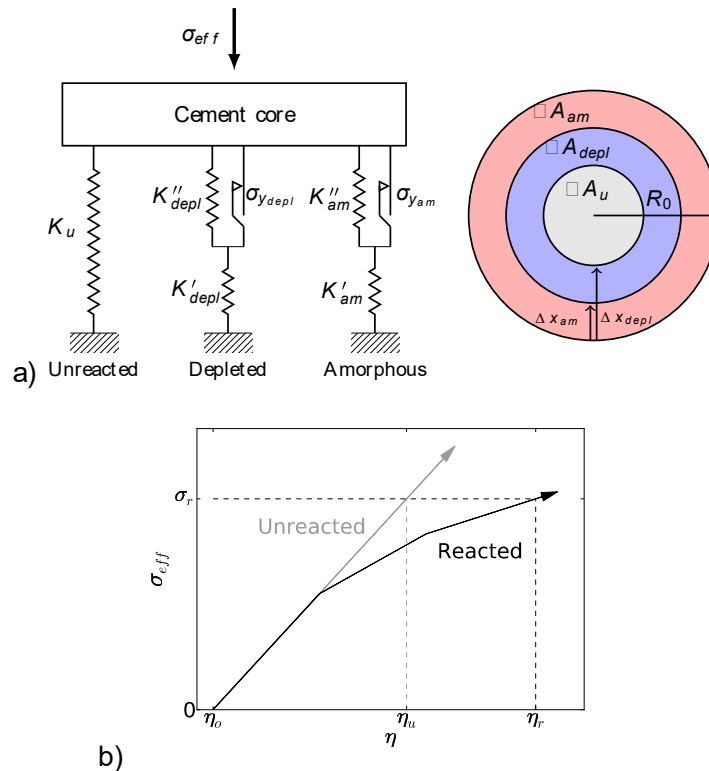


Figure 3: a) The relationship between σ_{eff} and η is modeled as three sets of parallel springs and frictional sliders representing the contributions of the different reaction fronts to the fracture response weighted by the relative contact area (A) of each alteration zone: unreacted (u), portlandite depleted ($depl$), and the amorphous silica (am) with a given stiffness (K). The carbonated zone is not considered because it was very thin (Walsh et al., 2014b).

Although empirical, the model provides a mechanism for extending the experimental observations to other fracture geometries and stress conditions. In particular, the model can be used to investigate the effects of asperity size and reaction front extent on the fracture transmissivity when coupled with fluid flow and transport. In the example simulation shown in Figure 4, the reaction front model is first used to determine the front extents, which are then provided as input to the spring/frictional slider model. The spring/slider model then updates the fracture aperture distribution based on the local effective stress—which in turn alters the flow and transport of the chemical species, thereby changing the conditions at the brine boundary in the reaction front model.

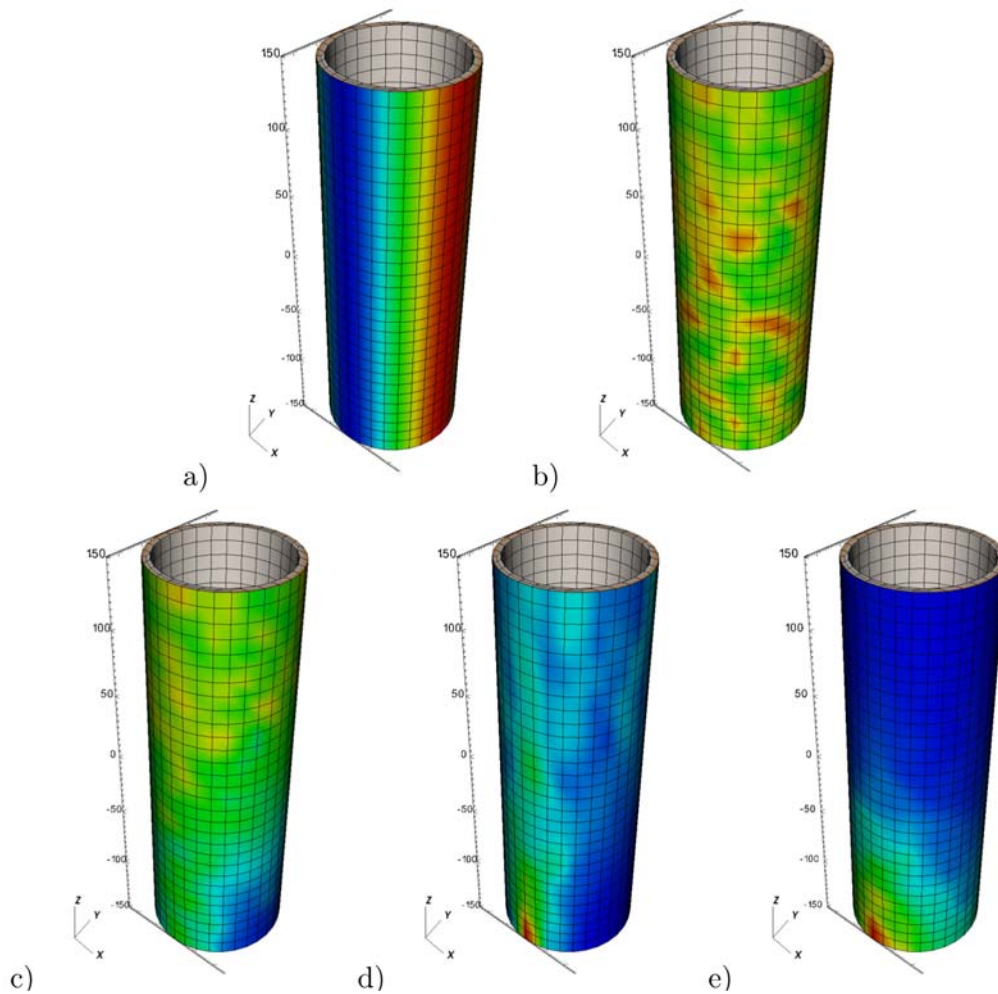


Figure 4: Simulation of a 30 cm section of leaky wellbore: a) distribution of confining pressure on the wellbore fracture (18–27 MPa, blue-red); b) initial hydraulic aperture distribution (0–75 μm , blue-red); c) hydraulic aperture distribution after one year of reaction with a 1 MPa pCO_2 brine (0–75 μm , blue-red); d) magnitude of vertical flux per unit length (0.0–0.7 mm^2/min , blue-red); and e) extent of amorphous layer (0.0–1.1 mm, blue-red) Additional details are in Walsh et al. (2014b).

This simulation is only one realization—ideally a broader range of parameters would be investigated to glean a better sense of the model response. Nevertheless, the example simulation shows that under reasonable stress a CO₂ storage environment reacts as follows:

- The hydraulic aperture decreases with alteration and is dependent upon the effective stress on the fracture
- The extent of alteration decreases up the flow path, and is consistent with field observations (Crow et al., 2009, 2010)

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- Walsh, S. D. C.; Smith, M. M.; Carroll, S. A. [Decoupling reaction and deformation in natural fractures with X-Ray Micro-tomography and Particle Image Velocimetry](#). 47th U.S. Rock Mechanics/Geomechanics Symposium, San Francisco, CA, June 23–26, 2013c.

APPENDIX

The following publications provide additional information on the chemical and mechanical components of the model and experimental analysis of the core-flood experiments on which the model was based.

- Mason, H. E.; Du Frane, W. L.; Walsh, S. D. C.; Dai, Z.; Charnvanichborikarn, S.; Carroll, S. A. [Chemical and mechanical properties of wellbore cement altered by CO₂-rich brine using a multi-analytical approach](#). *Environ. Sci. Technol.* **2013**, *47*, 1745–1752. DOI: 10.1021/es3039906
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NRAP is an initiative within DOE's Office of Fossil Energy and is led by the National Energy Technology Laboratory (NETL). It is a multi-national-lab effort that leverages broad technical capabilities across the DOE complex to develop an integrated science base that can be applied to risk assessment for long-term storage of carbon dioxide (CO₂). NRAP involves five DOE national laboratories: NETL, Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), and Pacific Northwest National Laboratory (PNNL).

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