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A Time-Dependent Chemo-Mechanical Analysis of Alkali-Silica Reaction for the Disparate Geometry of Concrete Meso-Structure

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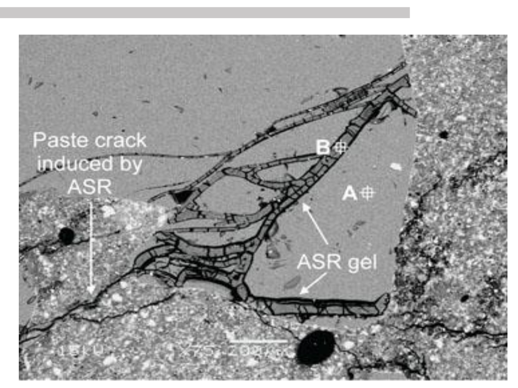
INTRODUCTION& MOTIVATION

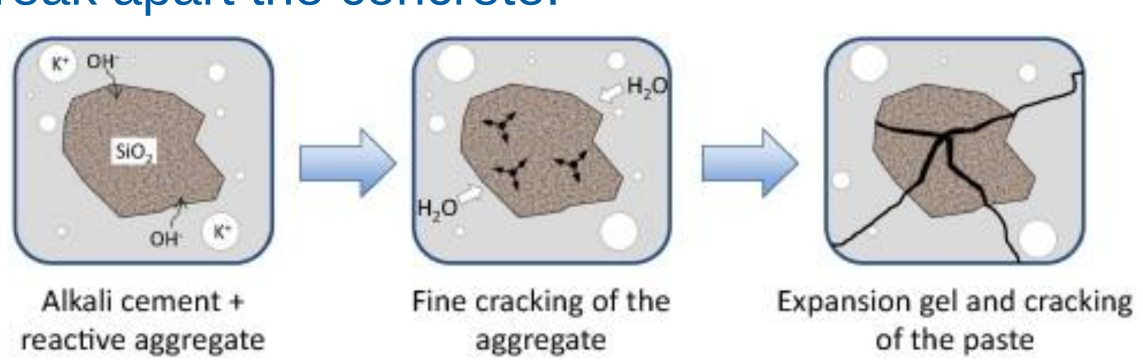
Portland cement concrete is a common construction material that is frequently used due to its durability, long service life and great economy. However, chemical reactions between reactive aggregate particles & cement paste lead to concrete degradation over time. Alkali-silica reaction (ASR) is one of those undesirable chemical reactions. ASR damage is caused internally and becomes visible when the structure is already damaged. It is a threat to socio-economic development of society. ASR is called as Concrete Cancer.

WHAT IS ASR?



Step 1: Silica in aggregates reacts with alkali in cement to produce a gel.

Step 2: The gel absorbs water, causing expansion and hydraulic pressures sufficient to fracture and break apart the concrete.



ASR DAMAGE

A threat to:

- Concrete Pavement & Bridges
- Nuclear Plant, Dams
- Airport Runway
- Other Concrete infrastructures

Nuclear Power Plant in Seabrook,

Pavement Damage due to ASR

CNN Newsletter April 3, 2019

47,052 bridges need urgent repairs in USA.

- Rhode Island (23%)
- West Virginia (19.8%)
- Iowa (19.3%)
- South Dakota (16.7%)
- Pennsylvania (16.5%)

Bridge Collapse in Tennessee

RESEARCH GOAL

- To generate concrete meso-structure based on cement-aggregate proportion.
- To develop a computational model as per ASR kinetics that can visualize damage propagation and predict concrete service life.

ASR MODEL: GOVERNING EQUATION SETS

Mass balance and Momentum balance:

$$\frac{\partial}{\partial t}(c_i) + \nabla\cdot(-D_i\nabla c_i) + \boldsymbol{u}\cdot\nabla c_i = R_i$$

Darcy's Law:

$$\frac{\partial}{\partial t}(\varepsilon_p\rho) + \nabla\cdot(\rho\boldsymbol{u}) = Q_m$$

$$\boldsymbol{u} = -\frac{\kappa}{\mu}\nabla p$$

- For Unsaturated Condition.

$$D = 2.021\times\varepsilon_{vol} - 0.195$$

$$\varepsilon_{vol} = \varepsilon_{gel} + \varepsilon_{stress}$$

$$\varepsilon_{gel} = \frac{\rho_{gel}}{\rho_c + \rho_{gel}}$$

$$\rho_{gel} = [\text{Expanded } ASR\ gel] \times M_{gel}$$

$$\frac{\partial}{\partial t}(u) + \nabla\cdot(-D_{gel}\nabla[ASR\ gel]) + \boldsymbol{u}\cdot\nabla u = f(u)$$

$$\frac{\partial}{\partial t}(\varepsilon_p\rho) + \nabla\cdot(\rho\boldsymbol{u}) = Q_m$$

$$\boldsymbol{u} = -\frac{\kappa}{\mu}\nabla p$$

$$Q_m = 0.018\times f_{[H2O]}$$

$$\varepsilon_{stress} = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}$$

$$u = [[Siloxane], [ROH], [ASR\ gel], [Silanol], [H2O], [Expanded\ ASR\ gel]]^T$$

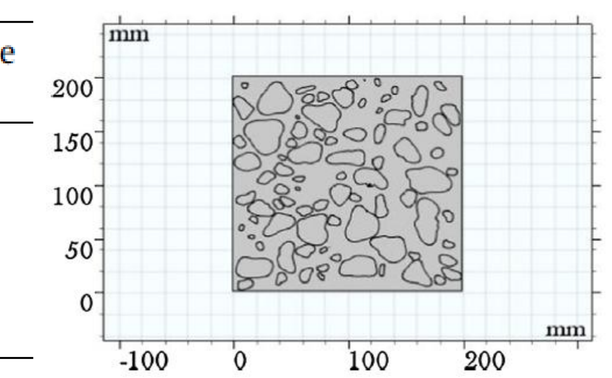
$$f_{[Siloxane]} = -k_1[Siloxane][ROH]$$
$$f_{[ROH]} = -k_1[Siloxane][ROH] - k_2[Silanol][ROH]$$
$$f_{[ASR\ gel]} = k_1[Siloxane][ROH] + k_2[Silanol][ROH] - k_3[ASR\ gel][H_2O]$$
$$f_{[Silanol]} = k_1[Siloxane][ROH] - k_2[Silanol][ROH]$$
$$f_{[H_2O]} = k_2[Silanol][ROH] - k_3[ASR\ gel][H_2O]$$
$$f_{[Expanded\ ASR\ gel]} = k_3[ASR\ gel][H_2O]$$

- ❑ i = Denotes Each Species, respectively
- ❑ C = Concentration of species
- ❑ Di = Diffusion Coefficient
- ❑ u = Velocity Field
- ❑ R, f(u) = Source Term
- ❑ Qm = Discharge
- ❑ P = Developed Pore Pressure
- ❑ D = Damage Function

PREDICTIVE MODEL

A 200mm*200mm Concrete block was considered.

Geometry Sets	Cement to Aggregate Ratio (C/A)
Case 1	1.13
Case 2	1.61
Case 3	2
Case 4	0.5
Case 5	1



Damage Function: $D = \begin{cases} 0 & when, \varepsilon_{gel} \le 0.1\% \\ w & when, \varepsilon_{gel} > 0.1\% \end{cases}$

For validation predictive model was run for 400 days.

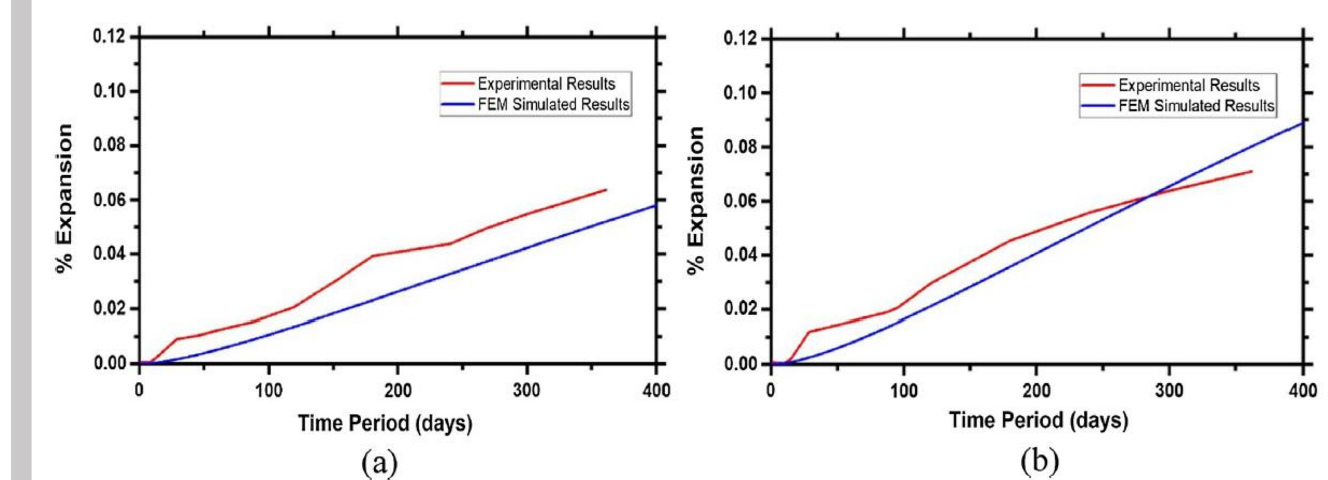


Fig.: Comparison of FEM simulated data with the experimental data as per case 4 (C/A: 0.5): (a) 20 degC ROH 0.8 mol/m3, (b) 20 degC ROH 1.2 mol/m3

RESULTS & DISCUSSIONS*

A 30 years simulation period as well as 10 case studies corresponding to concrete domain and ROH concentration, provide an in depth view of concrete degradation with the progression of time.

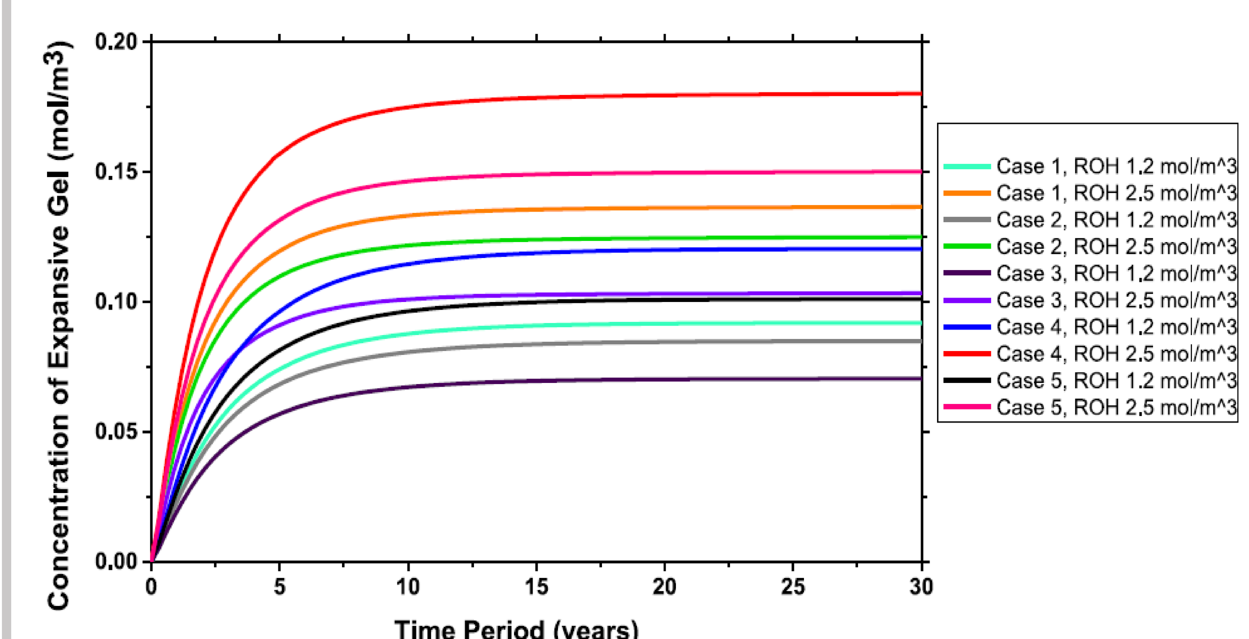


Fig.: Concentration of expansive ASR gel (mol/m3)

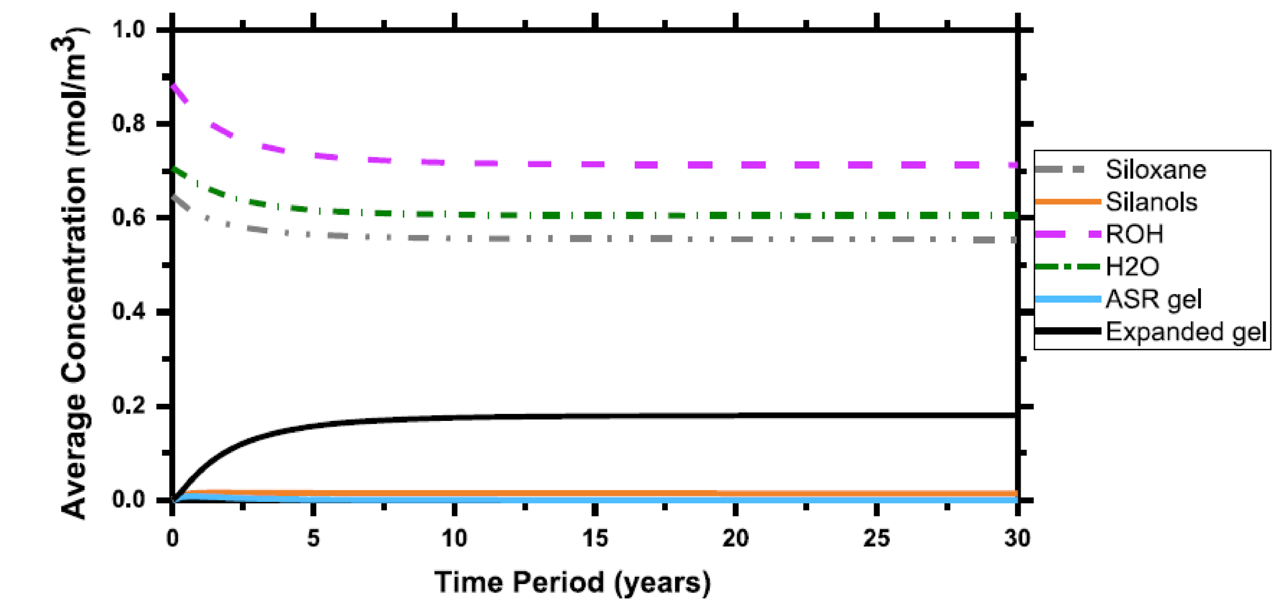


Fig.: Comparison between concentrations of all six species (mol/m3))

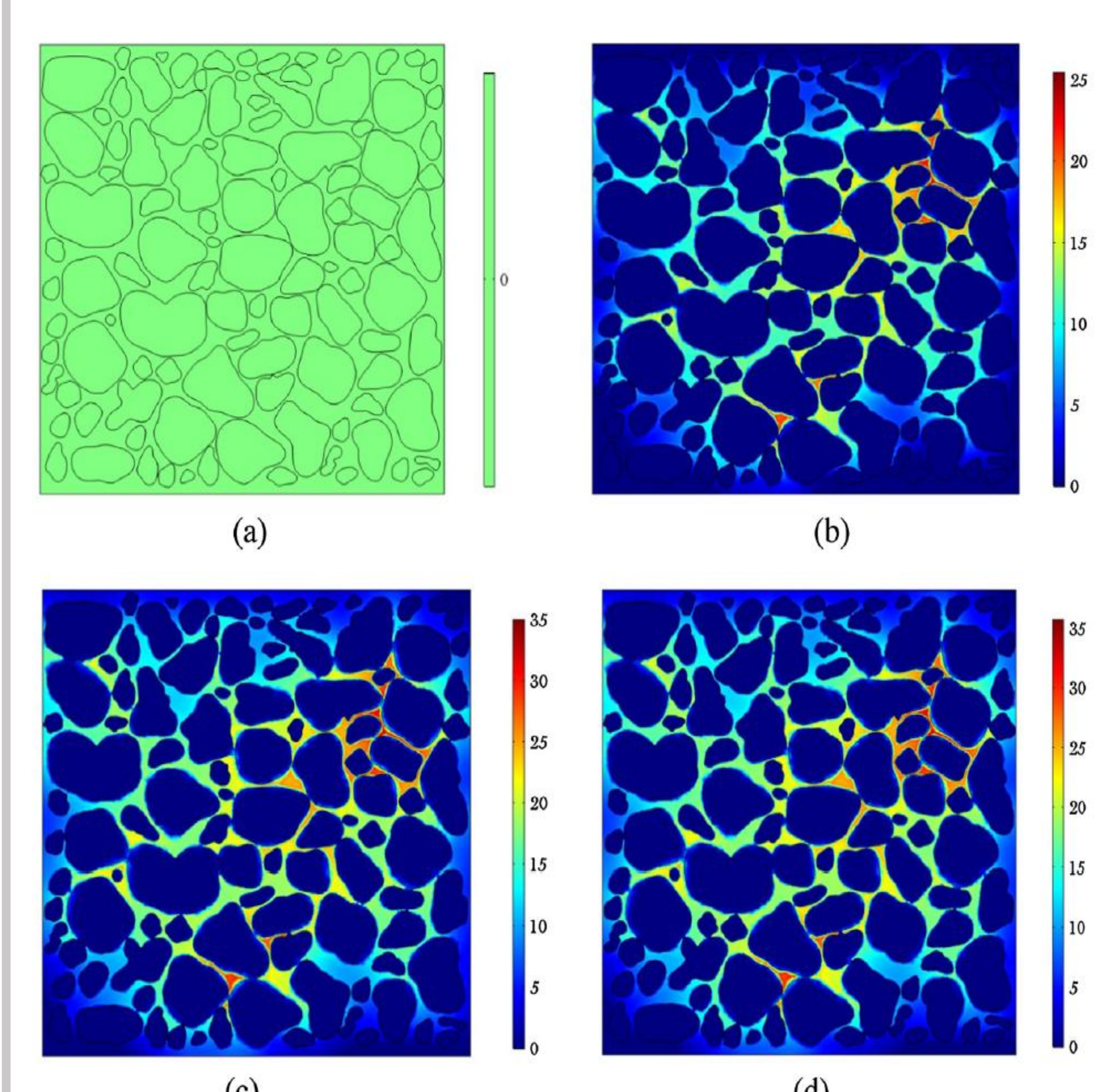


Fig.: Damage in concrete domain due to ASR gel case 4 with ROH of 1.2 mol/m3: (a) 0, (b) 5, (c) 15, and (d) 30 years..

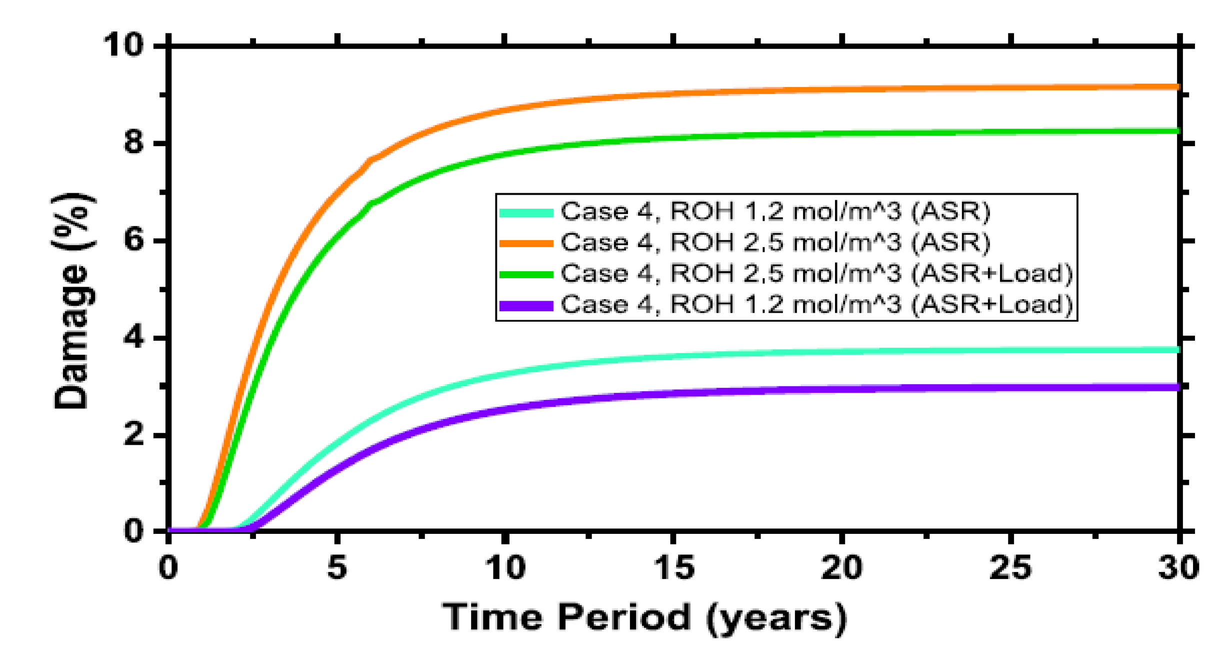


Fig.: Percentage of damage in concrete domain for case 4.

HEIGHLIGHTS

- ✓ An effective tool to predict service life of concrete.
- ✓ Applicable to any concrete structures, i.e., Pavement. Bridges, Dams. Nuclear reactor etc.
- ✓ Can act as a guideline for government or construction industries.
- ✓ Potentially minimize time consuming and costly lab tests.

FUTURE GOALS

- ✓ Create Database from developed model based on case study
- ✓ Develop an artificial neural network (ANN) interface to predict service life..

*Rahman, Md. Asif, Yang Lu, "A Time-Dependent Chemo-Mechanical Analysis Of Alkali-Silica Reaction For The Disparate Geometry Of Concrete Meso-Structure," Journal of Construction and Building Materials, Volume 211, 30 June 2019, Pages 847-857.