Production Asset Integrity and Corrosion Management: Best Practices and Innovations

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An Experimental and Modeling Investigation of Cement Sheath Degradation With Supercritical CO_2 for Wellbore Integrity

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1. Background & Challenges

2. Laboratory Tests of Cement Sheath Properties

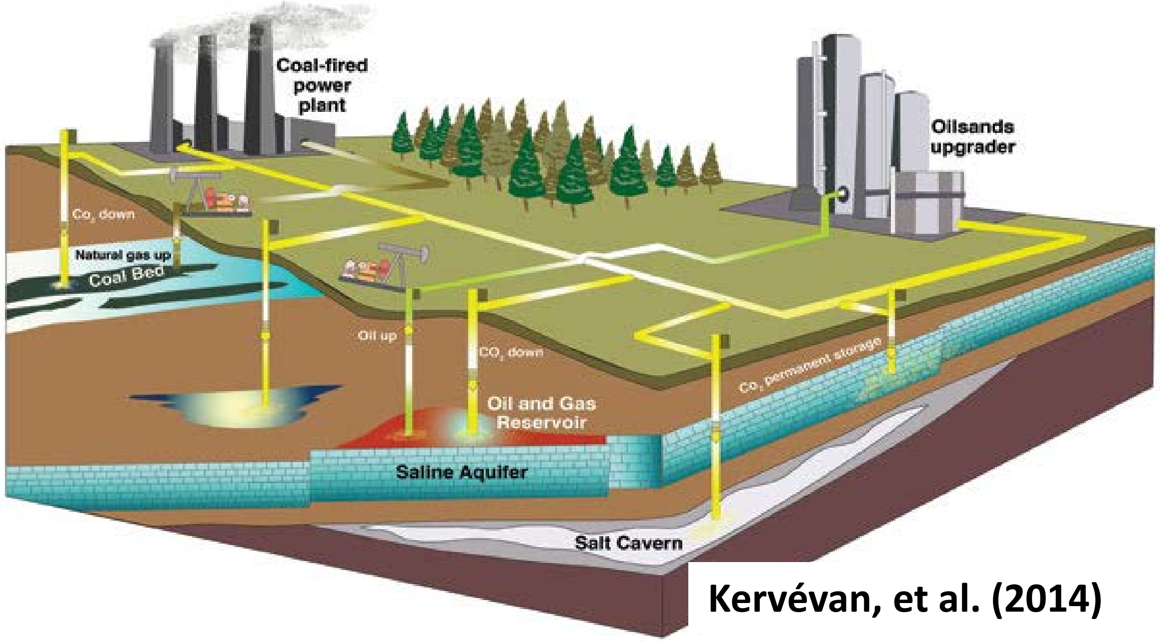
3. THMC Coupled Model of Cement Sheath Integrity

4. Prediction of Cement Sheath Failure

5. Summary and Suggestions

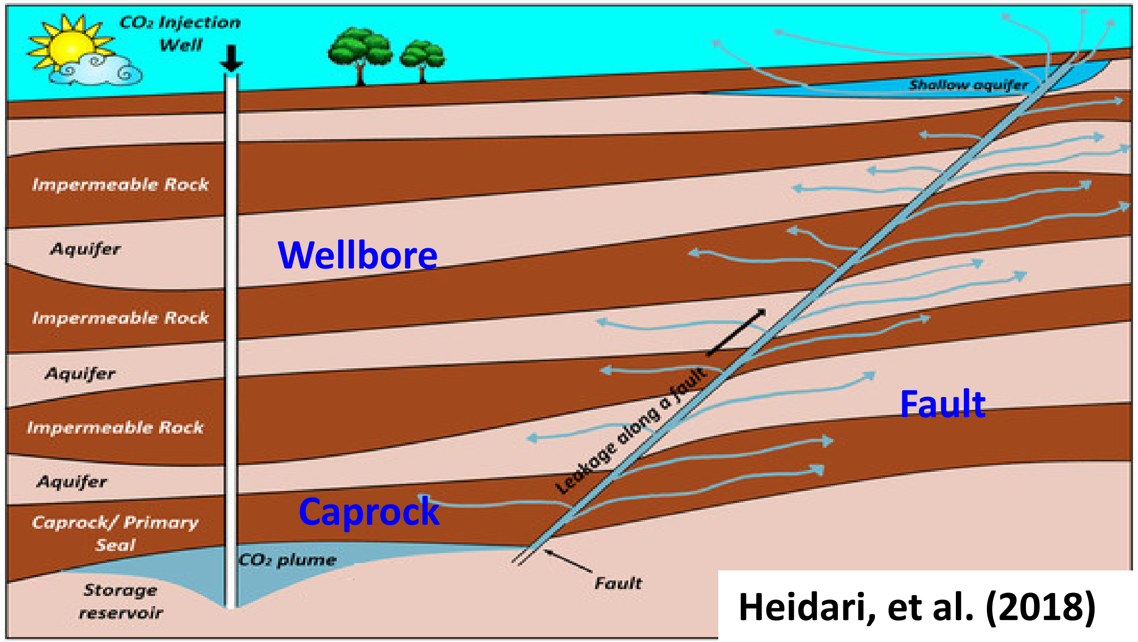
1. Background

- CCUS is one of the most useful methods to mitigate CO_2 emissions
- One of the primary potential pathways of CO_2 leakage is the failure of the cement sheath integrity



Kervévan, et al. (2014)

CCUS process

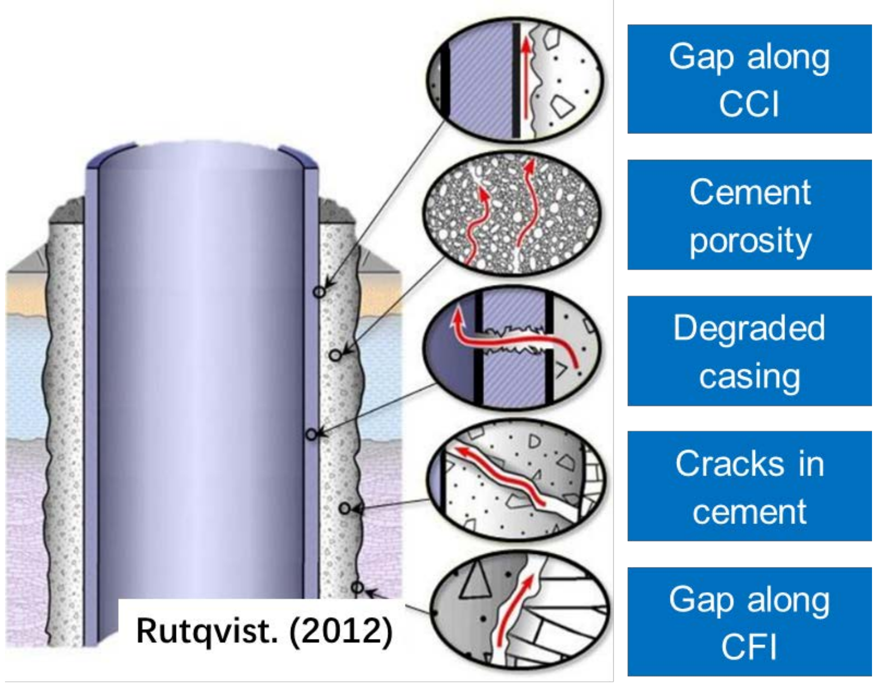


Heidari, et al. (2018)

CO_2 leakage in geological sequestration

1. Background

- Numerous factors affecting cement sheath integrity: cement properties, cementing quality, temperature, pressure, acid medium, storage conditions

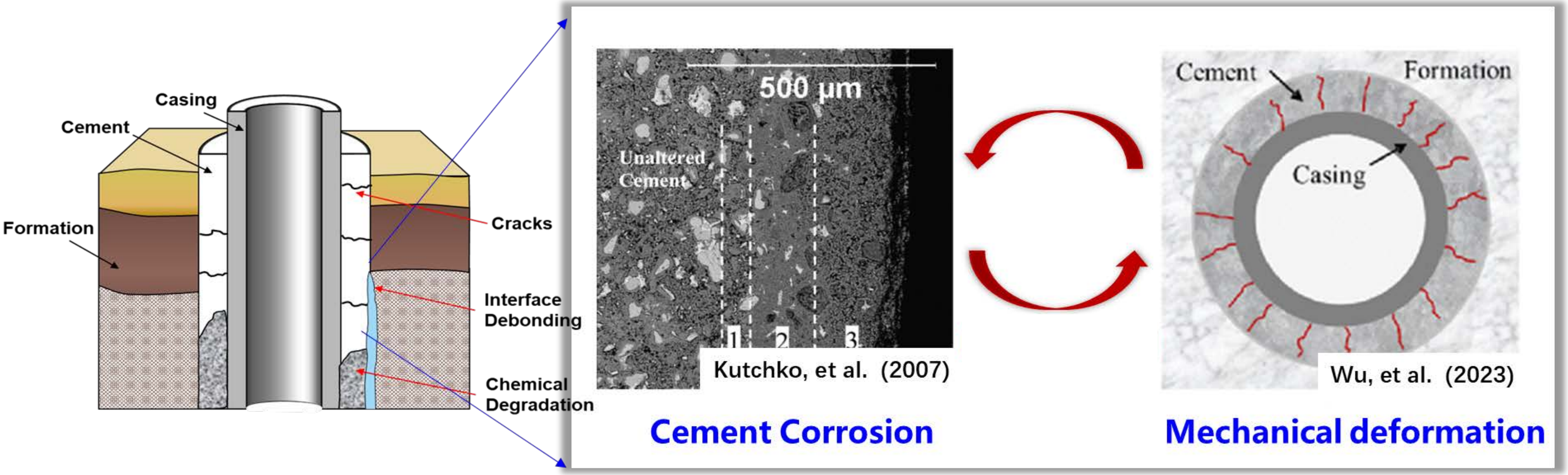


Typical failure modes of cement sheath

Factors	Specific features
Cement properties	o Volumetric shrinkage
	o Physical & mechanical properties
Cementing quality	o Casing eccentric
	o Replacement efficiency
	o Wellbore trajectory
Storage conditions	o Formation physical & mechanical properties
	o Supercritical CO_2 **(T>31℃，P>7.33MPa)**
	o Alternating T & P

1. Challenge

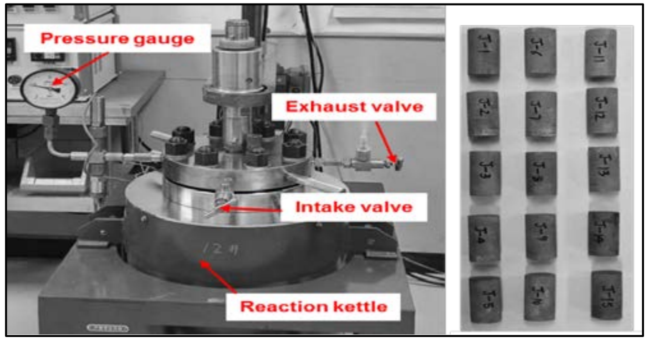
- It is difficult to construct a model to predict the failure of cement sheath integrity under the coupled corrosion and stress condition



Research Approach

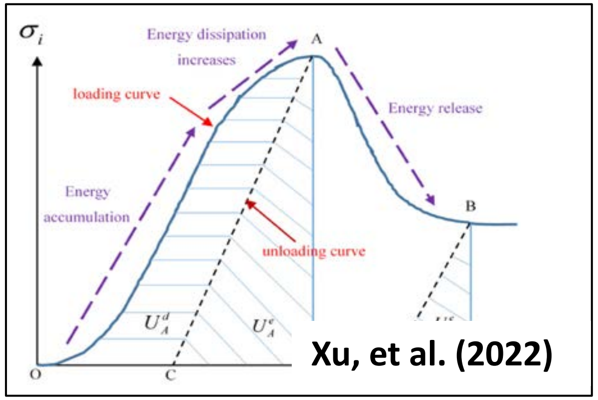
Cement sample scale

Corrosion tests of cement with supercritical CO_2



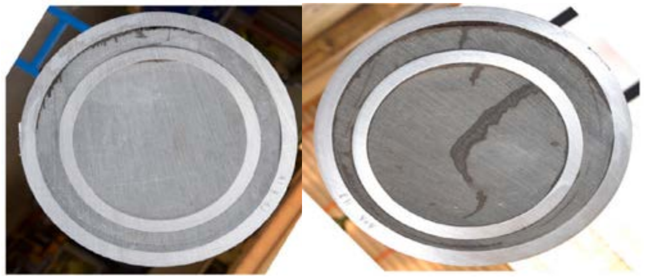
Cement sample scale

Properties evolution of cement before and after corrosion

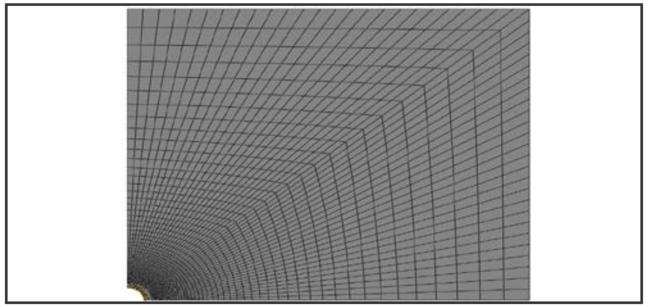


Xu, et al. (2022)

Cement sheath scale

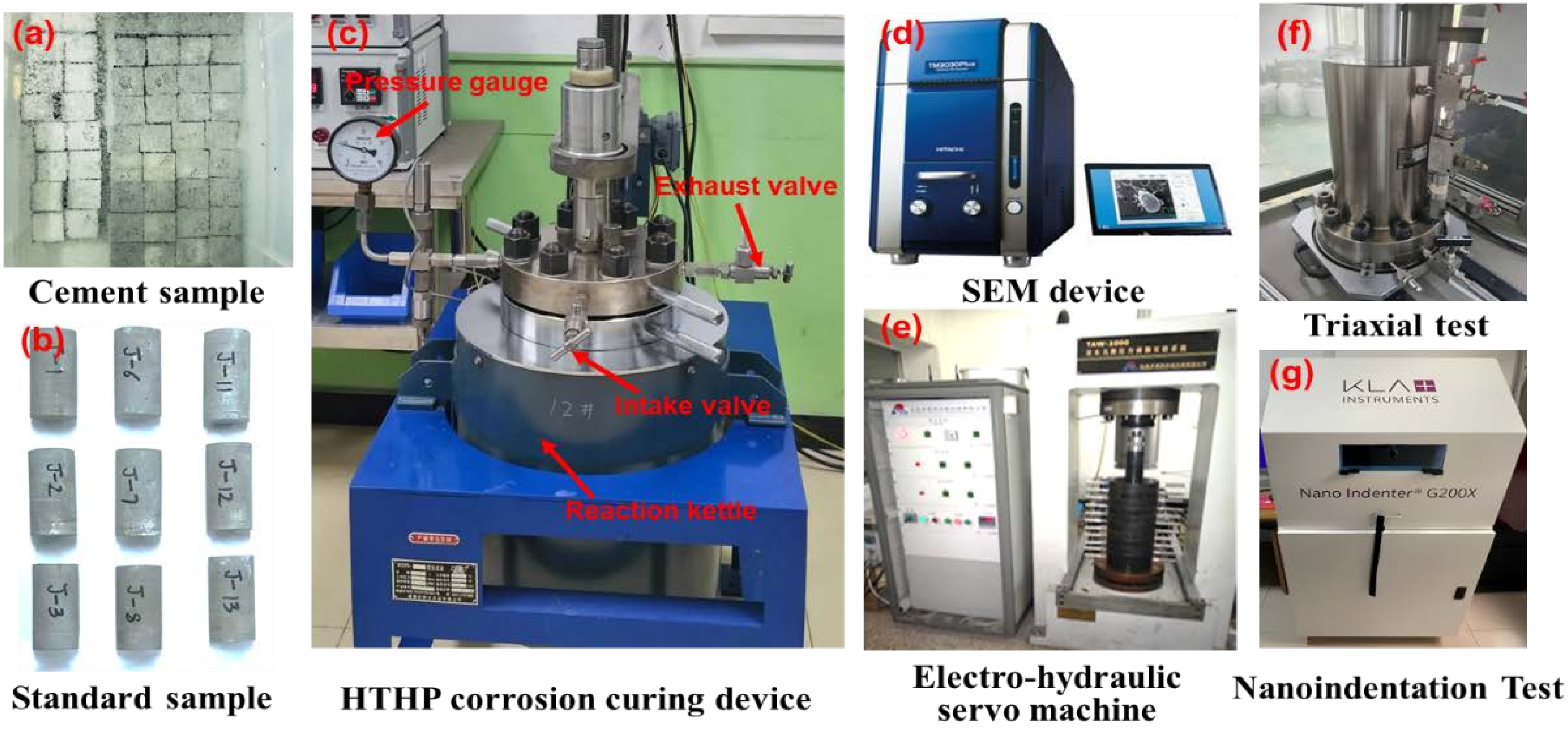


THMC coupled model of cement sheath integrity



2. Laboratory Tests of Cement Sheath Properties

- The overall process of the experiment



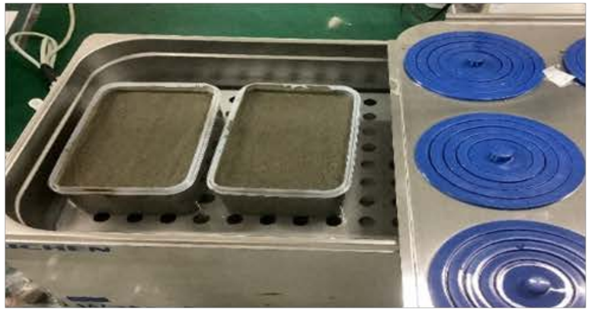
2. Laboratory Tests of Cement Sheath Properties

- Preparation of cement sheath samples

Weighing of cement slurry formulation →

Mixing and stirring of the cement slurry →

Vibration of the cement slurry for 15 minutes →



Preliminary curing and molding of the cement slurry

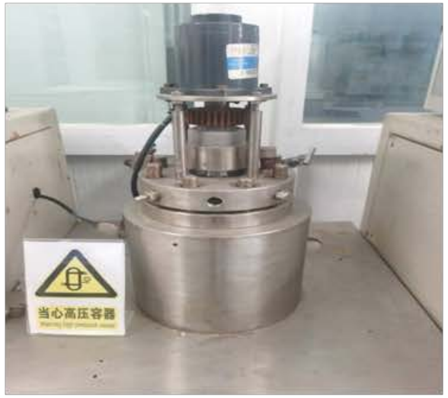
↓

GB/T 19139-2012 Standard

←

HTHP autoclave

←



2. Laboratory Tests of Cement Sheath Properties

- Corrosion experimental procedure

  - HTHP corrosion reactor setup
  - 0.4 mol/L NaCl solution (brine simulation)
  - N_2 deoxidation (2 hours)
  - **90 °C, 15 MPa** CO_2 exposure
  - Corrosion time: 14d, 28d

2. Laboratory Tests of Cement Sheath Properties

- Microscopic morphology of cement sheath samples

1. CO_2 Dissolution

$$CO_2+H_2O \rightleftharpoons H_2CO_3$$

2. Carbonation Reaction

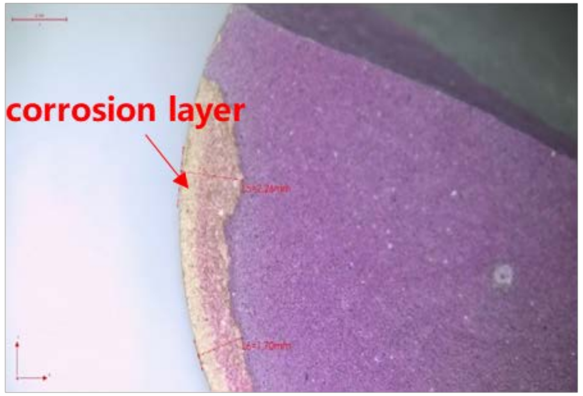
$$Ca(OH)_2+H_2CO_3 \rightarrow CaCO_3+H_2O$$

$$CSH+H_2CO_3 \rightarrow CaCO_3+SiO_2.nH_2O$$

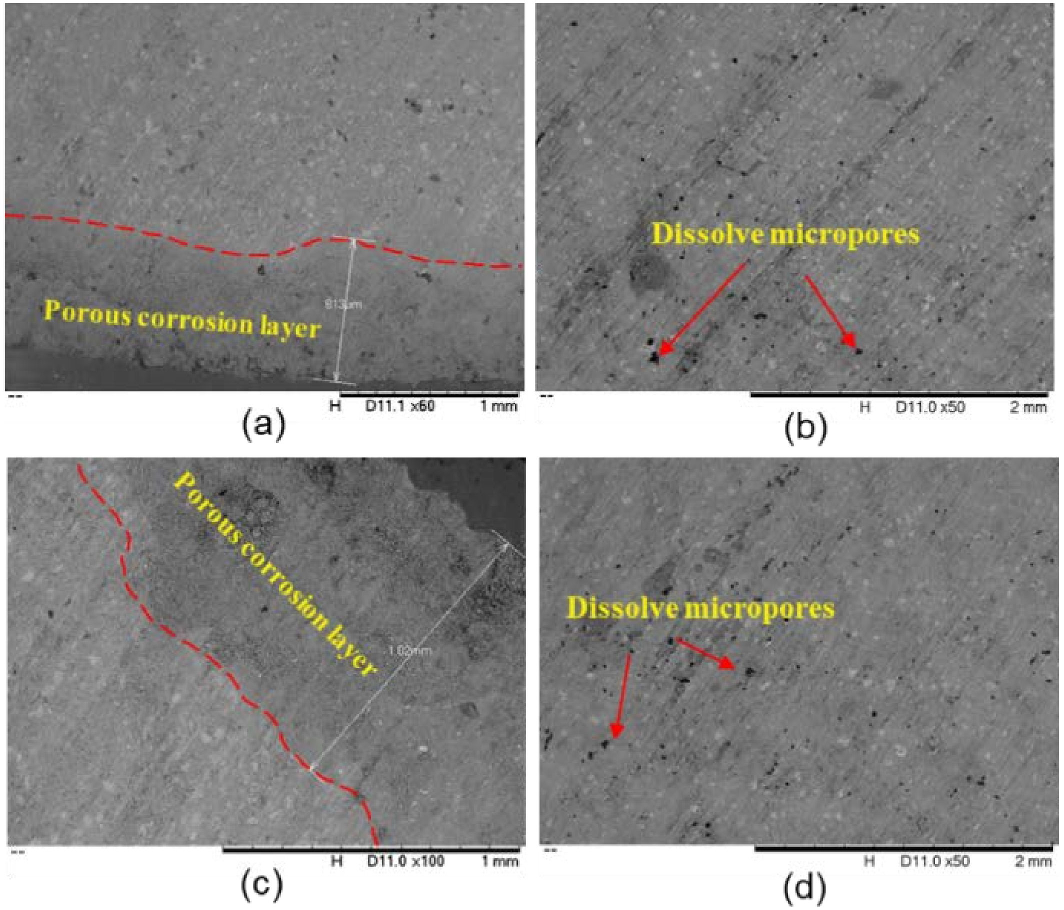
3. Ca^{2+} Leaching Process

$$CaCO_3+CO_2+H_2O \rightarrow Ca^{2+}+2HCO^{3-}$$

Before corrosion　After corrosion



Radial section after corrosion

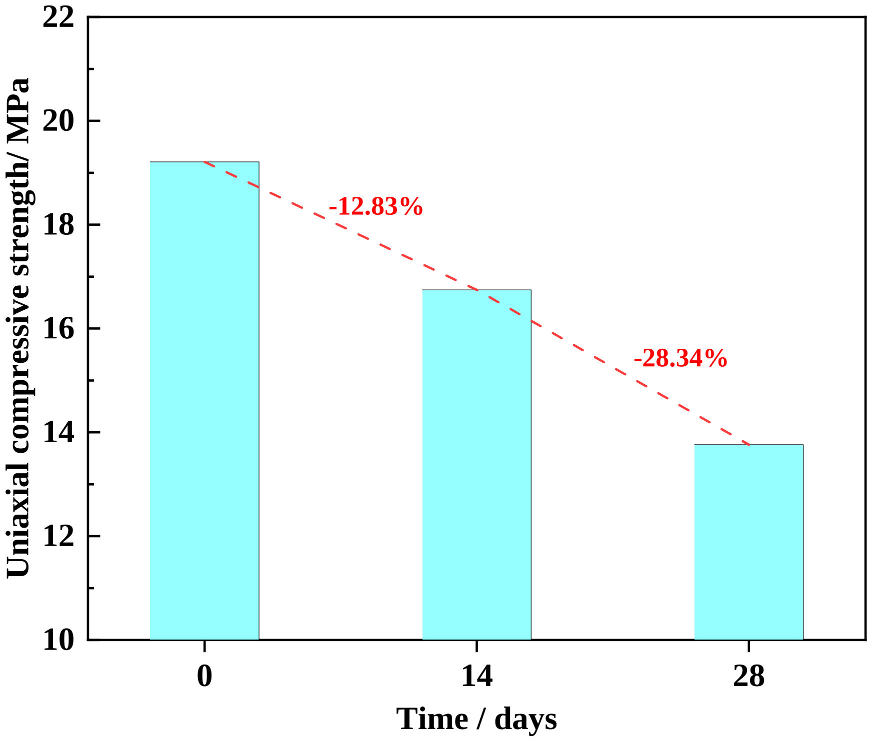


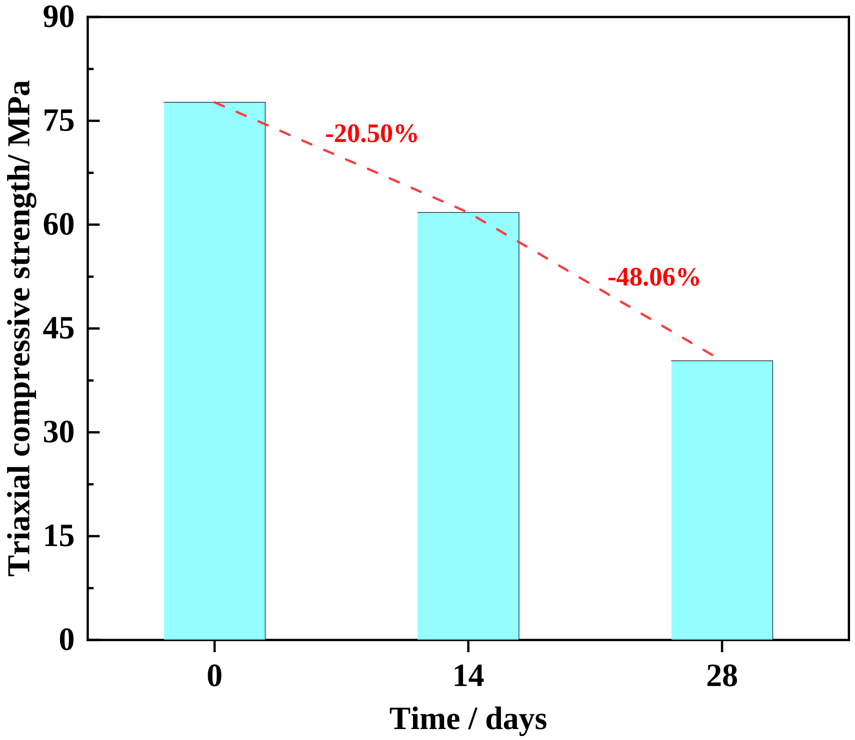
2. Laboratory Tests of Cement Sheath Properties

- Strength changes of cement sheath samples

Uniaxial compressive strength
- Initial: 19.208 MPa
- After 14 days: 16.74 MPa
- After 28 days: 13.764 MPa
- **28% decrease** in strength

Triaxial compressive strength
- Initial: 77.68 MPa
- After 14 days: 61.75 MPa
- After 28 days: 40.34 MPa
- **48% decrease** in strength

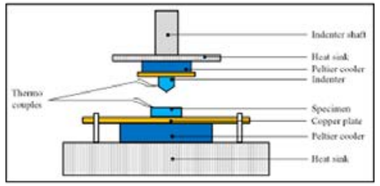


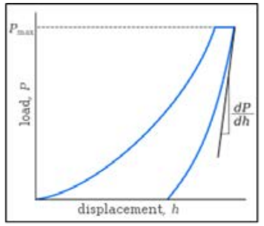


2. Laboratory Tests of Cement Sheath Properties

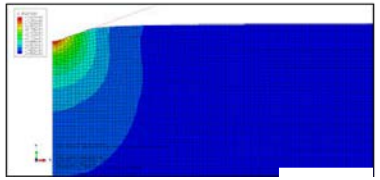
- Calibration of the mechanical properties of corroded zone

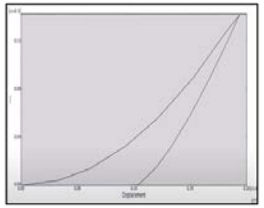
Elastic properties

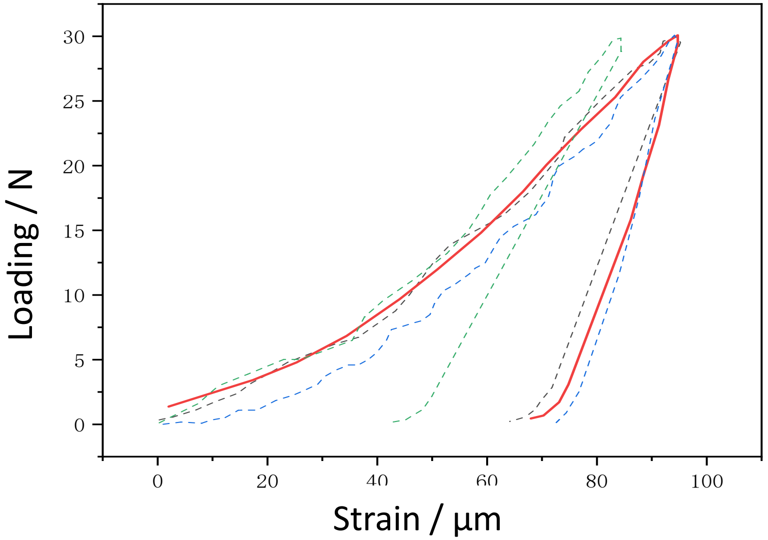


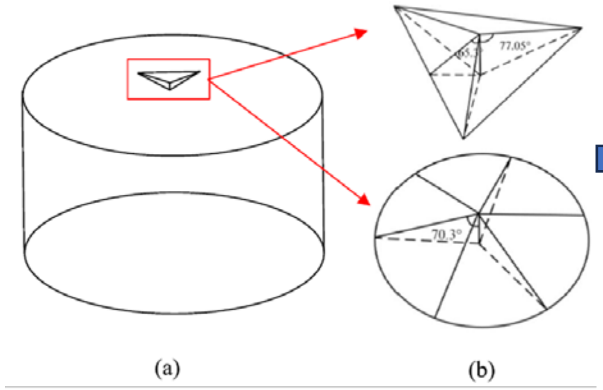


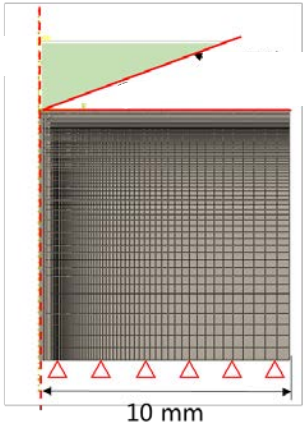
Elastoplastic properties











Mech. Properties	Values
Young's Modulus	7.81 GPa
Poisson's ratio	0.25
Cohesive strength	5 MPa
Friction angle	27 °

3. THMC Coupled Model of Cement Sheath Integrity

- Based on Fick's law and the principle of mass conservation, a theoretical model for the carbonation reaction in the cement sheath was developed

➢ Corrosion reaction mechanism

$$\begin{cases} Ca(OH)_2(s) \rightarrow Ca^{2+}(aq) + 2OH^-(aq) \\ Ca(OH)_2(aq) + CO_2(aq) \rightarrow CaCO_3(s) + H_2O \\ 3CaO\cdot 2SiO_2\cdot 3H_2O + 3CO_2(aq) \rightarrow 3CaCO_3\cdot 2SiO_2\cdot 3H_2O \\ 2CaO\cdot SiO_2 + 2CO_2(aq) + nH_2O \rightarrow SiO_2\cdot nH_2O + 2CaCO_3 \\ 3CaO\cdot SiO_2 + 3CO_2(aq) + nH_2O \rightarrow SiO_2\cdot nH_2O + 3CaCO_3 \end{cases}$$

$$\frac{\partial C_{CO_2}}{\partial t} = \frac{\partial}{\partial x}\left(D_{CO_2} \times \frac{\partial C_{CO_2}}{\partial x}\right) - \varepsilon(t)\times r_{CC,CH} - 3r_{CC,CSH}$$

$$\frac{\partial C_{Ca(OH)_2}}{\partial t} = \frac{\partial}{\partial x}\left(D_{Ca(OH)_2} \times \frac{\partial C_{Ca(OH)_2}}{\partial x}\right) - \varepsilon(t)\times r_{CC,CH}$$

$$\frac{\partial C_{CSH}}{\partial t} = -r_{CC,CSH}$$

$$\frac{\partial C_{CaCO_3}}{\partial t} = \varepsilon(t)\times r_{CC,CH} + 3r_{CC,CSH}$$

$$\frac{\partial s}{\partial t} = \frac{\partial}{\partial x}\left(D_s \times \frac{\partial s}{\partial x}\right) + \varepsilon(t)\times r_{CP,H_2O}$$

The diffusion coefficient of CO_2 cement

$$D_{CO_2} = D^0_{CO_2} \times [\varepsilon(t)]^{1.8} \times (1-s)^{2.2}$$

The diffusion coefficient of water in cement

$$D_s = D_1 \times f(s) \times f(t) \times f(T) \times f(c)$$

The carbonation reaction rate of CH (calcium hydroxide)

$$r_{cc,CH} = H\cdot R\cdot T\cdot K_{CH}\cdot C_{CH}\cdot C_{CO_2}$$

The carbonation reaction rate of CSH

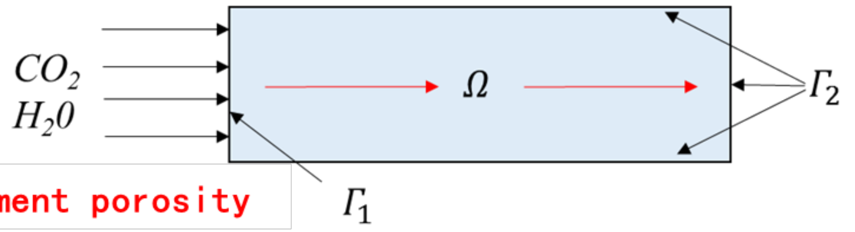
$$r_{cc,CSH} = H\cdot R\cdot T\cdot K_{CSH}\cdot C_{CSH}\cdot C_{CO_2}$$

➢ Initial and boundary conditions

$$C_f(P\in\Omega, t=0) = C_{f,init}$$

$$C_f(P\in\Gamma_1, t) = C_{f,b}$$

$$\vec{n}\cdot\left(D\nabla C_f(P\in\Gamma_2)\right) = 0$$



Cement porosity

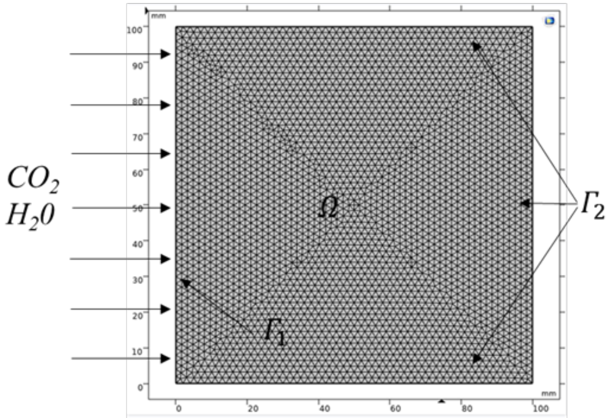
$$\varepsilon(t) = (\varepsilon_0 - \Delta\varepsilon_h(t) - \Delta\varepsilon_c(t))$$

$$\Delta\varepsilon_h(t) = [C_3S]_0 \times F_{C_3S}(t)\times\Delta V_{C_3S} + [C_2S]_0\times F_{C_2S}(t)\times\Delta V_{C_2S}$$

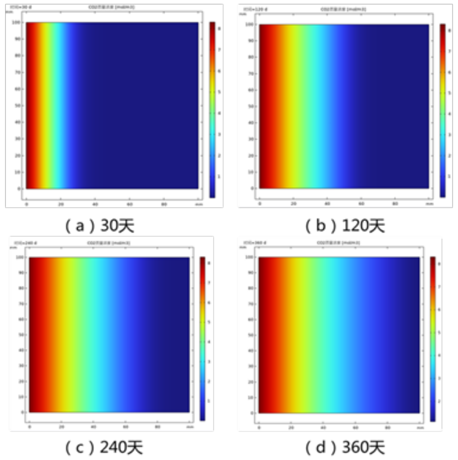
$$\Delta\varepsilon_c(t) = ([CH]_0 - [CH])\cdot\Delta V_{CH} + ([CSH]_0 - [CSH])\cdot\Delta V_{CSH}$$

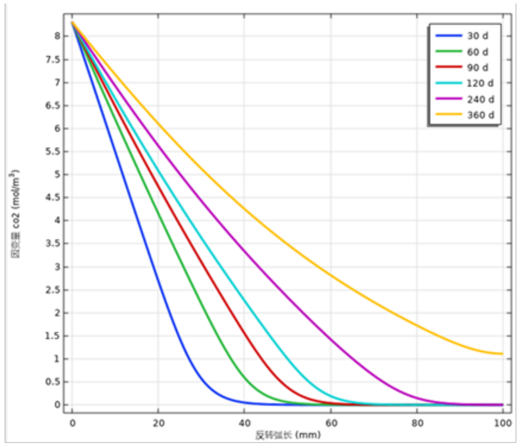
3. THHC Coupled Model of Cement Sheath Integrity

- Based on Fick's law and the principle of mass conservation, a theoretical model for the carbonation reaction in the cement sheath was developed

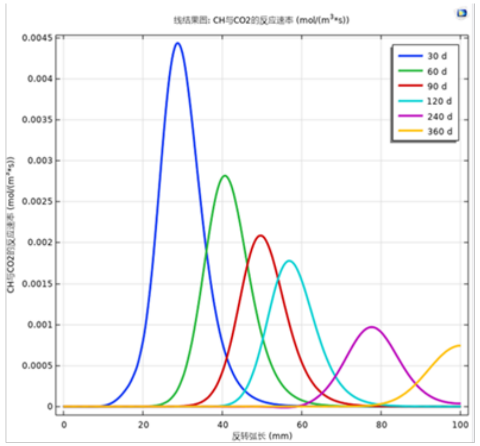


models

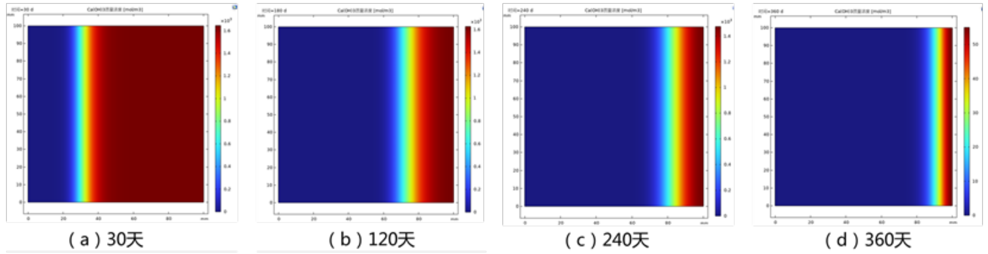




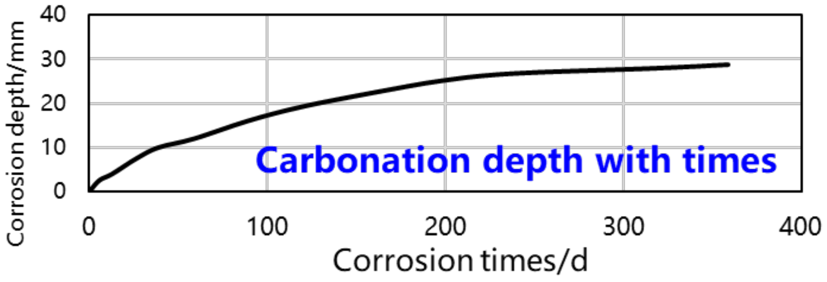
CO_2 contents during different corrosion times



The consumption rate of the carbonation reaction of $Ca(OH)_2$



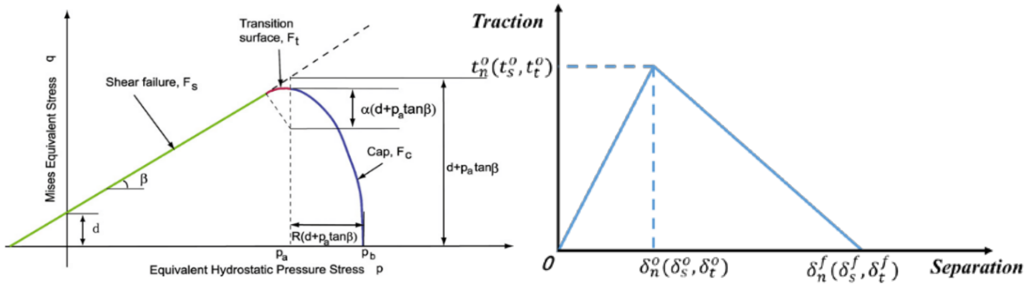
$Ca(OH)_2$ contents with different times



Carbonation depth with times

3. THMC Coupled Model of Cement Sheath Integrity

Constitutive Relationship



- **Casing**: linear elastic;
- **Cement sheath**: poroelastoplastic & M-C yield criterion
- **Formation**: Poroelastoplastic-transverse isotropy
- **Casing-cement-formation interface**: traction-separation criteria

Fluid Flow

$$q = -\frac{k}{\mu}\ p$$

$$\bar{k} = \frac{k_s}{\left(1 + \beta\sqrt{v_w v_w}\right)}\ k$$

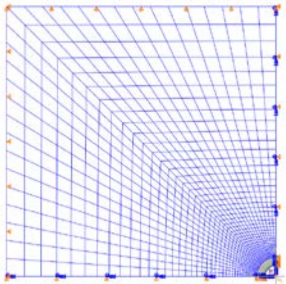
$\beta = 0.0$ **Darcy's criterion**

Cement and formation:

Fluid flow field

Temperature Field

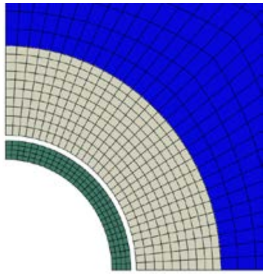
$$\frac{\rho c}{\lambda}\frac{\partial T}{\partial t} = \nabla^2 T$$



Heat transfer between fluid and casing

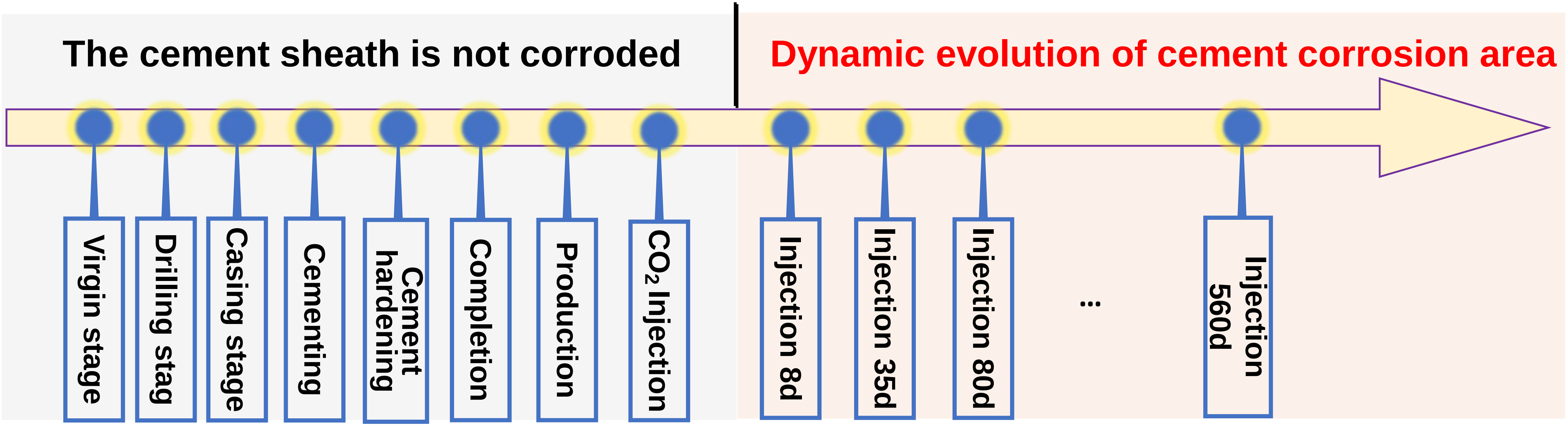
$$q = -h\,(T_s - T_l)$$

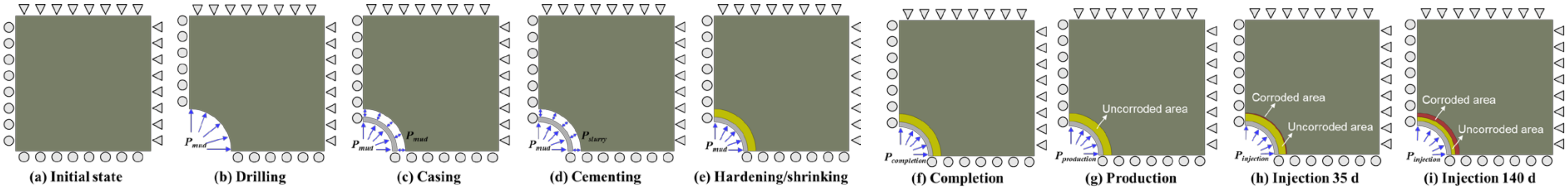
Thermal convection at debonding interface



$$q_{cont} = k(\theta_A - \theta_B)$$

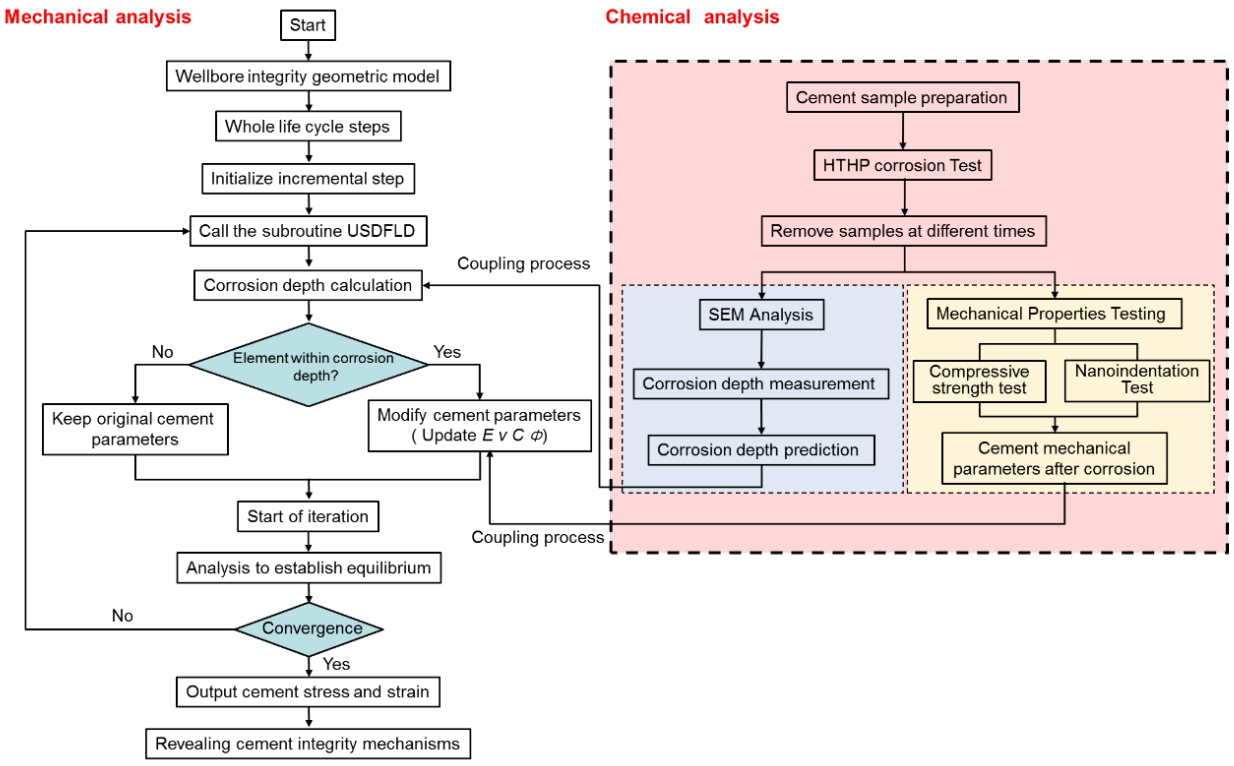
3. THMC Coupled Model of Cement Sheath Integrity

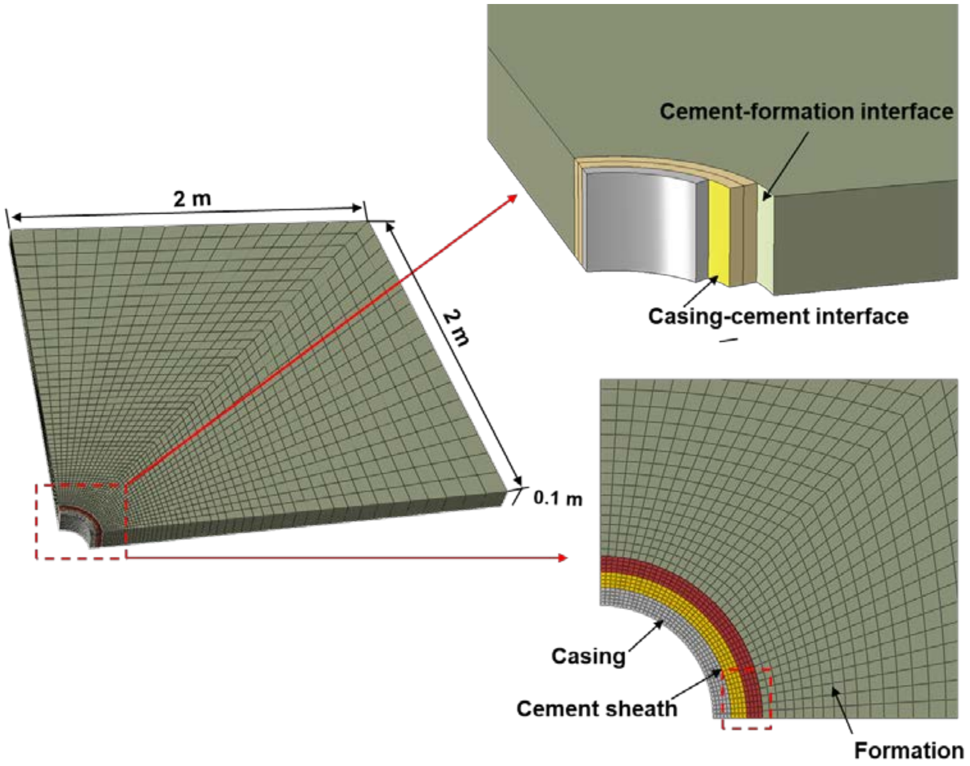




3. THMC Coupled Model of Cement Sheath Integrity

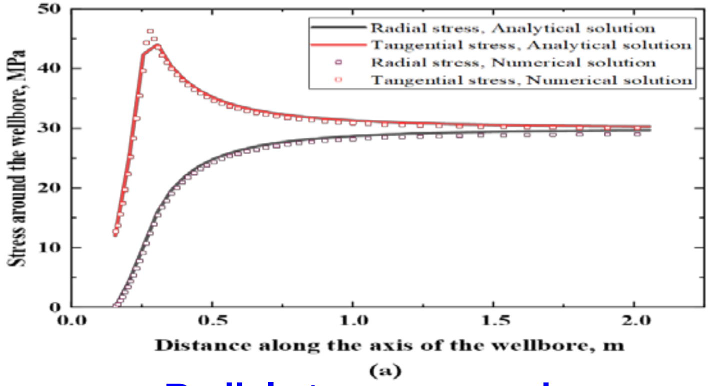
- An Abquas USDFLD subroutine for cement sheath corrosion depth and properties over time was written using FORTRAN





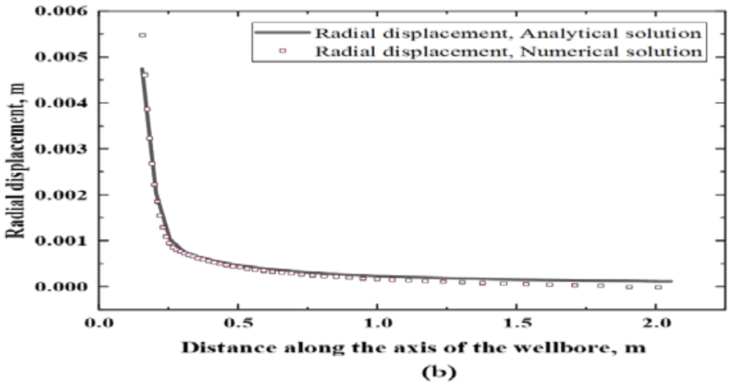
3. THMC Coupled Model of Cement Sheath Integrity

- Model verification (theoretical / experimental verification)



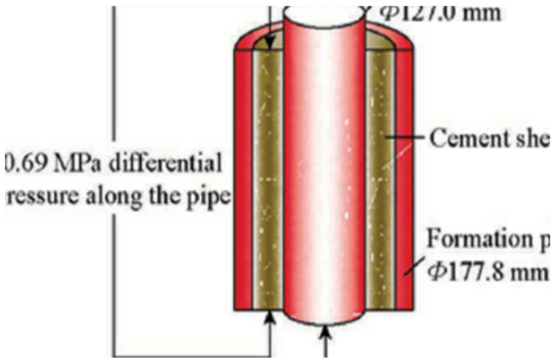
(a)

Radial stress comparison

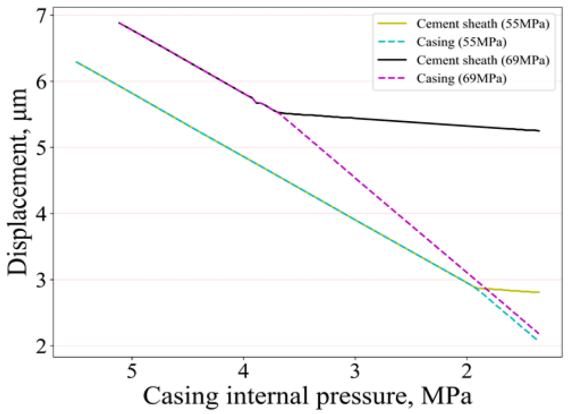


(b)

Radial displacement comparison



Jackson and Murphey, 1993



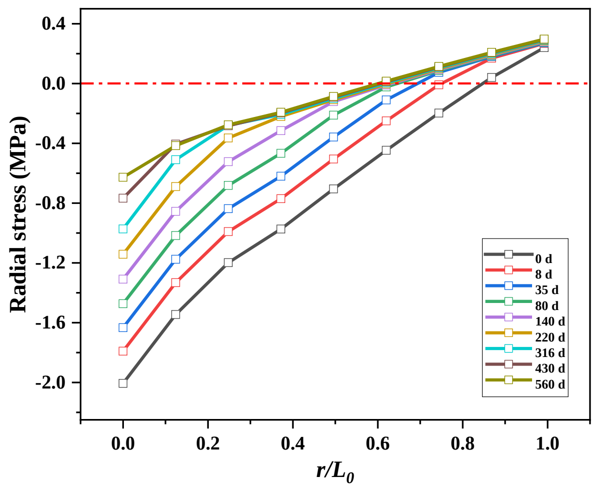
Experimental schematic

Numerical result

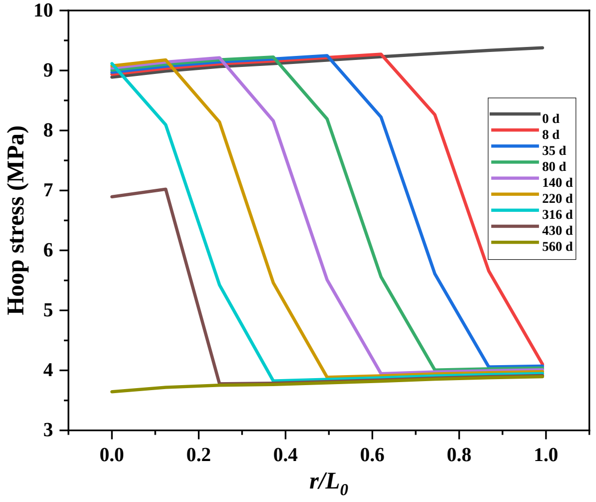
The numerical results (3.65 MPa、1.8 MPa) are **consistent with** the Jackson experimental results.

4. Prediction of Cement Sheath Failure

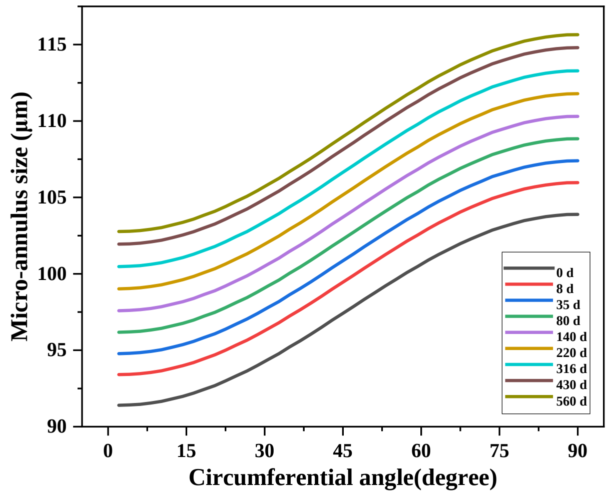
- Stress, displacement, and damage evolution at different corrosion time



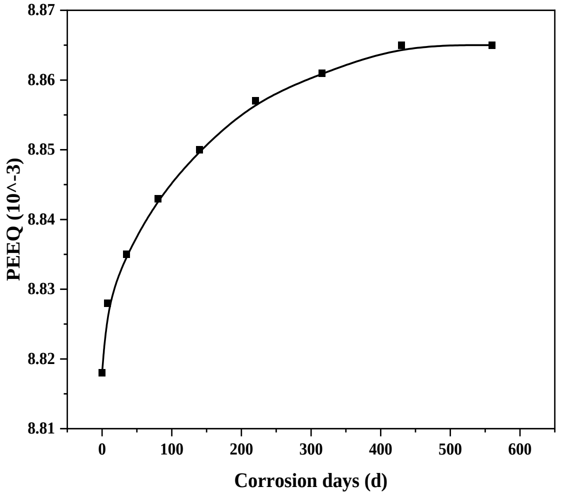
Radial stress distribution



Hoop stress distribution



Micro-annulus at cement interface

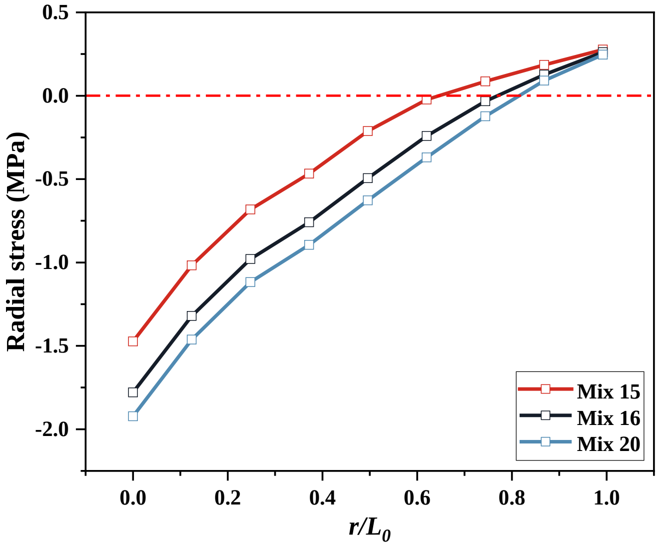


PEEQ of cement

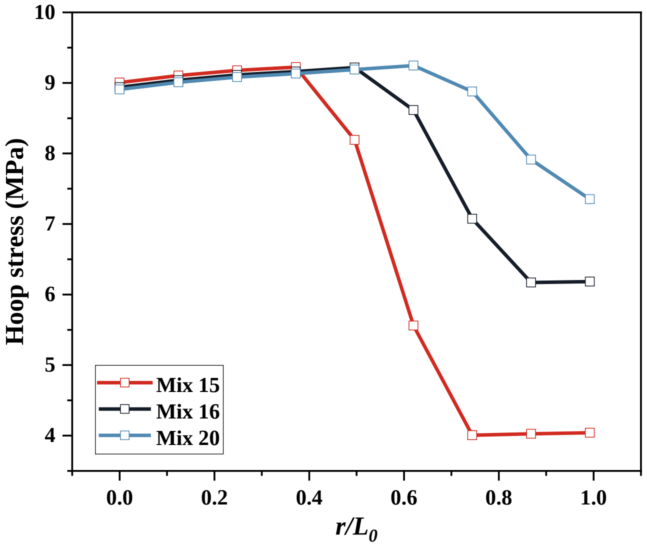
- The tensile stress at the II interface increases with time, and the hoop stress gradually decreases
- The micro-annulus increases with corrosion time, and the maximum micro-annulus reaches 115.7 microns after 560 days of corrosion
- The PEEQ increases with the corrosion time, and the yield damage also increases

4. Prediction of Cement Sheath Failure

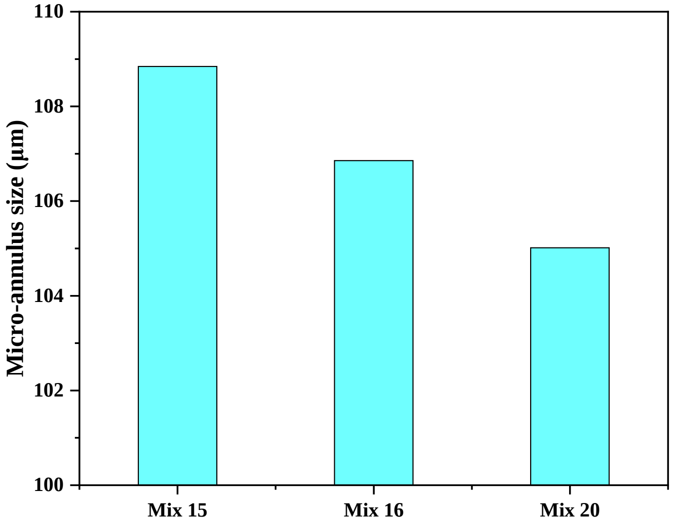
- The anti-corrosion effects of Mix 15 (silica fume), Mix 16 (liquid silicon) and Mix 20 (latex) were evaluated



Radial stress of different cements



Hoop stress of different cements

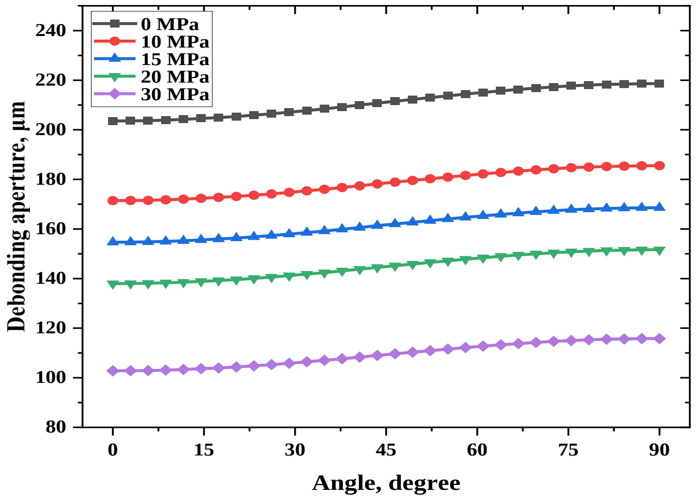


Different cement interface micro-annulus

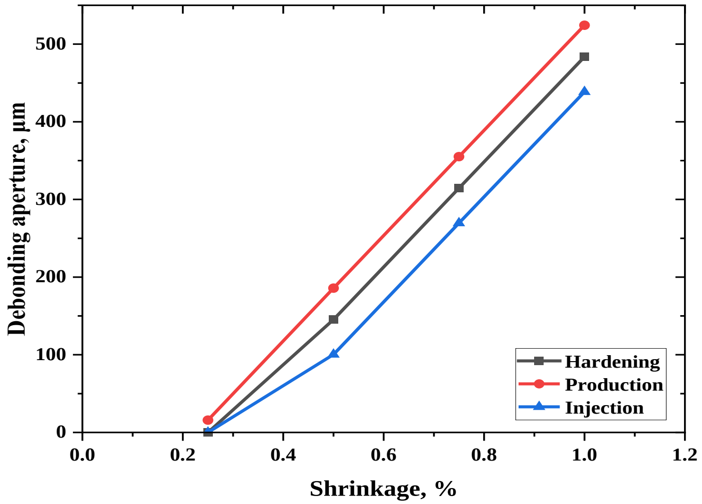
- The corrosion depth of Mix 20 cement is the smallest, and the radial tensile stress at the second interface is the lowest
- The area of low stress distribution in the three cements gradually decreases
- Mix 20 cement has the smallest micro-annulus, and it has a better anti-corrosion effect

4. Prediction of Cement Sheath Failure

- The influence of initial stress and cement shrinkage on cement sheath integrity



Influence of "initial stress" on cement sheath interface



Effect of cement sheath shrinkage on interface debonding

- The initial stress of the cement sheath increases, the contact pressure at the interface is greater, and the risk of interface separation is lower
- The micro-annulus increases with the increase of the cement volume shrinkage, and the interface debonding increases with the increase of the elastic modulus

5. Summary and Suggestions

An analysis model for cement sheath integrity with supercritical CO_2 was established, and the failure of cement sheath seal integrity under coupled corrosion-stress was investigated

1. Under supercritical CO_2 corrosion conditions, the outside of cement sample forms a large number of dissolved micropores. Corrosion depth gradually increases.
2. The generation of $CaCO_3$ increases the cement compressive strength. The increase in temperature leads to a faster rate of calcium ion loss, leading to a decrease in the cement mechanical properties.
3. The radial stress, debonding aperture and PEEQ of cement sheath increases with the corrosion time.
4. Mix 20 (Cement formulations with added latex) has better anti-corrosion effect.
5. The greater of the cement initial stress and the smaller of volume shrinkage, the lower risk of interfacial debonding.

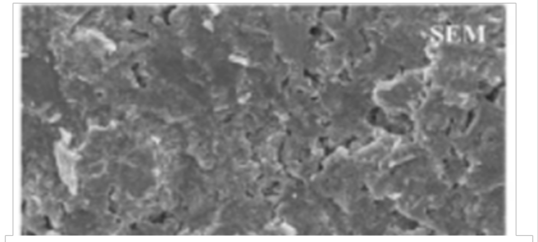
5. Summary and Suggestions

Prediction + **Prevention** + **Monitoring** + **Remedial**

Casing corrosion

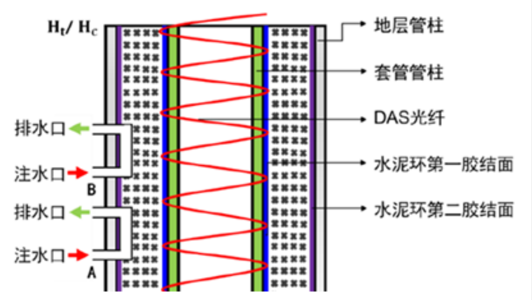
Cement corrosion

Rock corrosion

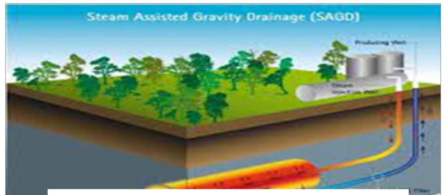


Anti-corrosion cement

Anti-corrosion casing

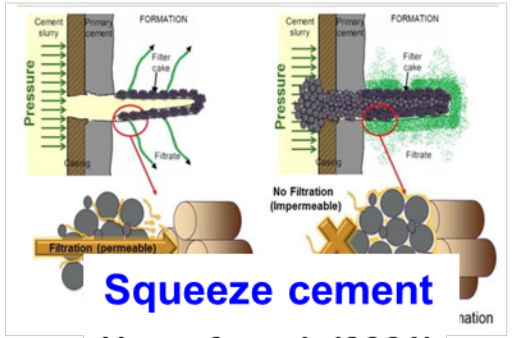


DAS monitoring



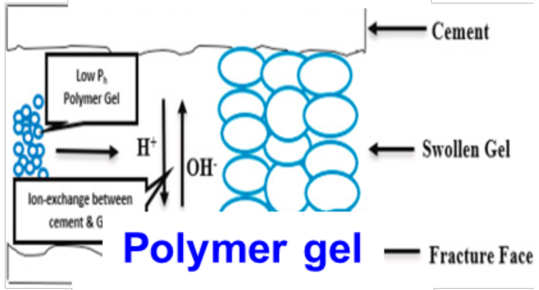
DTS monitoring

Mawalkar, et al. (2019)



Squeeze cement

Yousuf, et al. (2021)



Polymer gel

Yousuf, et al. (2021)

Thank You / Questions

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