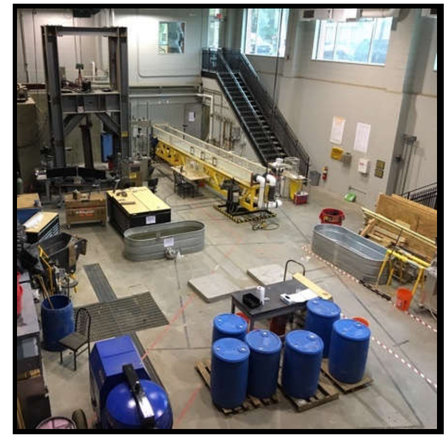
ADVANCED REINFORCED CONCRETE MATERIALS FOR TRANSPORTATION INFRASTRUCTURE



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matslab
materials and structures laboratory at NJIT
NJIT

DEPARTMENT OF TRANSPORTATION
THE STATE OF NEW JERSEY

About Us

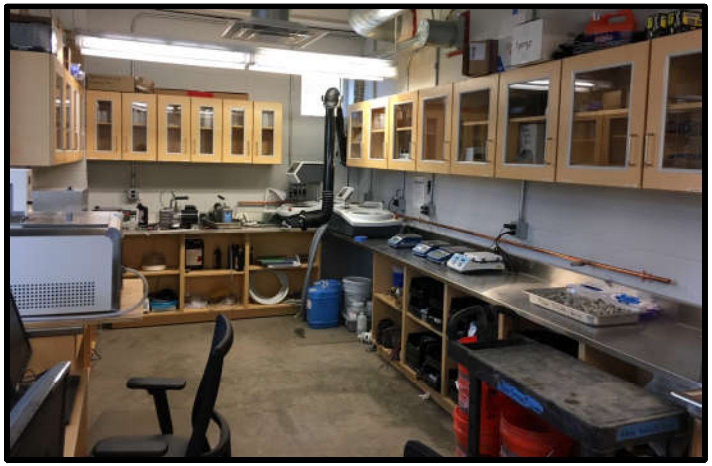
Matthew P. Adams, Ph.D., F.ACI

- Ph.D., Oregon State University
- Chemical and mechanical characterization of infrastructure materials
- Accelerated laboratory and field testing of infrastructure materials

Matthew J. Bandelt, Ph.D., P.E.

- Ph.D., Stanford University
- Experimental behavior and design of structural connections and components with innovative construction materials
- Computational modeling and testing of emerging materials

Materials and Structures Laboratory (MatSLab)



Materials and Structures Laboratory (MatSLab)

- Experimental testing facilities are used for testing material durability and basic mechanical properties

- Equipment includes:
    - 700 kip compression testing machine
    - 55 kip tensile testing machine
    - Pore-solution extractor
    - 3 high temperature ovens
    - Sieve shaker
    - Dry-curing and moist curing rooms
    - 6 ft^3 rotary drum mixer
    - 9 ft^3 high shear planetary mixer
    - Automatic cylinder end grinder
    - Freeze/Thaw Cabinet
    - Corrosion testing Equipment

MATERIALS AND STRUCTURES LABORATORY (MATSLAB)

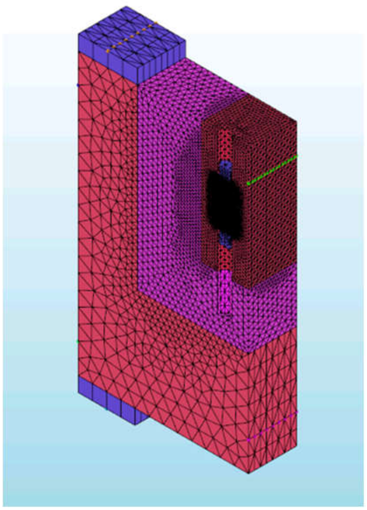
- Experimental testing facilities are used for measuring the chemical composition and performance of cement based materials
- Equipment includes:
  - Mounting and polishing equipment for advanced microscopic analysis
  - Sample preparation for ICP-OES
  - Sample preparation for XRD

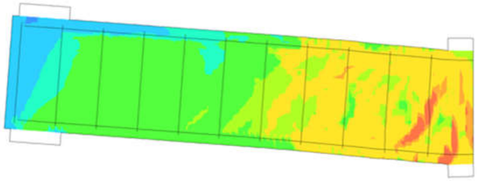
MATERIALS AND STRUCTURES LABORATORY (MATSLAB)

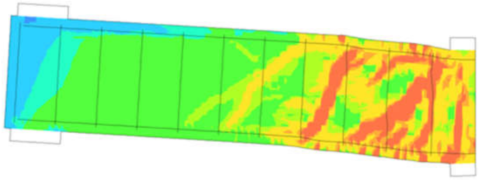
- Experimental testing facilities are used for testing structural components to various loading conditions

- Equipment includes:
  - Three servo-hydraulic actuators capable of fatigue testing at 200, 100, and 55 kip capacities
  - 16 channel high speed data acquisition system capable of recording at 1000hz
  - 3000 ft^2 high bay space for fabricating elements

Materials and Structures Laboratory (MatSLab)







- Computational workstation facility used to validate experimental findings and perform parametric studies

- Capabilities include:
  - Deterioration modeling
  - Structural simulation
  - Young hardening concrete analysis
  - Soil/structure interaction

OUTLINE

- Motivation and background information
- Experimental Program
- Results of the Study
- Numerical Framework
- Conclusions and future work

Motivation and Background Information

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materials and structures
laboratory at NJIT

NJIT

Durability Issues

Corrosion

ethz.ch

Shrinkage

theconstructor.org

Salt Scaling

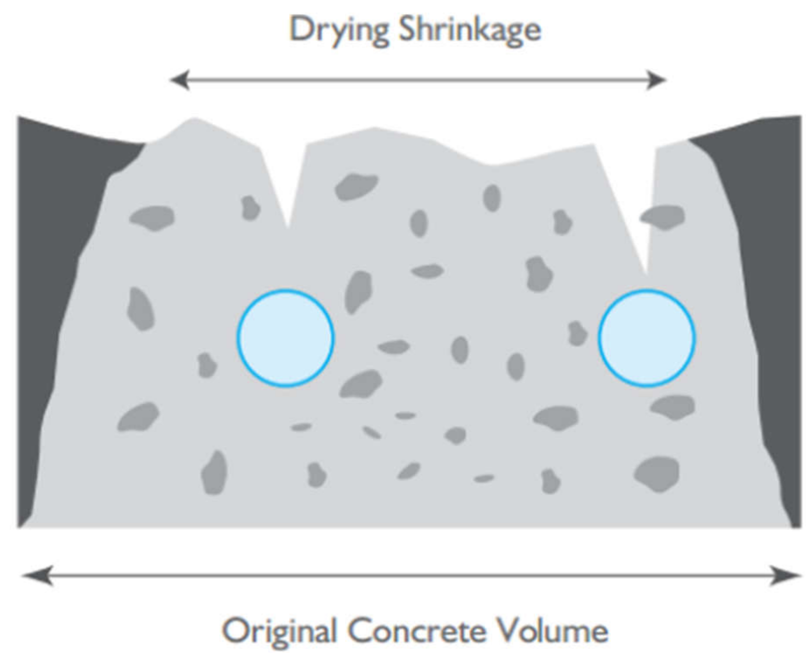
u-cart.ca

Freeze-Thaw

publish.illinois.edu

Deterioration Mechanisms

Drying shrinkage happens due to moisture loss and moving water to empty capillaries and out of concrete



www.giatecscientific.com

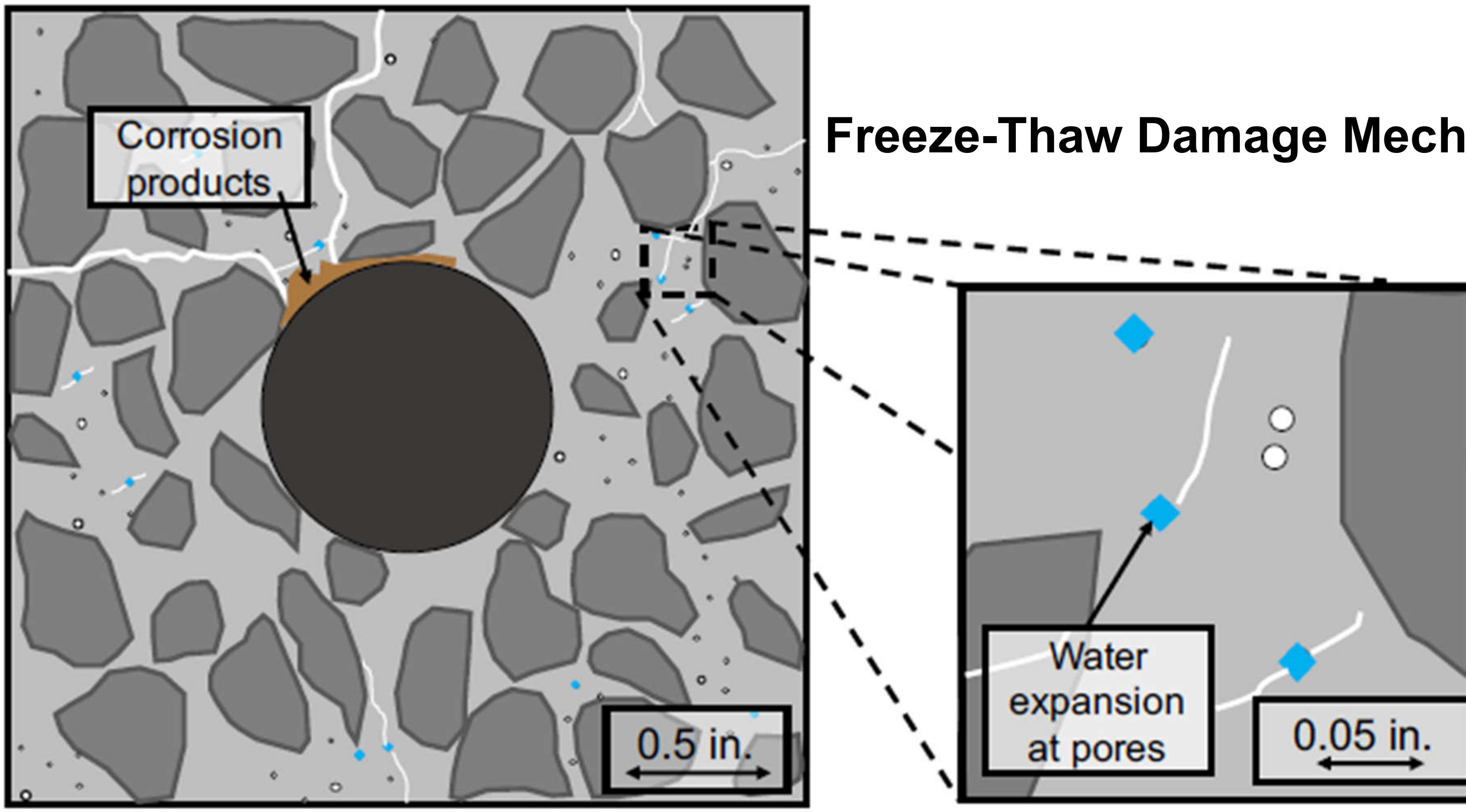
Salt scaling mechanism:

- Deicing salts increase number of freeze-thaw cycles and osmotic pressure that occur during freezing
- Salt attracts water and more water to freeze
- Salt cause top layer to thaw and creates localized temperature differential and impose stress to top layer

Deterioration Mechanisms

Corrosion Damage Mechanism

Freeze-Thaw Damage Mechanism

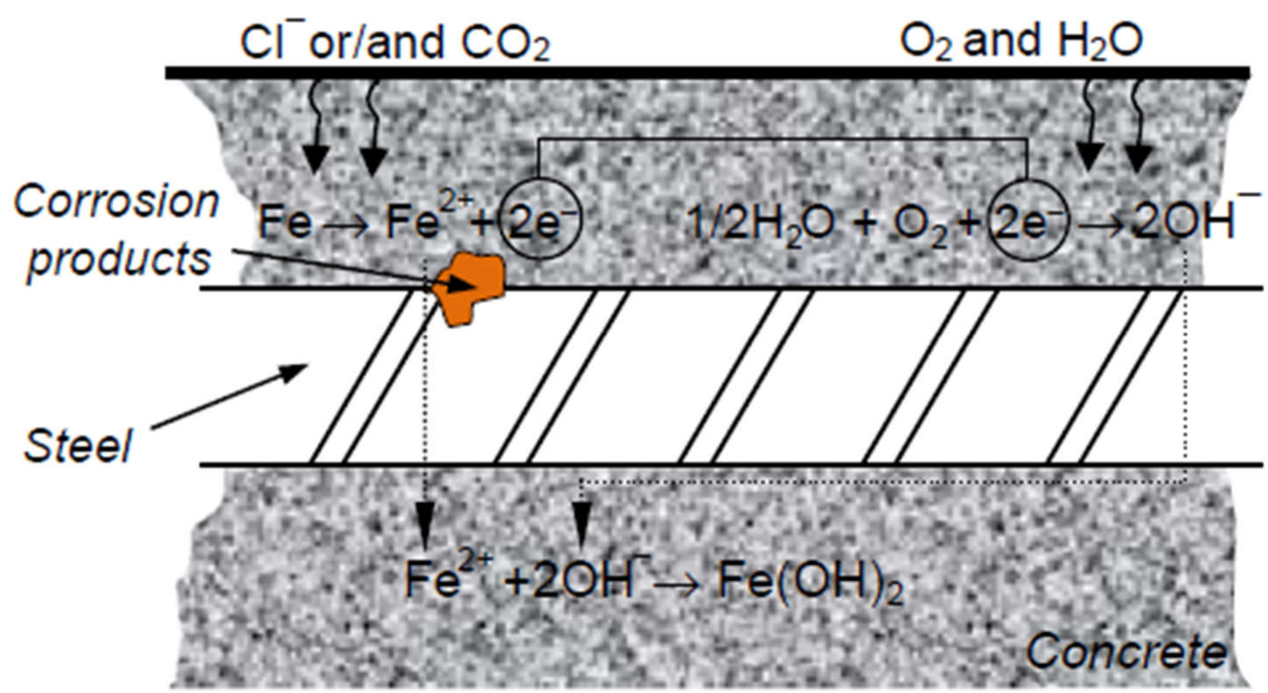


What Happens in Corrosion

$$Anodic\ Reaction: 2Fe \rightarrow 2Fe^{2+} + 4e^-$$

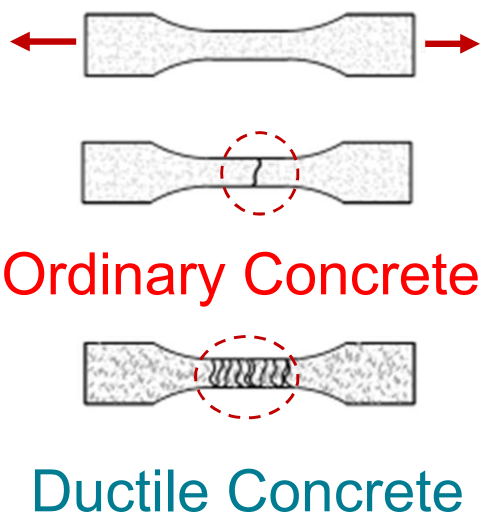
$$Cathodic\ Reaction: O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

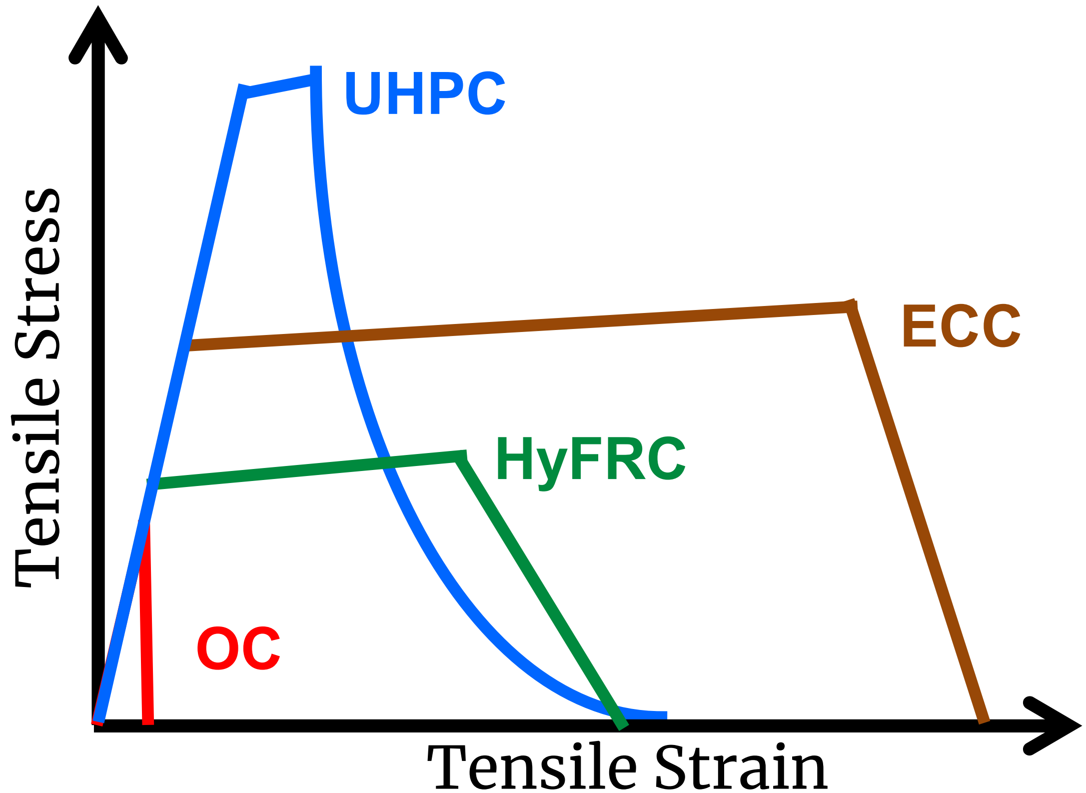
$$Total\ Reaction: 2Fe + 2H_2O + O_2 \rightarrow 2Fe(OH)_2$$



Ahmed, 2003

Ductile Concrete Mechanical Behavior





UHPC – f'_c = 20,000 psi; f_t = 1,100 psi; ε_{tp} = 0.2%

ECC – f'_c = 8,000 psi; f_t = 400 psi; ε_{tp} = 1%

HyFRC – f'_c = 6,500 psi; f_t = 275 psi; ε_{tp} = 0.3%

Generally **do not spall** and retain **residual strength** in compression

MICROCRACKING BEHAVIOR IN DUCTILE CONCRETE SYSTEMS

Li, 2003

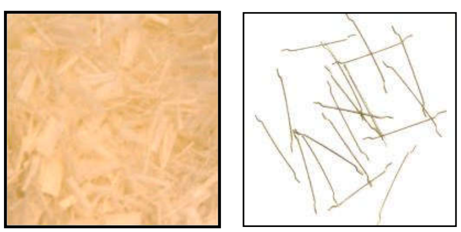
Ductile Concrete Materials

Binder
(Cement, Fly Ash, Silica Fume, Glass Quartz)

Fine Aggregate
(Sand)

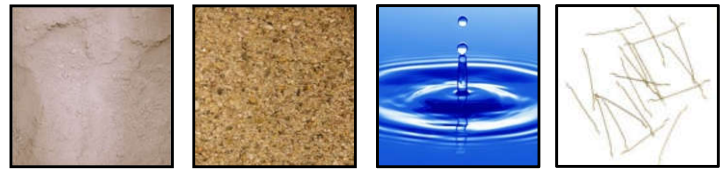
Water and Admixtures

Coarse Aggregate
(Crushed Stone)

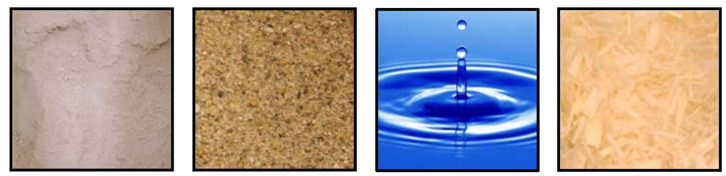


Fibers
(Polymeric, steel)

UHPC - Ultra high performance concrete



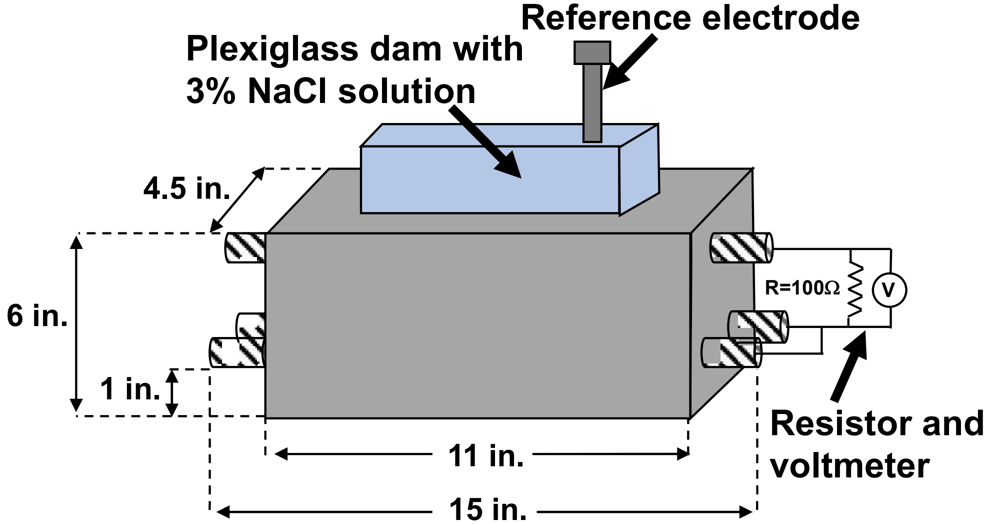
ECC - Engineered cementitious composite



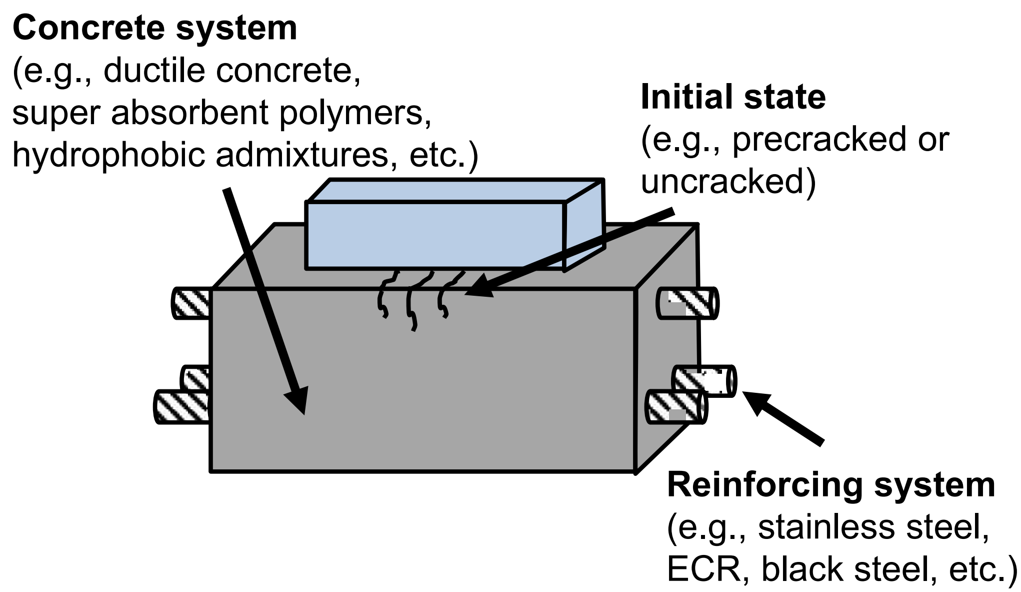
HyFRC - Hybrid fiber-reinforced concrete

Project Scope

Durability testing example – corrosion benchmarking



ASTM G109 Corrosion Testing Experimental Setup



Test Parameters to Investigate and Compare Perfromance

Other areas of interest:

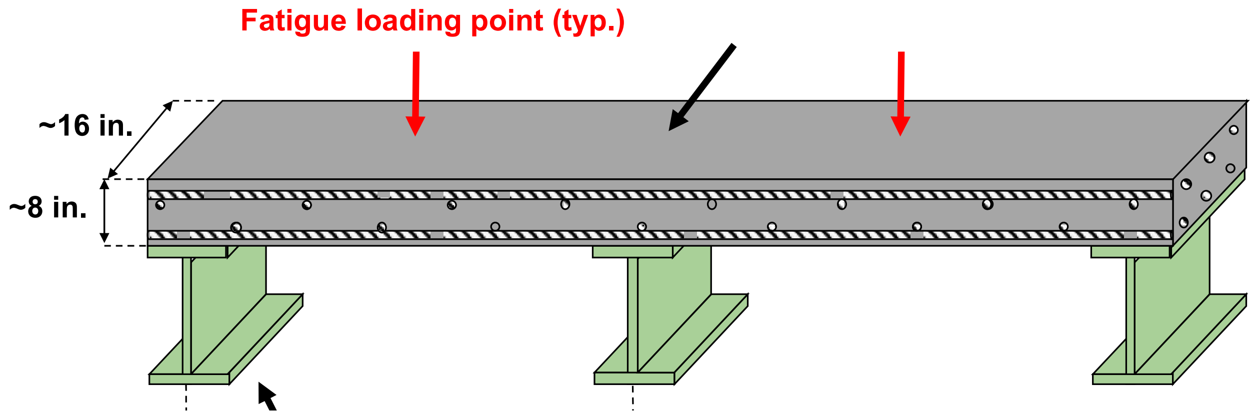
Carbonation → Freeze-thaw → Abrasion → Shrinkage

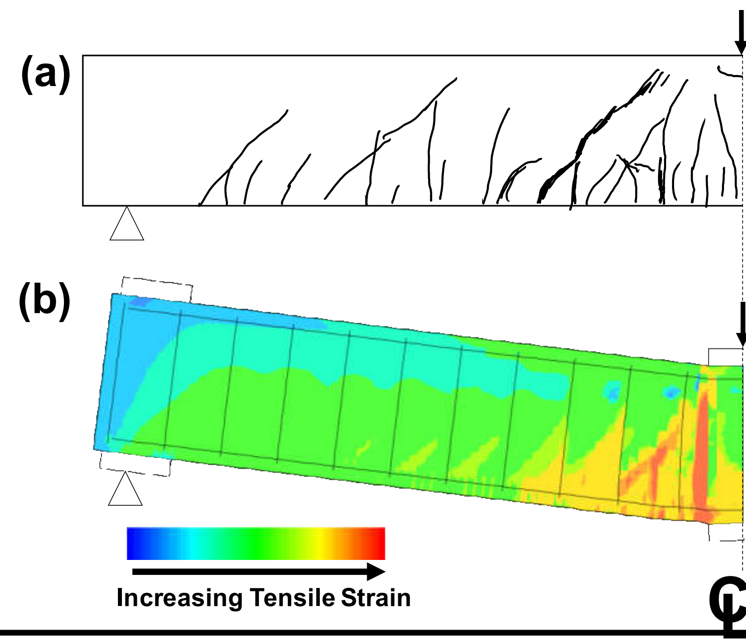
Project Scope

Other areas of interest:

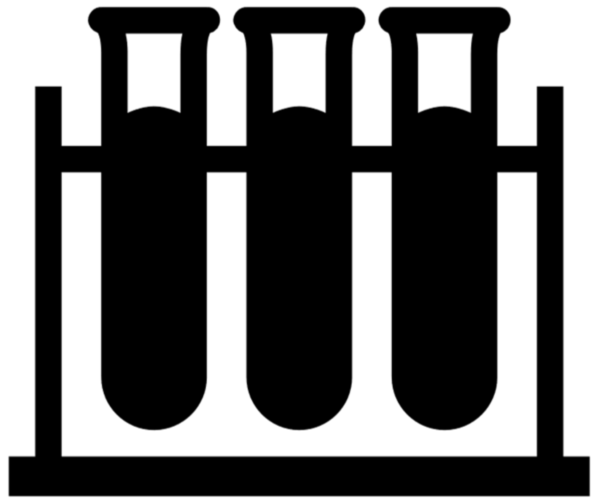
Brick decks and overlay systems

Predictions of response using numerical simulation





EXPERIMENTAL PROGRAM



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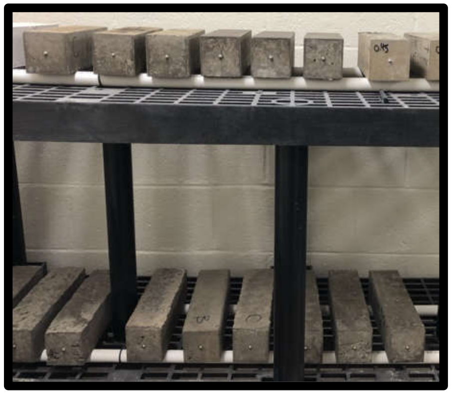
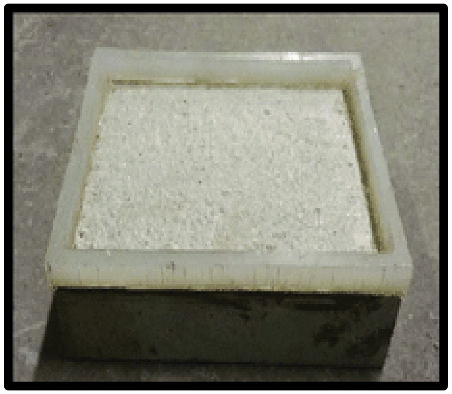
Durability of Ductile Concrete Systems



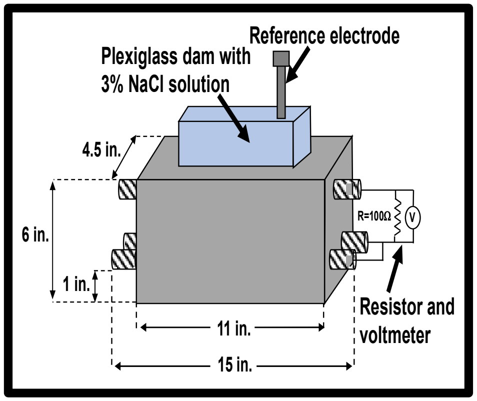
Drying shrinkage (ASTM C157)

Freezing and thawing (ASTM C666)

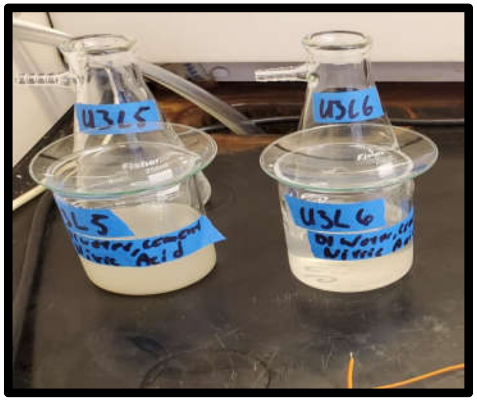


Salt scaling (ASTM C672)

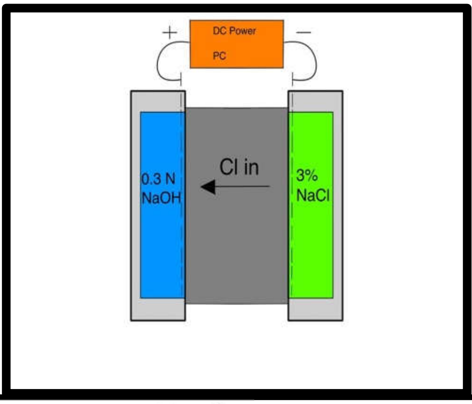
Comparative Study of the Chloride Permeability and Corrosion Performance of Ductile Concrete Systems



Accelerated corrosion (ASTM G109)



Chloride profiling and coefficient of chloride diffusion (ASTM C 1152)



Rapid chloride penetration test (ASTM C1202)

Concrete Materials

- Two ordinary concrete systems
  - Self consolidating concrete (SCC P)
  - High performance concrete (HCP)

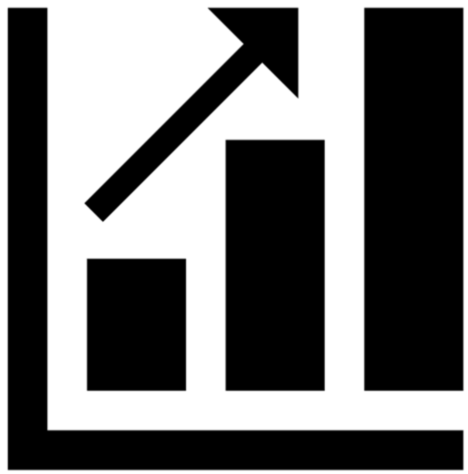
- Three ductile concrete systems
  - ECC
  - HyFRC
  - UHPC

Reinforcement Materials (G109 only)

- Five types of reinforcement
  - Black
  - Epoxy Coated
  - Galvanized
  - ChromX
  - Stainless Steel

- Additional set with pre-damaged reinforcement
  - Epoxy coated

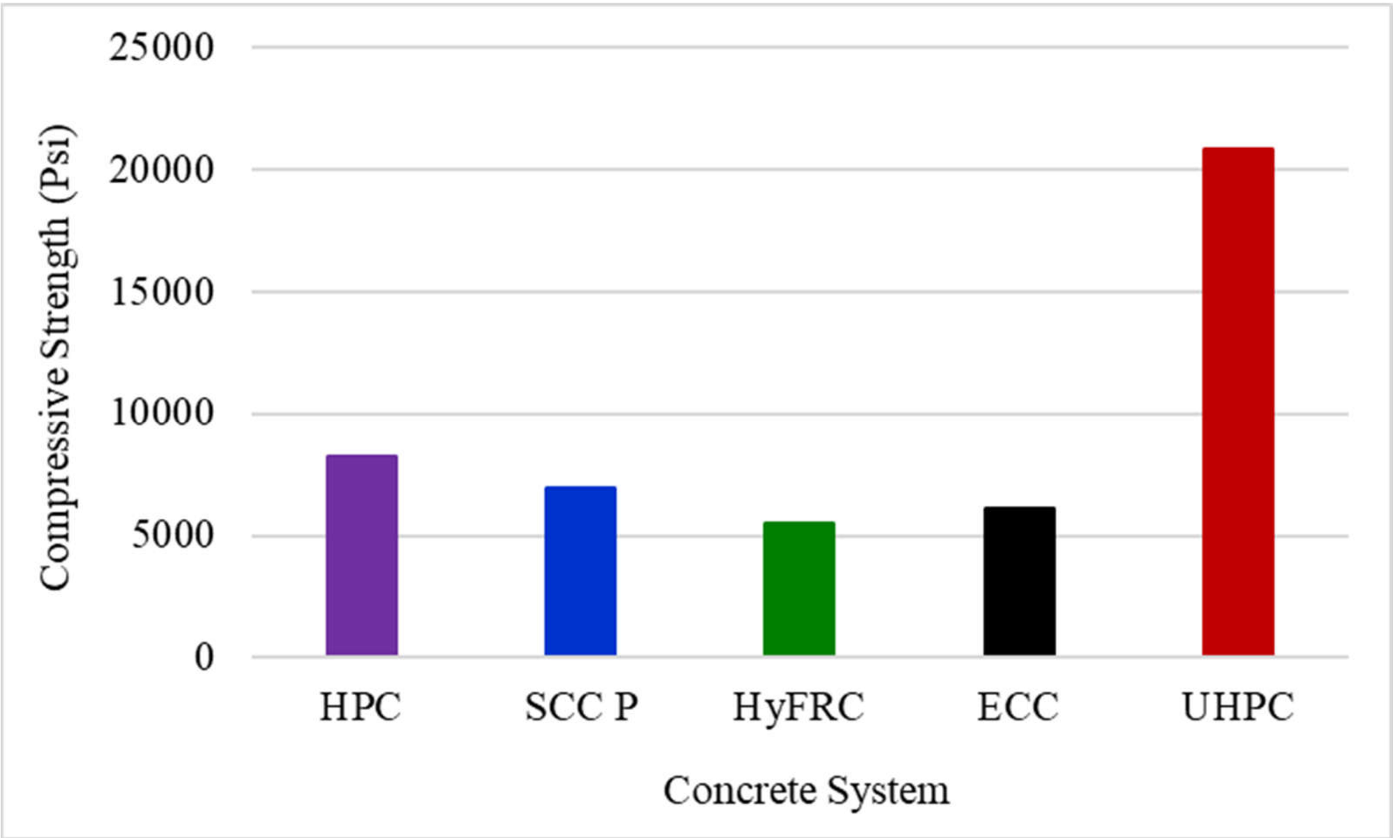
Results



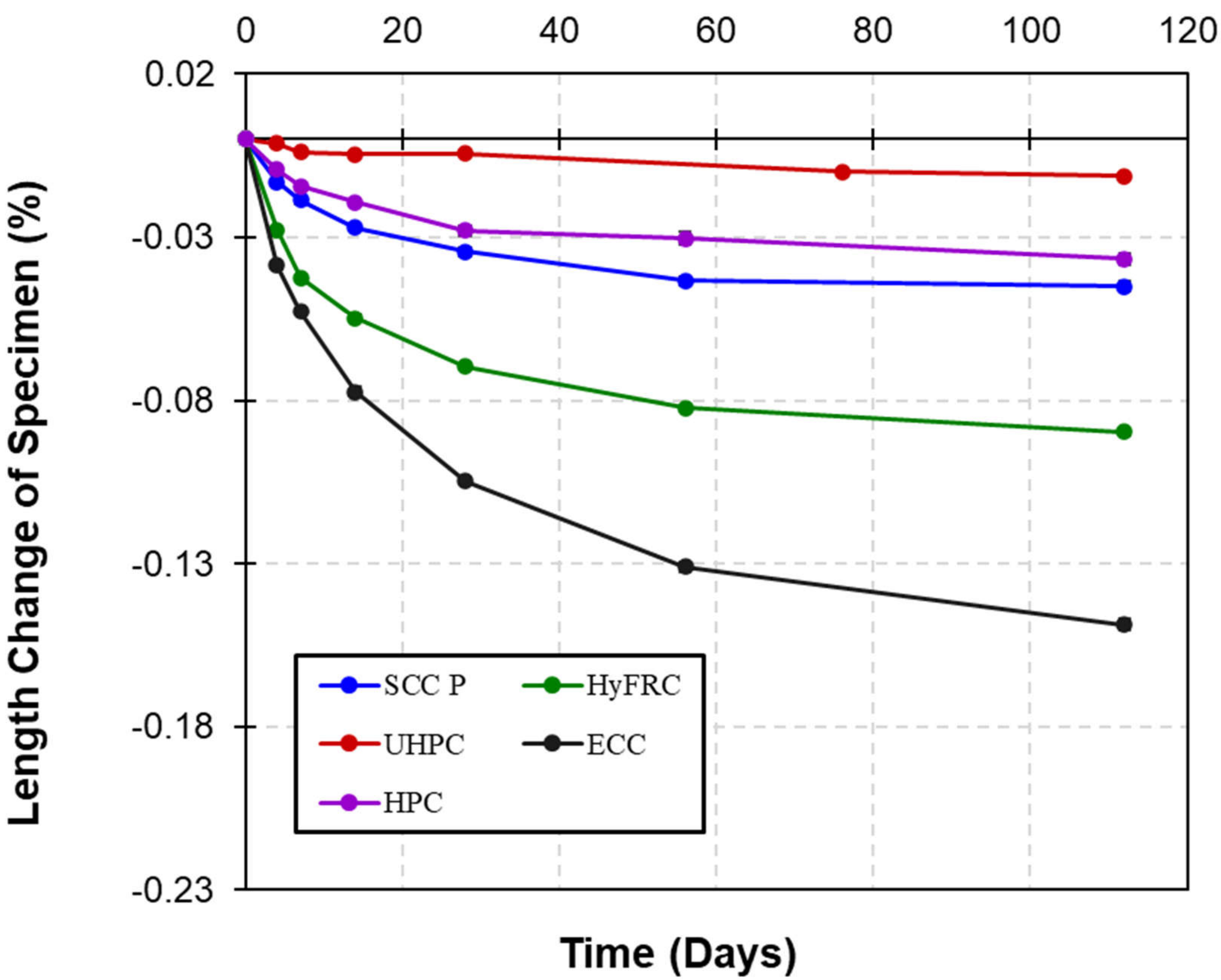
Fresh and Hardened Properties

Concrete Type	Slump/Flow (in)
HPC	3.5
SCC P	20.5
HyFRC	21
ECC	7.5
UHPC	8.5

Concrete Type	Air Content (%)
HPC	3.5
SCC P	4
HyFRC	7.5
ECC	5
UHPC	5



DRYING SHRINKAGE



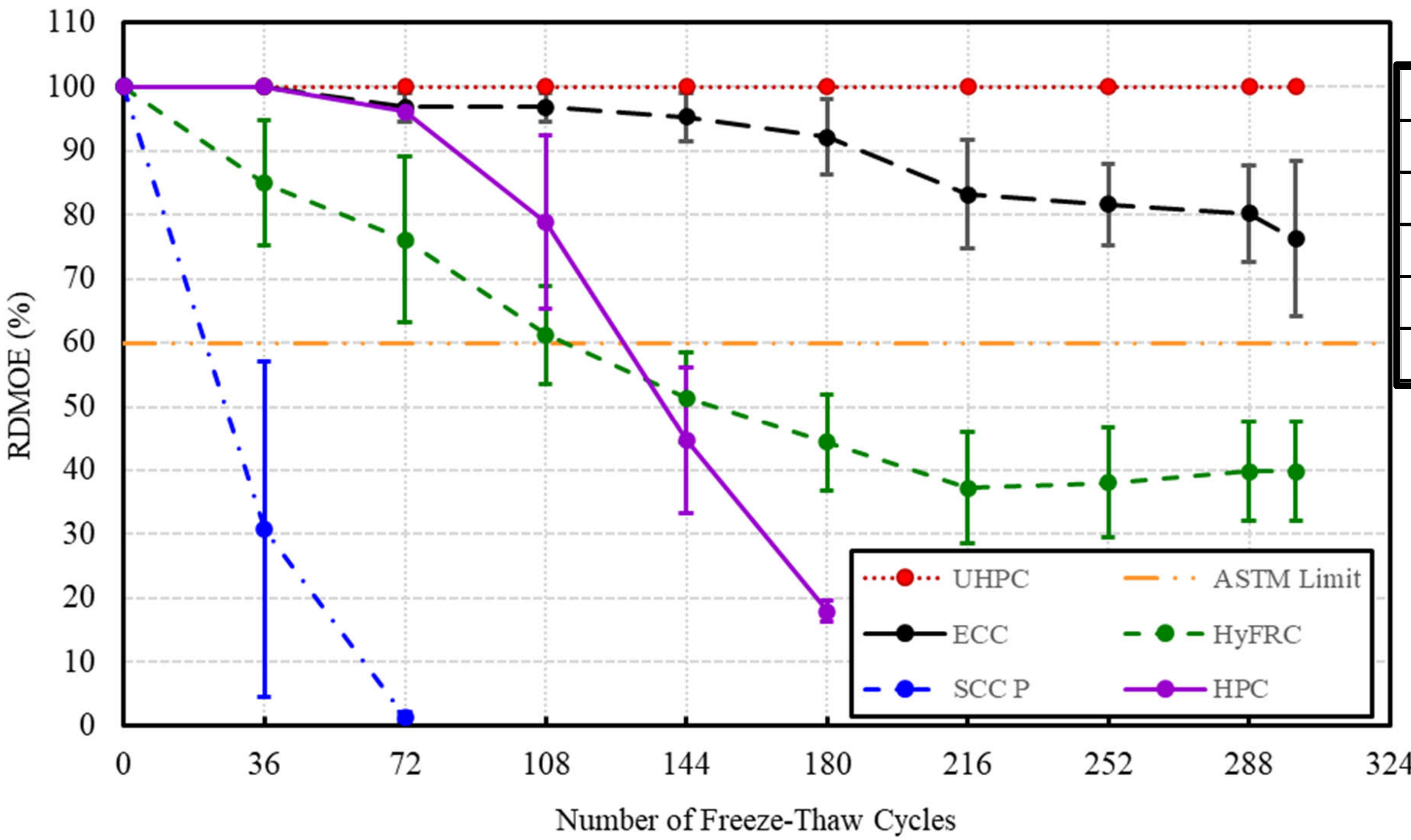
Drying Shrinkage

- Ductile concrete systems tend to have higher shrinkage
  - Higher cement contents
  - ASTM C157 does not necessarily measure cracking propensity

- UHPC has lowest drying shrinkage
  - Test does not capture autogenous shrinkage, which is typically a bigger issue for UHPC

FREEZE-THAW

- Relative Modulus of Elasticity Results



Concrete Type	Air Content (%)
HPC	3.5
SCC P	4
HyFRC	7.5
ECC	5
UHPC	5

Specimens at the End of the Test

HPC

SCC P

HyFRC

ECC

UHPC

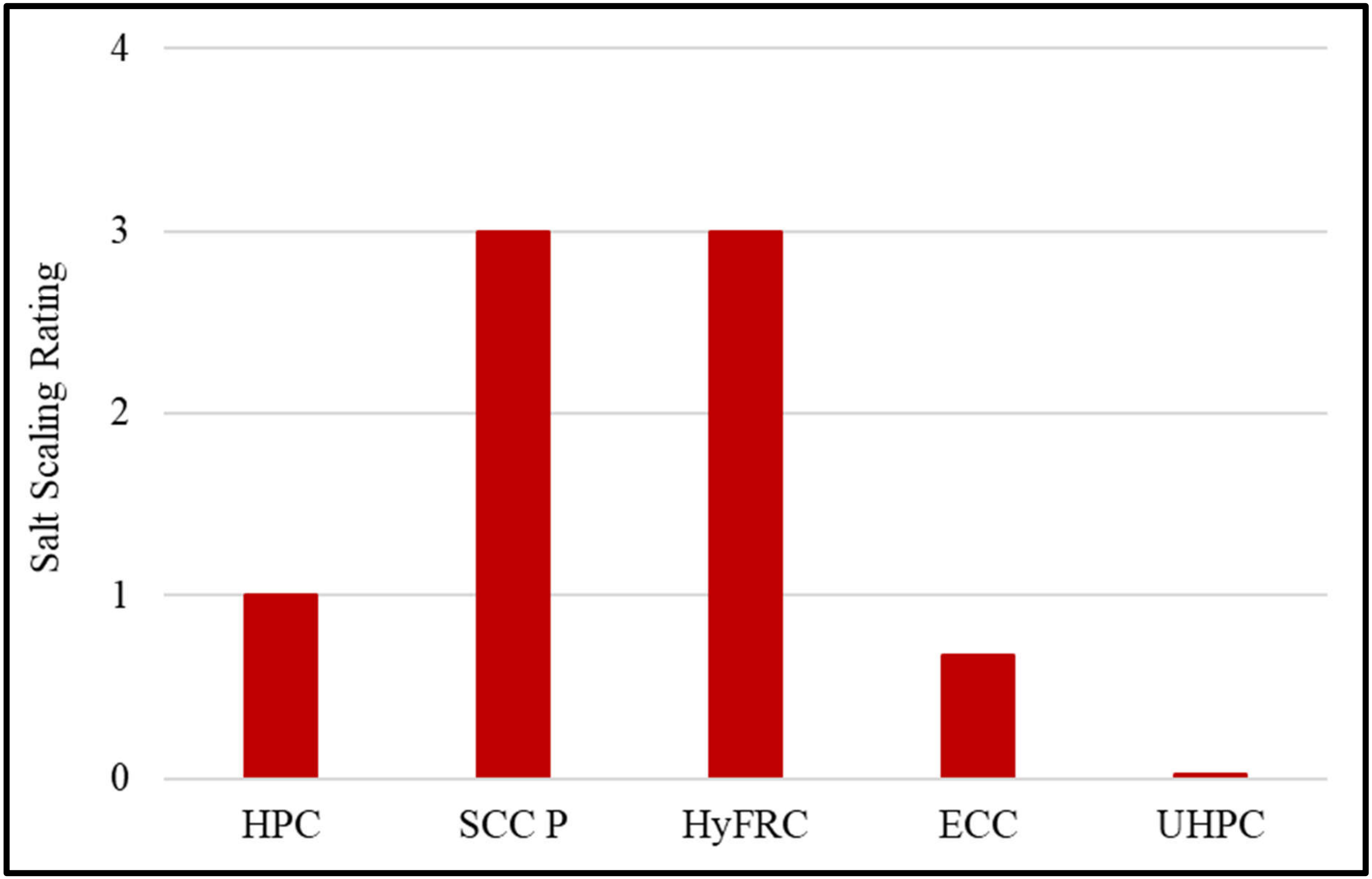
Freeze Thaw

Concrete Type	HPC	SCC P	HyFRC	ECC	UHPC
Durability Factor	25.1	3.7	21.3	76.3	100

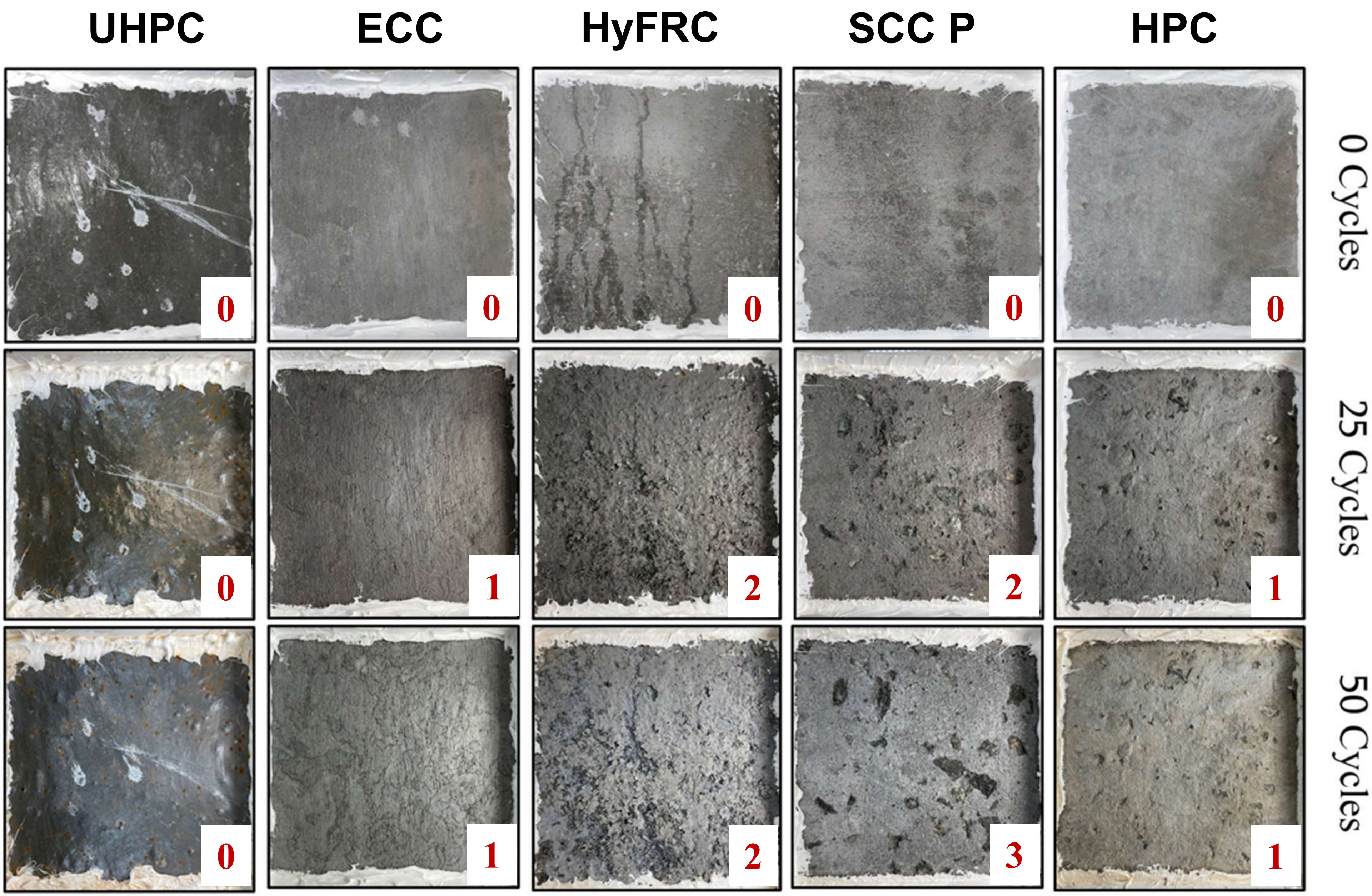
- Ordinary concrete was difficult to air entrain
- HyFRC performed poorly despite adequare air entraining
- ECC and UHPC met requirements

SALT SCALING

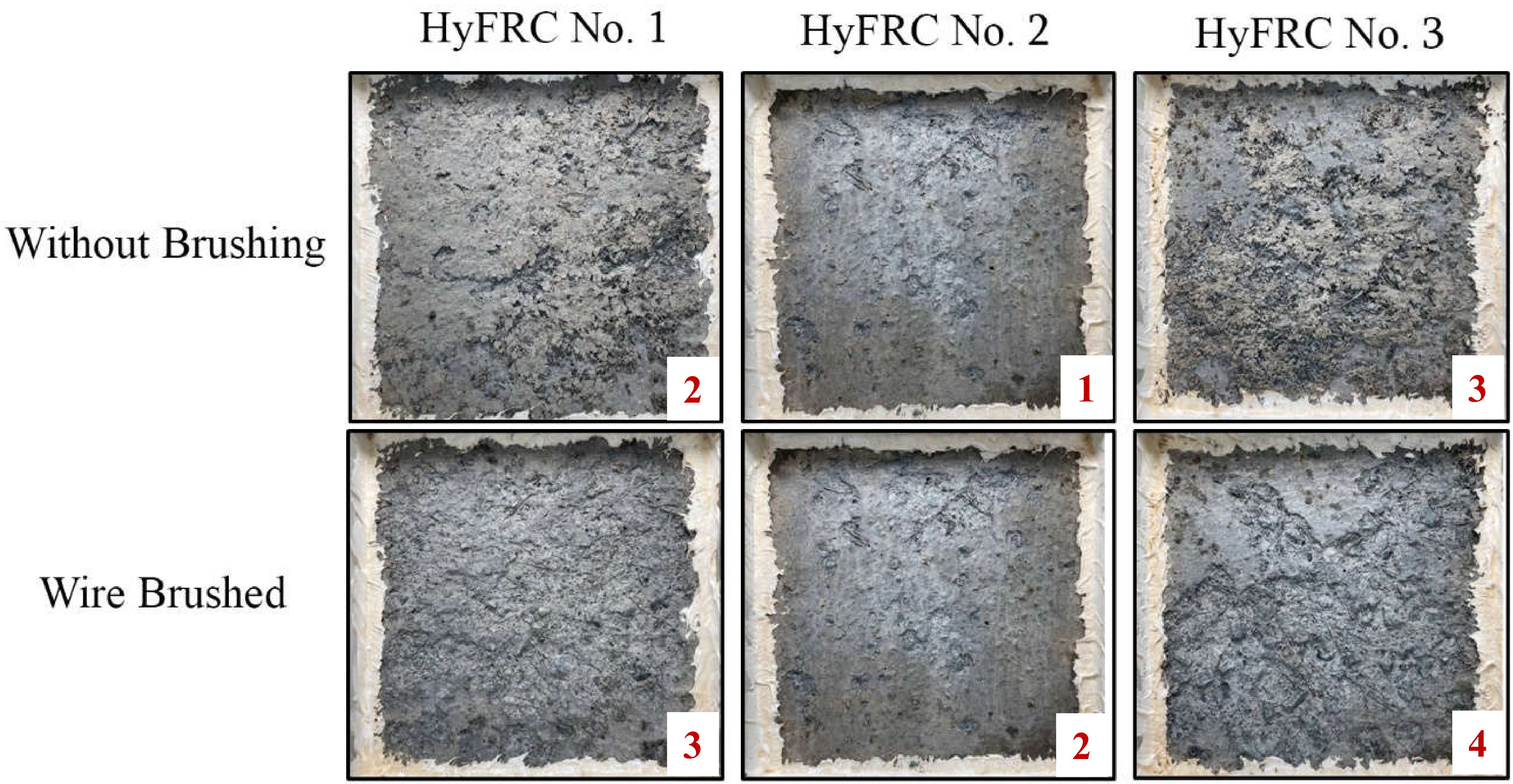
AVERAGE SALT SCALING RATING



SPECIMENS AFTER 50 CYCLES



Effect of Wire Brushing



SCALING DAMAGE ON ECC

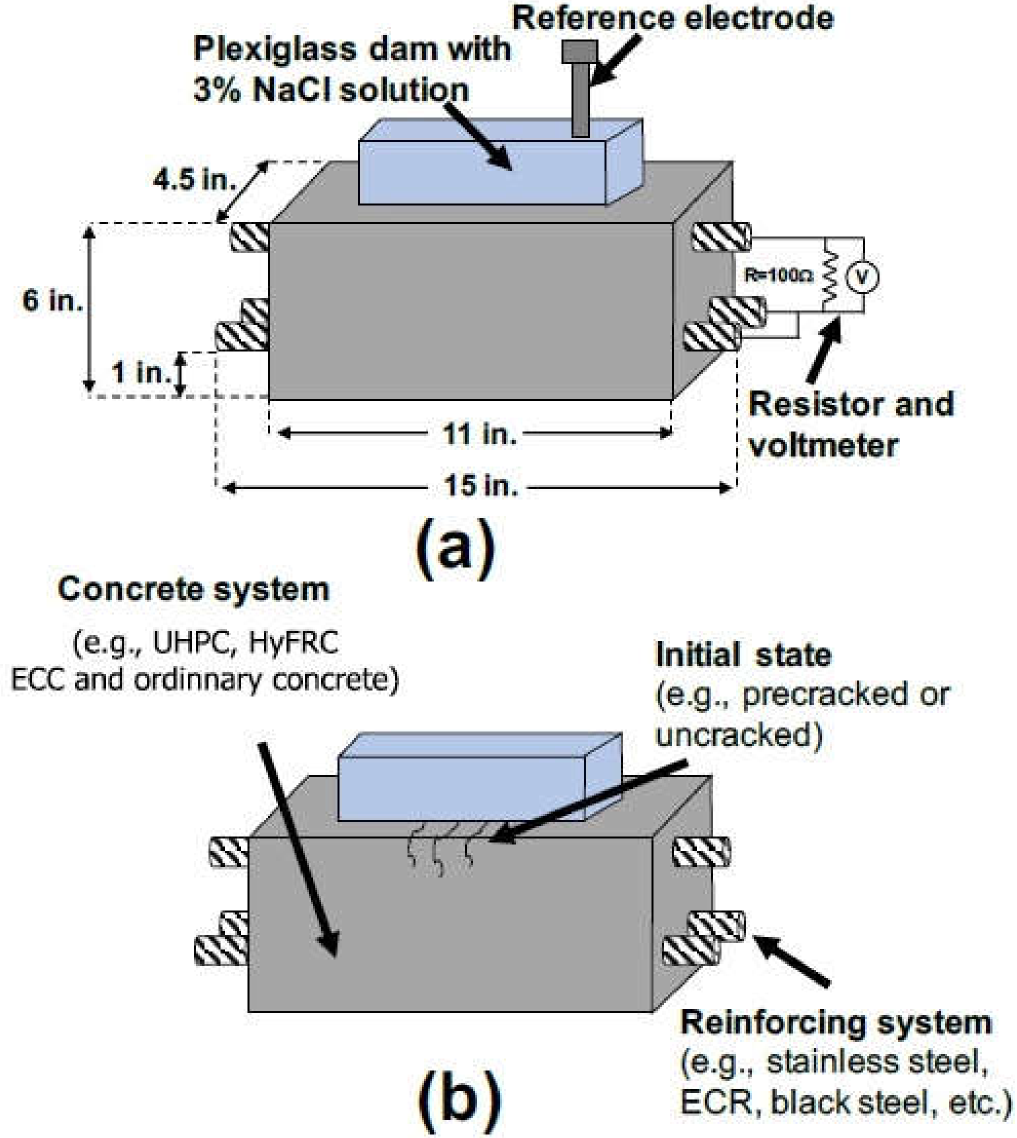
- A different type of damage was observed in ECC

Takeaways of Durability Testing of Ductile Concrete Systems

- UHPC had the best durability performance in ductile concrete systems
- Ductile concrete systems improve the durability of reinforced concrete systems
- Scaling tests need reconsideration for evaluation of ductile concrete systems in terms of surface finishing, evaluation method and rating criteria
- Corrosion testing is needed to investigate the improvements in corrosion performance of ductile concrete systems

ASTM G109 Corrosion Test Method

- Accelerated corrosion test
- Apply wetting and drying cycles every two weeks
- Measures corrosion current
- Modification: Applied preloading to develop pre-cracks



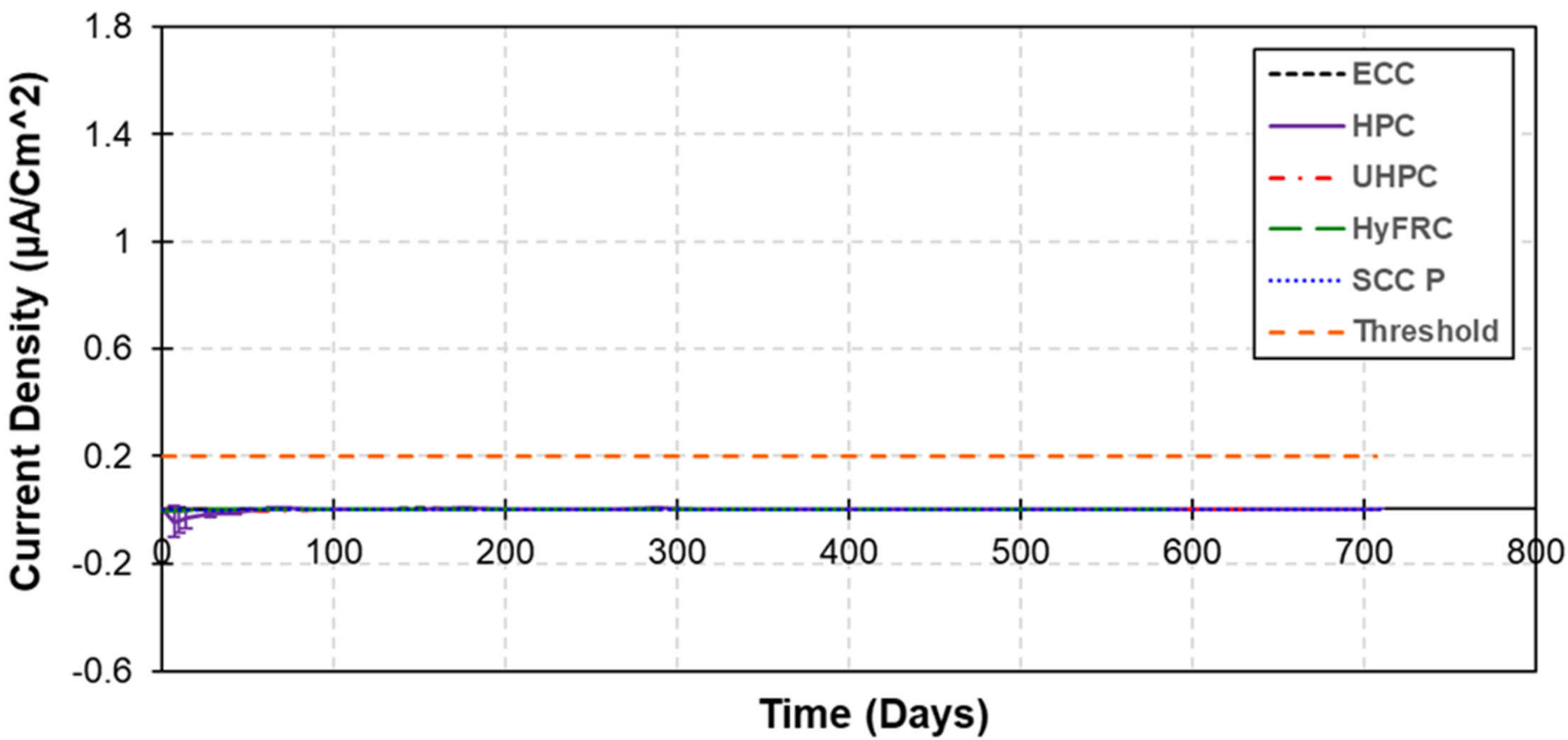
Corrosion Testing Plan

Concrete / *Rebar*	NJ DOT HPC	NJ DOT SCC P	UHPC	HyFRC	ECC
Black	✓✓	✓	✓✓	✓✓	✓✓
ECR	✓✓	✓	✓✓	✓✓	✓
ECR-Damaged	✓✓	✓	✓	✓	✓
ChromX	✓	✓	✓✓	✓✓	-
Galvanized	✓✓	✓	-	-	-
Stainless Steel	✓	✓	-	-	-

✓: Uncracked ✓: Cracked

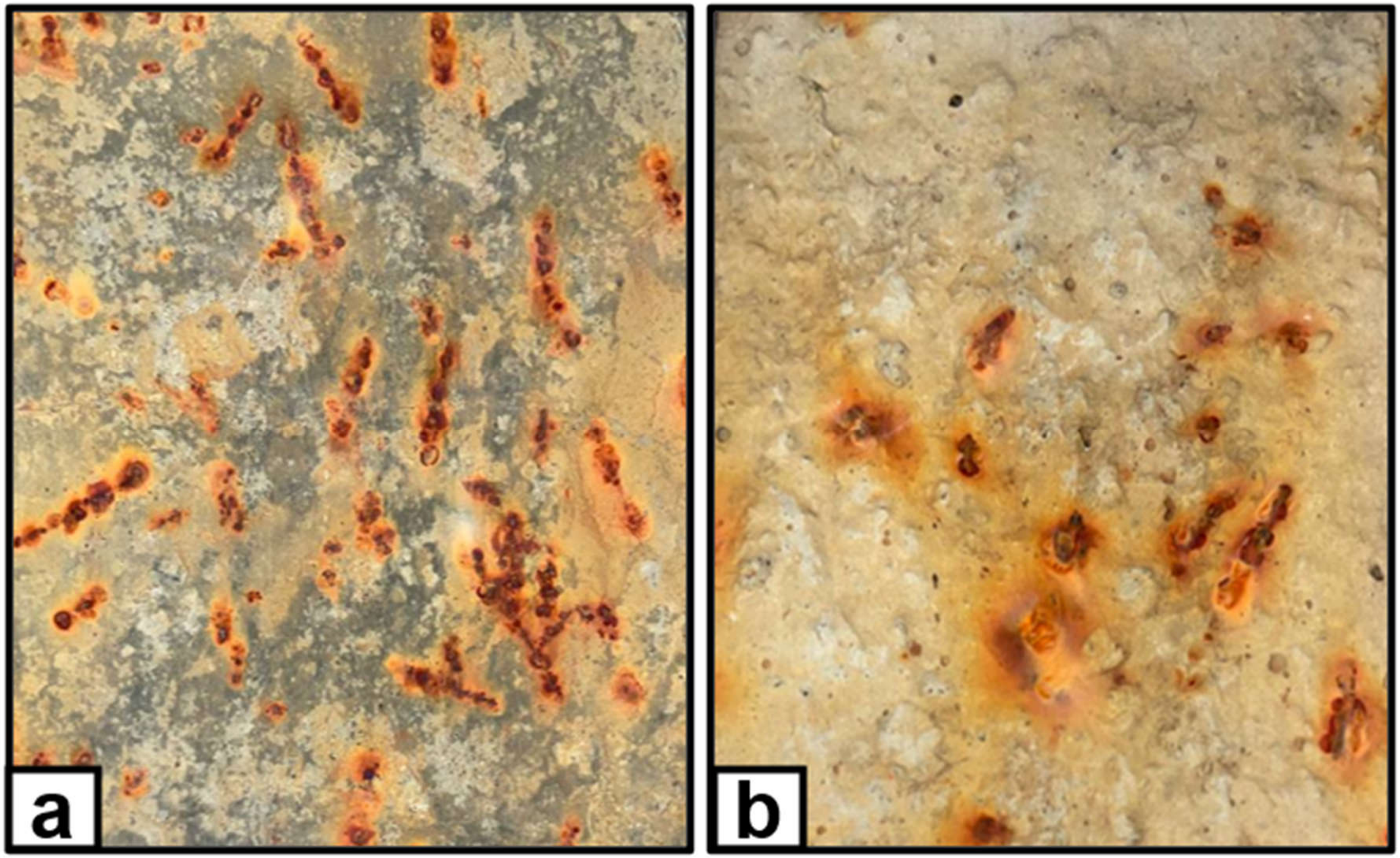
Corrosion Results of Uncracked Beams

- No corrosion was observed in uncracked specimens with ordinary black reinforcement



Corroded Fibers at the Surface

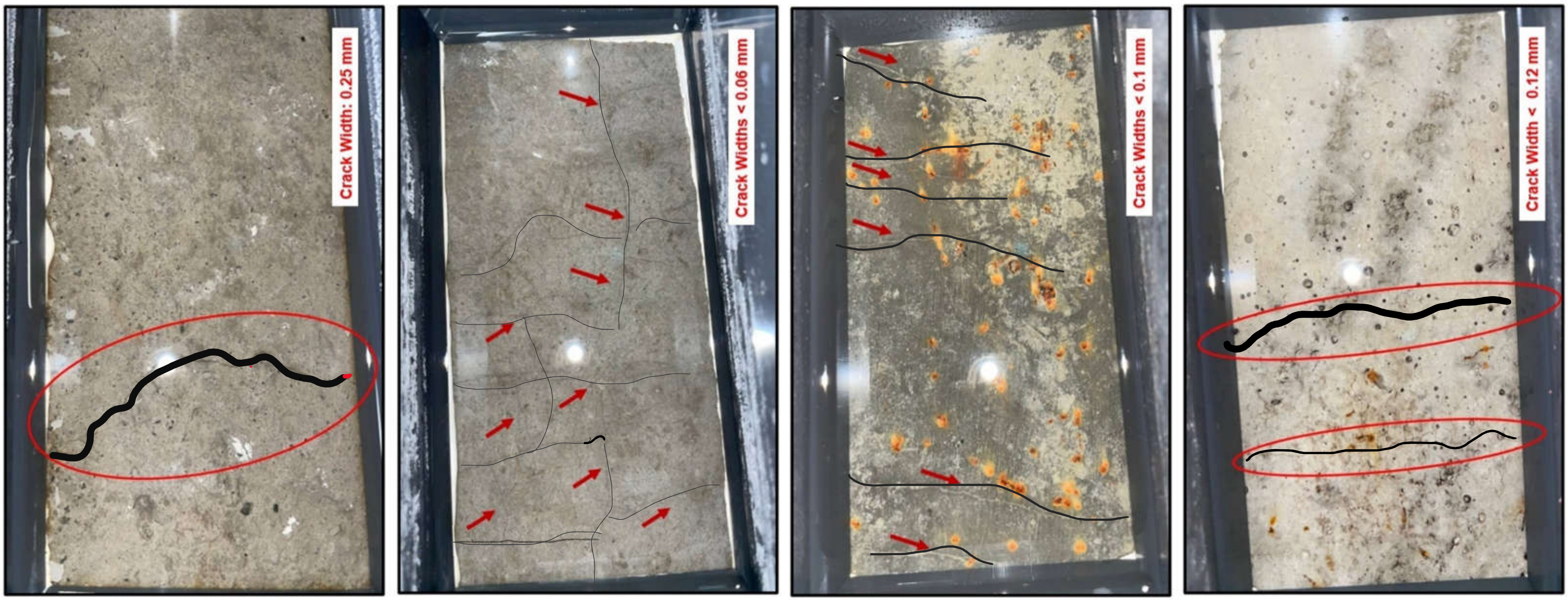
- Corroded Fibers have no negative effect on the corrosion performance of reinforcement



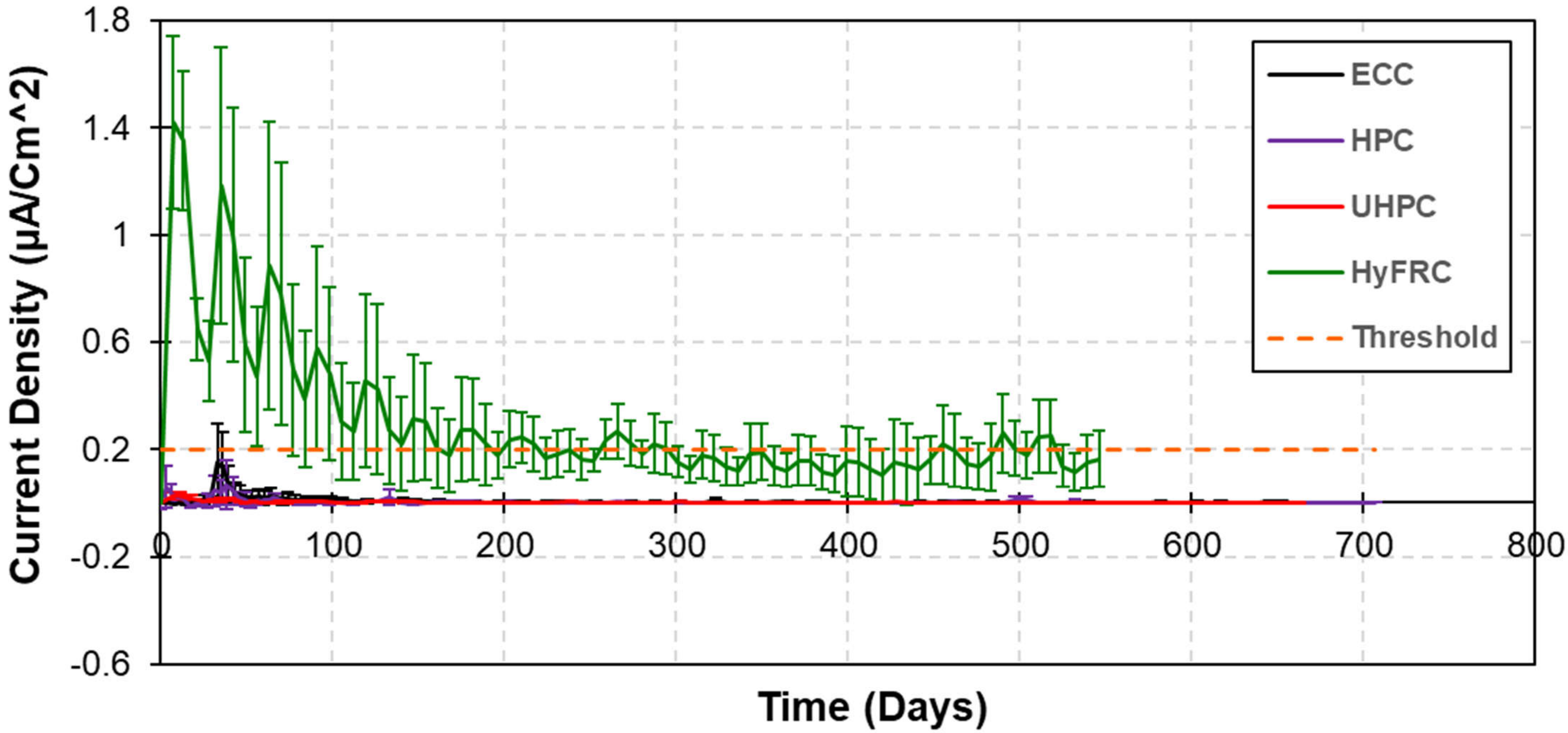
CRACKING BEHAVIOR OF CONCRETE SYSTEMS

- Multiple macrocracking behavior was observed in ductile systems compared to big crack in HPC

HPC **ECC** **UHPC** **HyFRC**

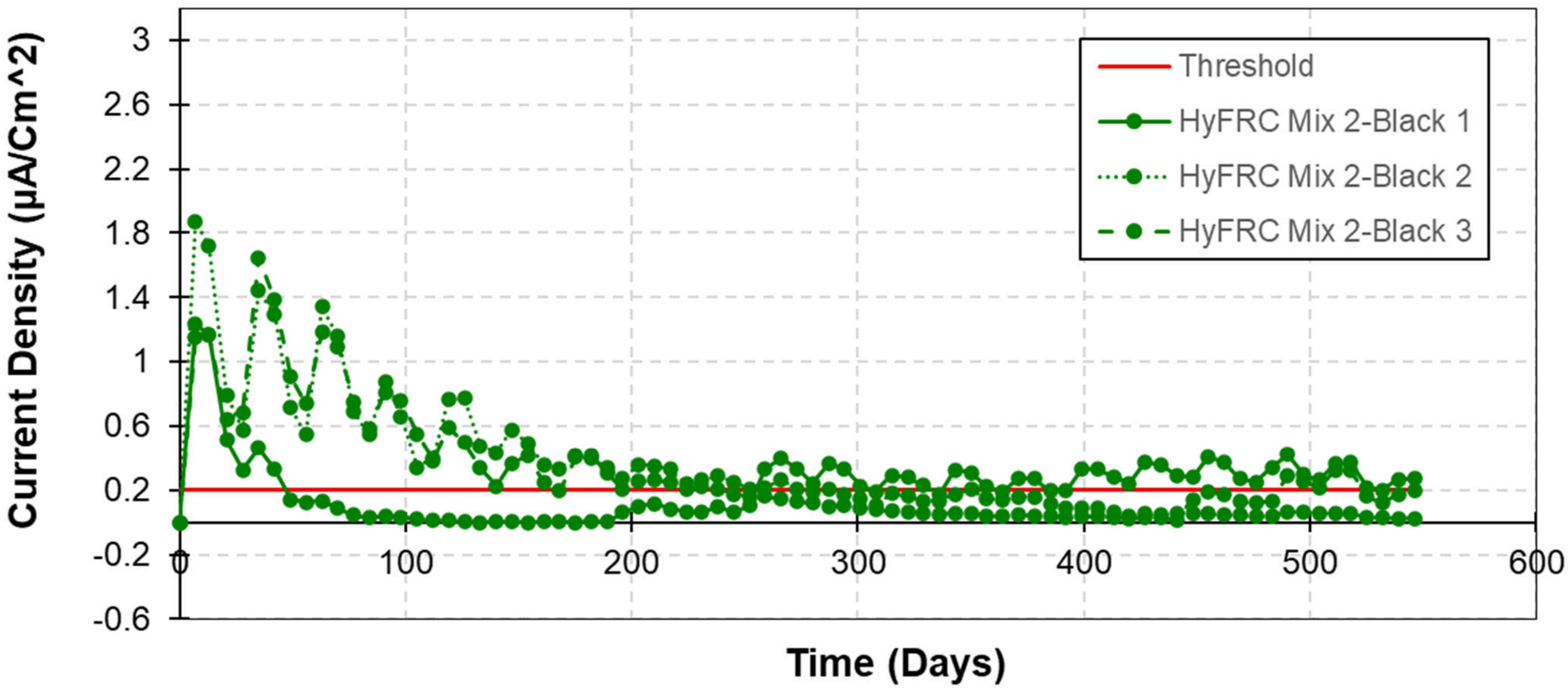


Corrosion Results of Cracked Beams



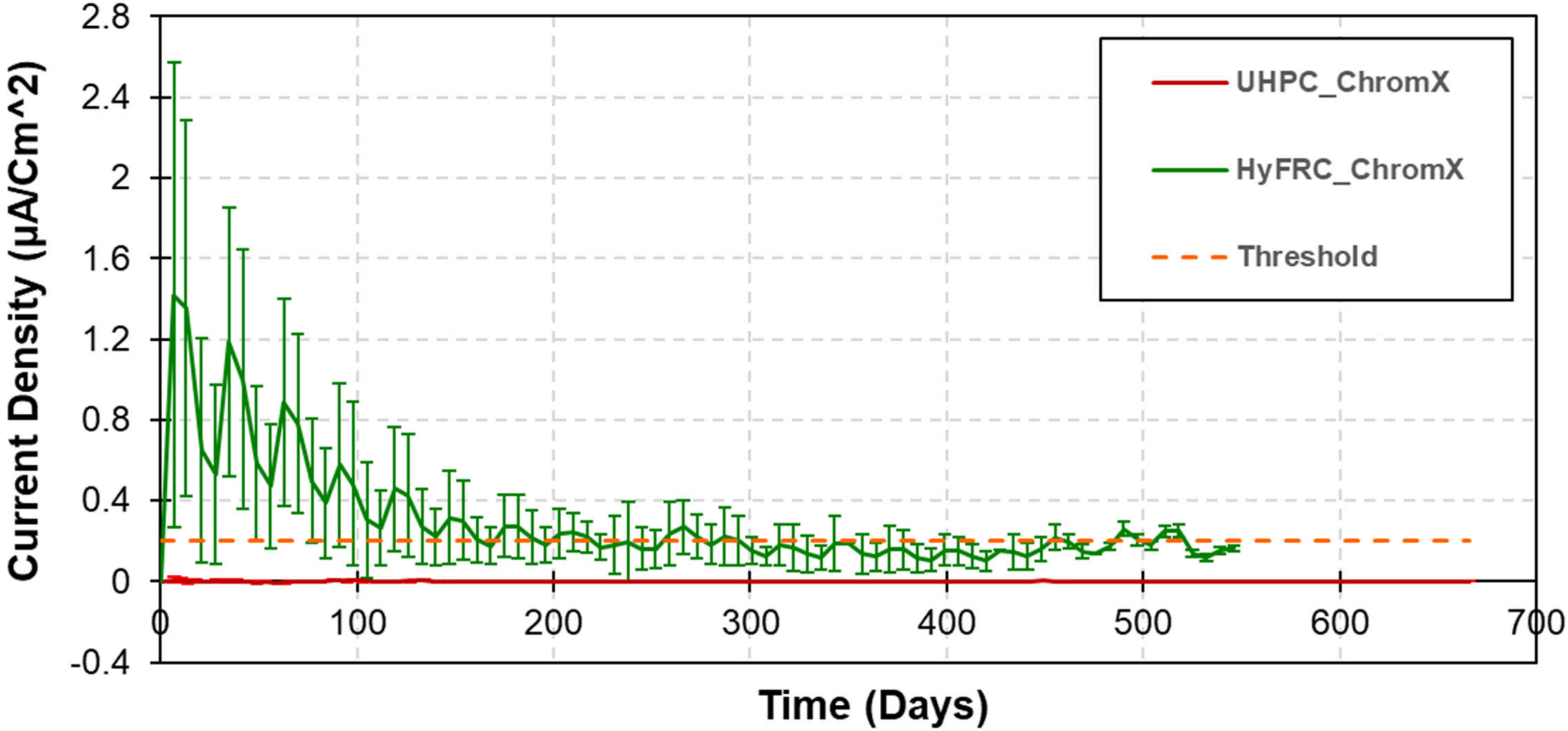
Corrosion in Cracked HyFRC

Specimen	Load (Kn)	Location 1	Crack Width (mm)	Location 2	Crack Width (mm)
HyFRC-Black-1	88	Center	0.1	Center	0.08
HyFRC-Black-2	88	Center	0.15	Center	0.2
HyFRC-Black-3	88	Center	0.2	Center	0.15



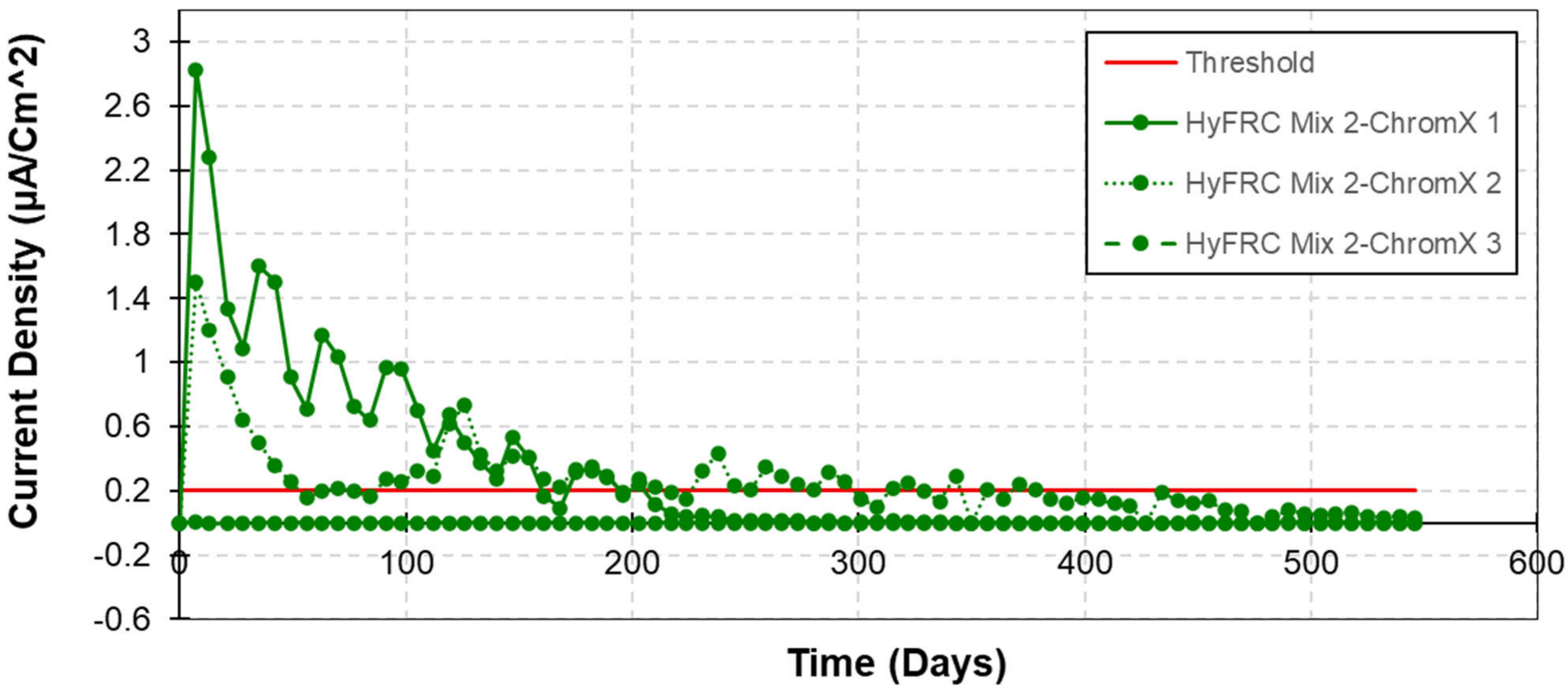
Corrosion in Alternative Reinforcement (ChromX)

- Cracked Beams



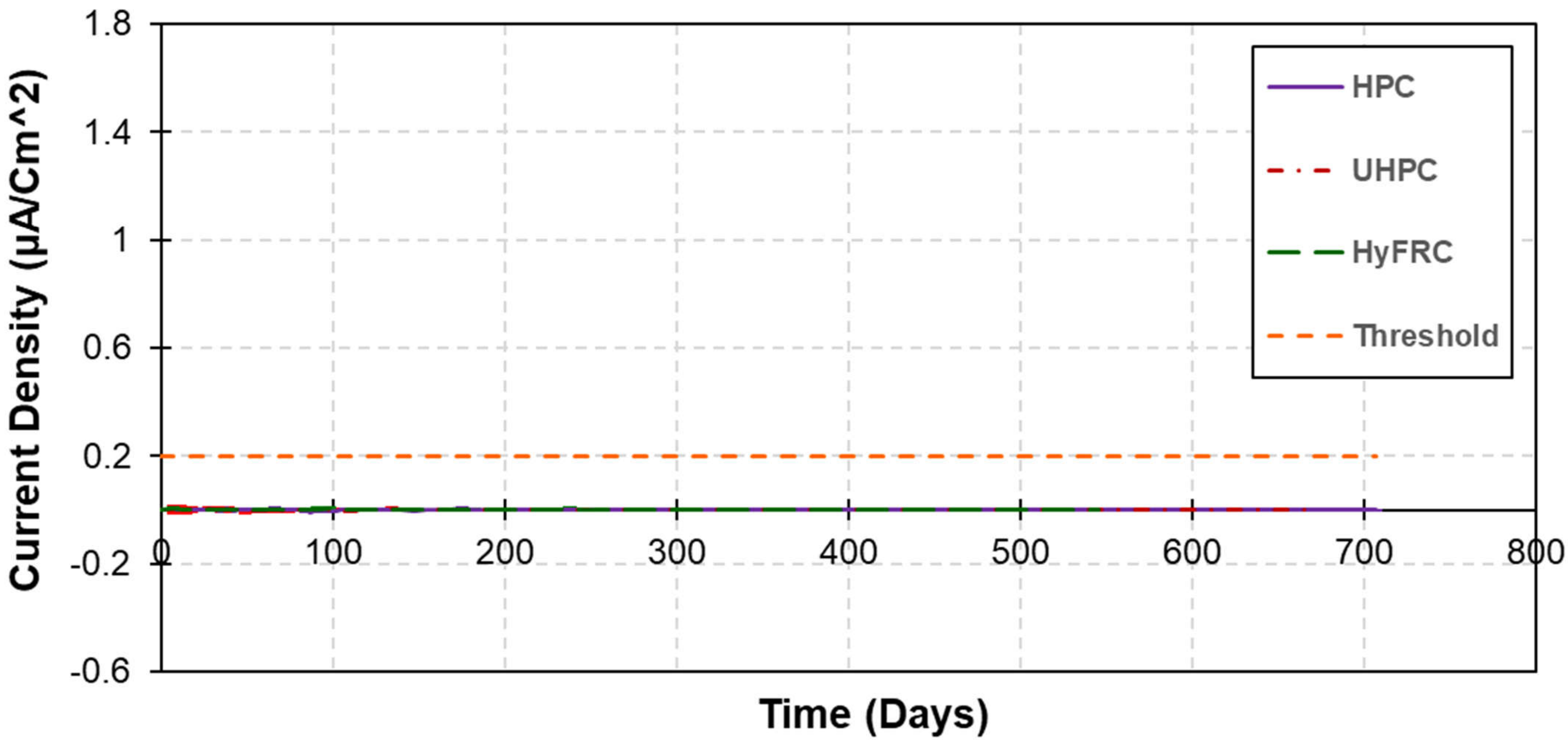
CORROSION IN CRACKED HYFRC WITH CHROMX

Specimen	Load (Kn)	Location 1	Crack Width (mm)	Location 2	Crack Width (mm)
HyFRC-ChromX-1	88	Center	0.2	Center	-
HyFRC-ChromX-2	88	Center	0.12	Center	0.08 (Longitudinal)
HyFRC-ChromX-3	88	Center	0.04	Center	-

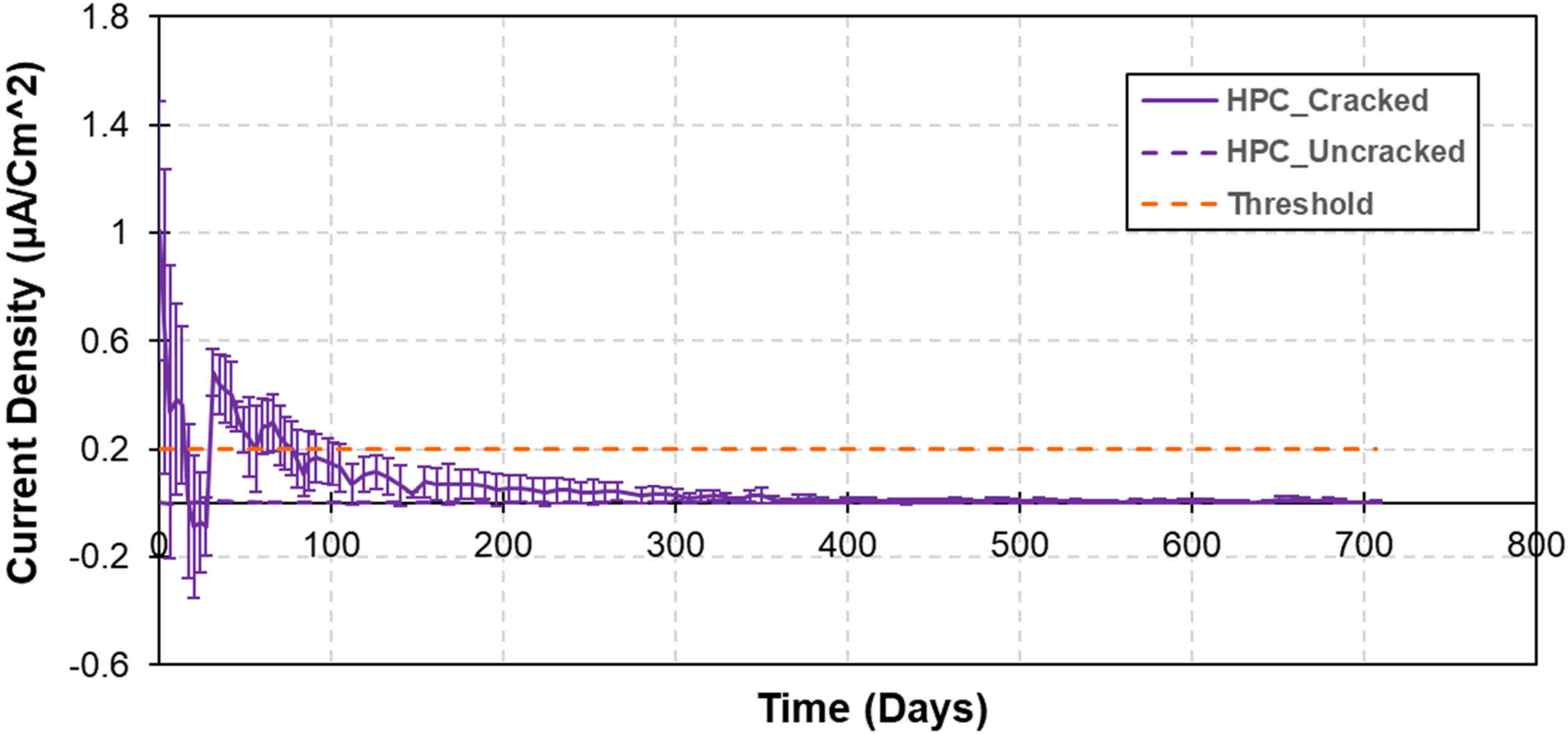


Corrosion in Alternative Reinforcement (ECR)

- Cracked Beams



Corrosion in Alternative Reinforcement (Galvanized)



Takeaways of Corrosion Testing of Ductile Concrete Systems and Alternative Reinforcement

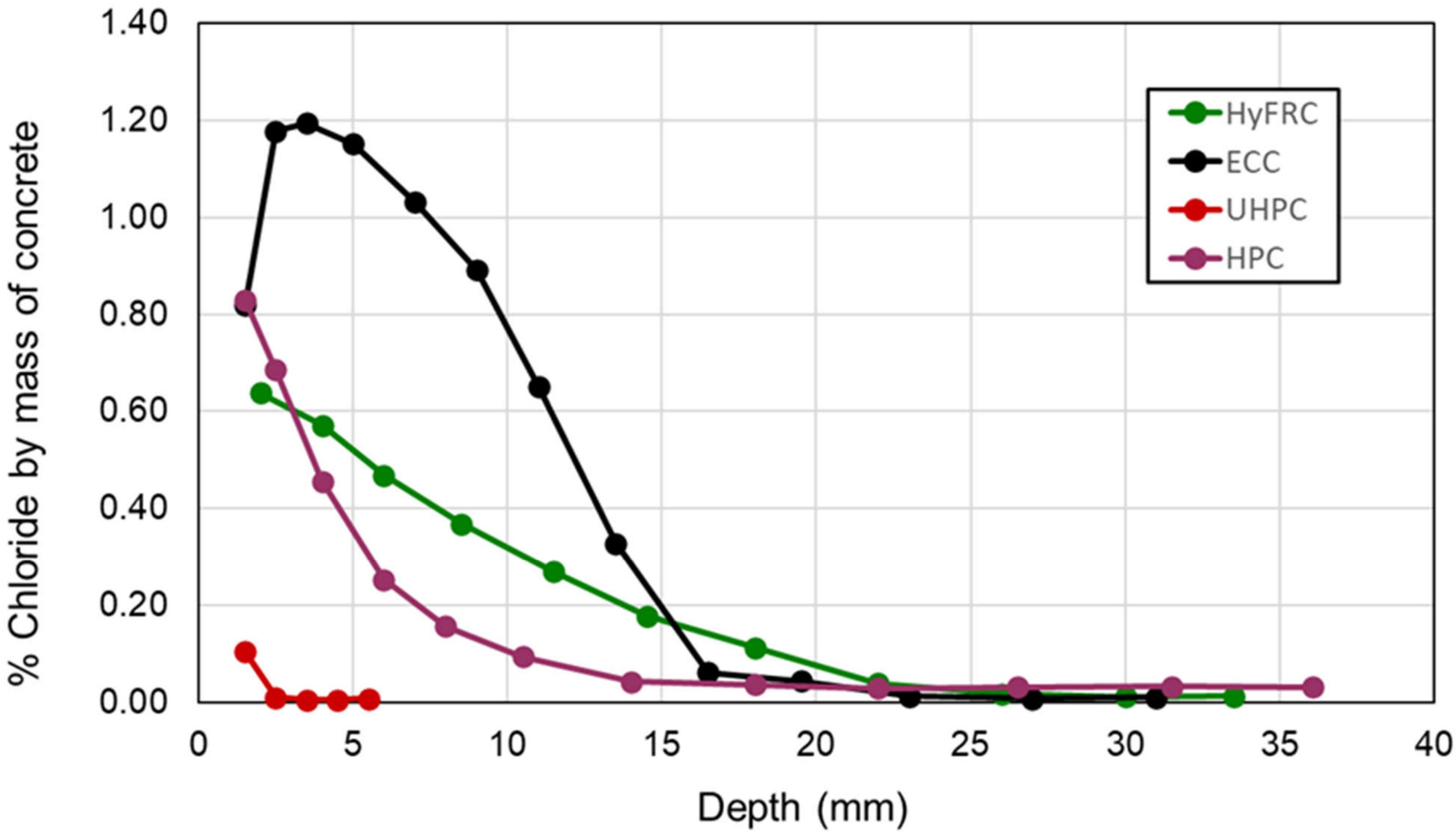
- Cracking affects the corrosion performance of ductile concrete systems

- Small cracks can be blocked by corrosion products and salt

- Longer time is needed for corrosion initiation in concrete systems and alternative reinforcement

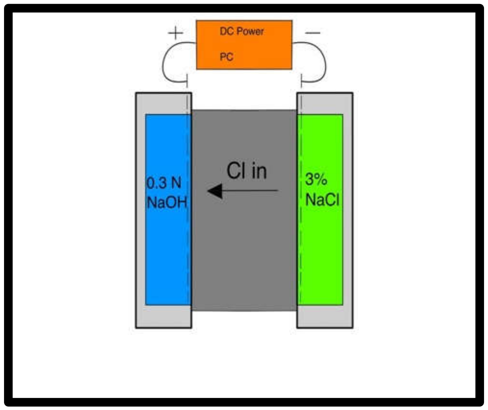
- Chloride profiling measurements were done to evaluate the chloride penetration and corrosion resistance

Chloride Profiling



Rapid chloride penetration testing was done to compare the results with long term ponding test

Rapid Chloride Penetration Testing of Ductile Concrete Systems



Rapid chloride penetration test (ASTM C1202)

- Rapid chloride penetration test has been widely used by department of transportation for concrete systems

Charge Passed (coulombs)	Chloride Ion Penetrability
>4,000	High
2,000–4,000	Moderate
1,000–2,000	Low
100–1,000	Very Low
<100	Negligible

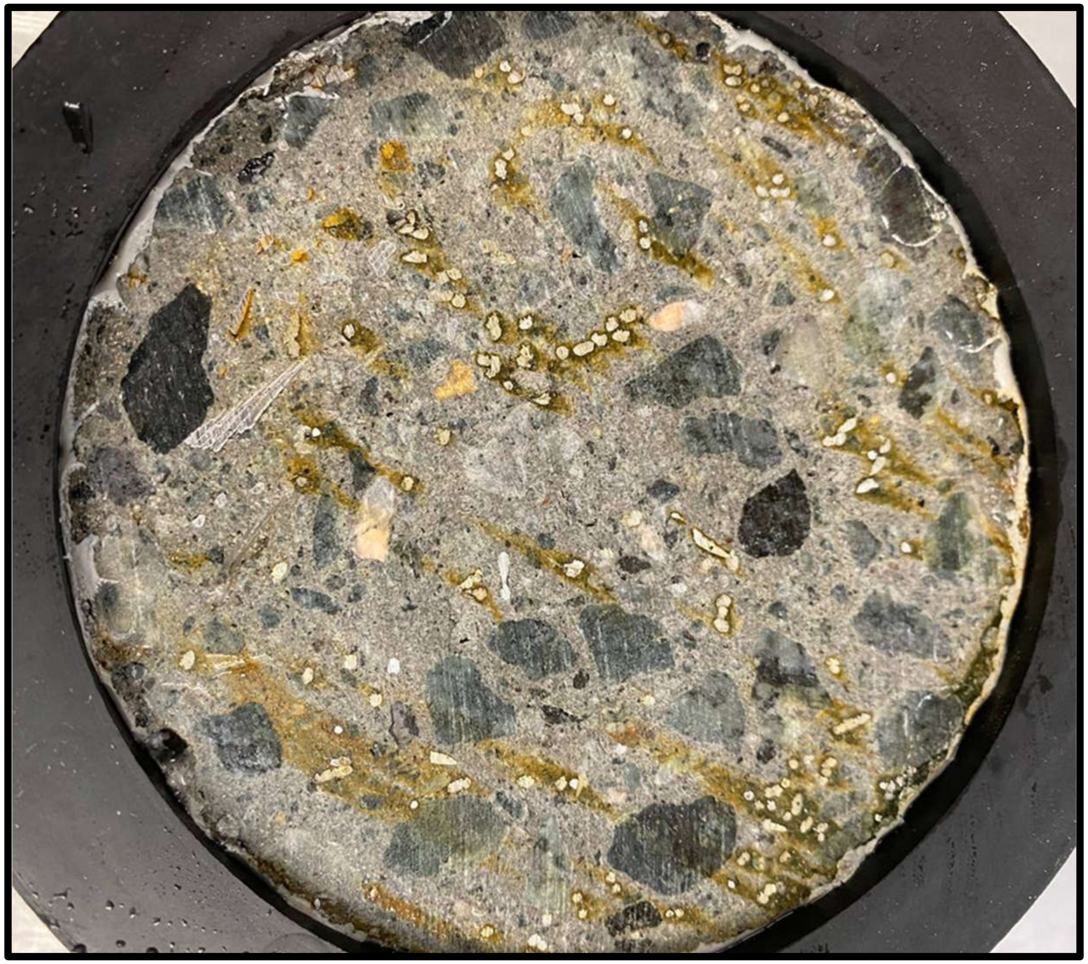
Rapid Chloride Penetration Testing of Ductile Concrete Systems

- No result was recorded for HyFRC due to testing device error (passing charges so quickly through fibers)
- Incorporation of fibers increased the passed charge in all concrete systems

Concrete Type	Passed Charged (Coulombs)			ASTM C1202 Classification
	Specimen 1	Specimen 2	Average	
HPC	381	385	**383.00**	**Very Low**
SCC P	1,399	1,533	**1,466.00**	**Low**
ECC	2,682	2,723	**2,702.50**	**Moderate**
UHPC	177	210	**193.50**	**Very Low**
HyFRC	N/A	N/A	**N/A**	**N/A**
ECC No Fiber	2,382	2,347	**2,364.50**	**Moderate**
UHPC No Fiber	16	17	**16.50**	**Negligible**
HyFRC No Fiber	2,693	2,639	**2,666.00**	**Moderate**

Failed HyFRC Specimen in RCPT

- Charge passed through fibers quickly and corroded the fibers. Tests was stopped automatically after few seconds.



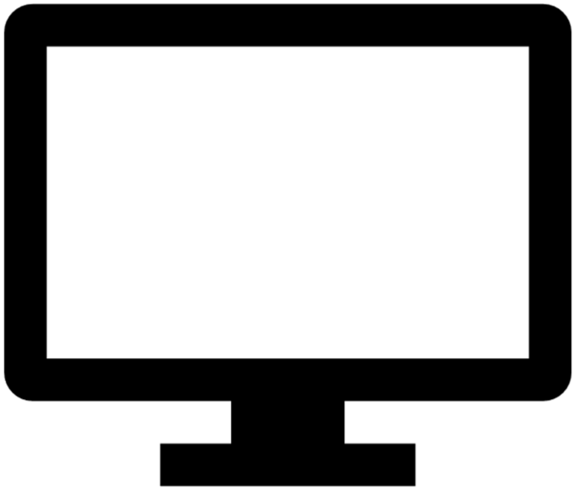
Takeaways of Rapid Chloride Penetration Testing of Ductile Concrete Systems

- Same trend was observed in RCPT of ductile concrete systems compared to chloride profiling results

- RCPT could not show the extent of difference between results with chloride profiling

- Fibers changed the RCPT results in ductile concrete systems

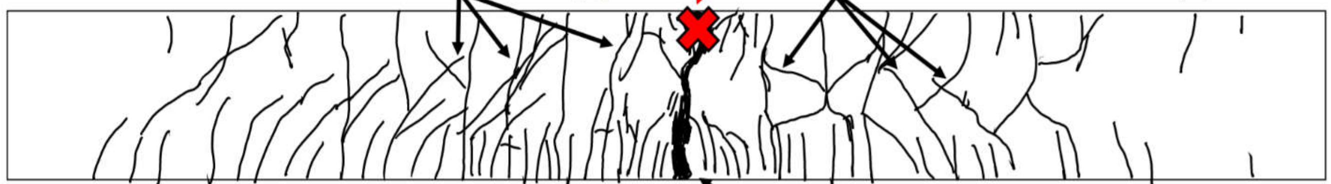
Numerical Framework



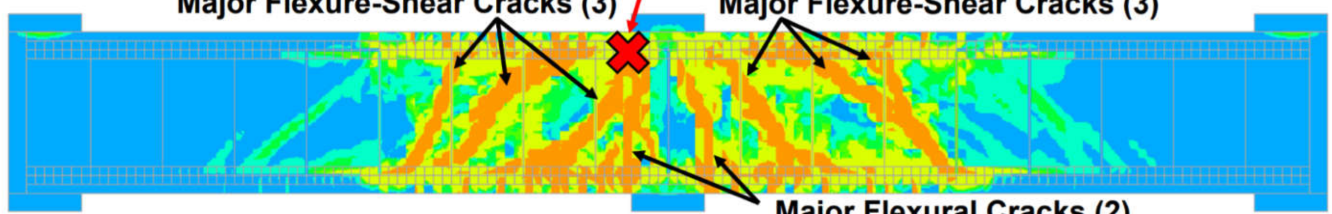
Service Life Evaluation Methods

- Two ways to evaluate the service life: experimental & numerical

- Experimental :
  - ❖ accurate
  - ❖ Intuitive



- Numerical:
  - ❖ cost efficient
  - ❖ time efficient
  - ❖ easily extended to various scenarios



References: Pokhrel, Bandelt, 2019.

Gaps in Current Numerical Modeling

Image Source: dlteng.com

Initial cracks not included

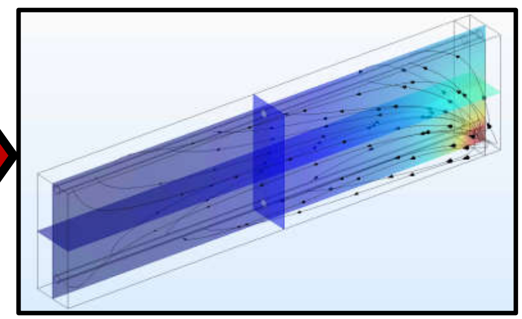
Image Sources: Gucunski et al. 2012

Boundary conditions not updated

Image Source: ethz.ch

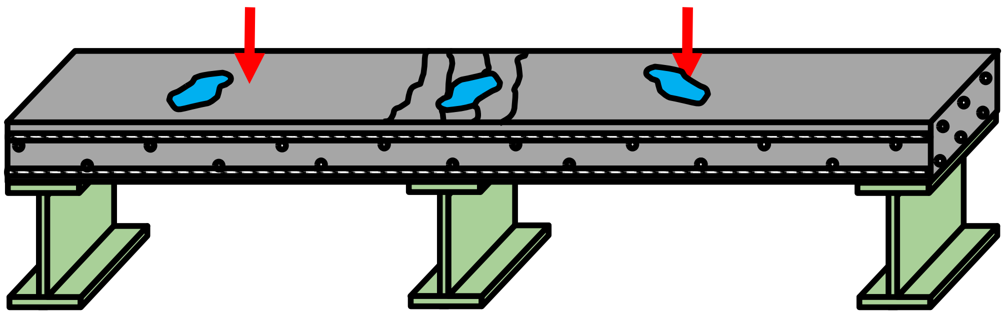
Structural deterioration not coupled

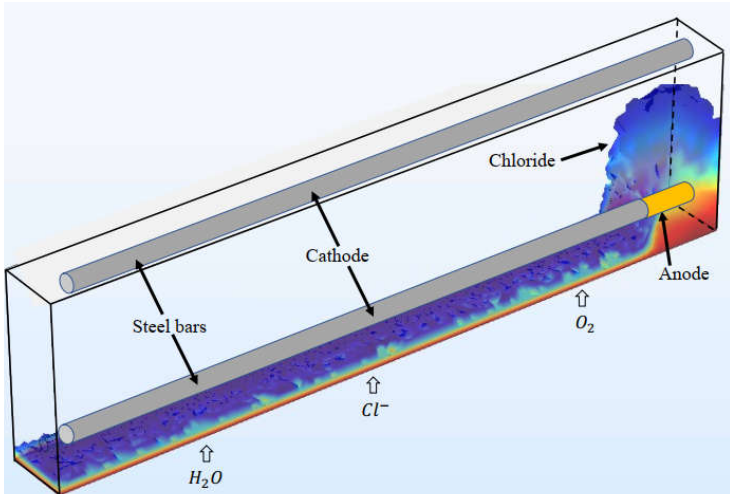
Corrosion behavior needs to be quantified



Coupling Effects and Time-dependent Effects

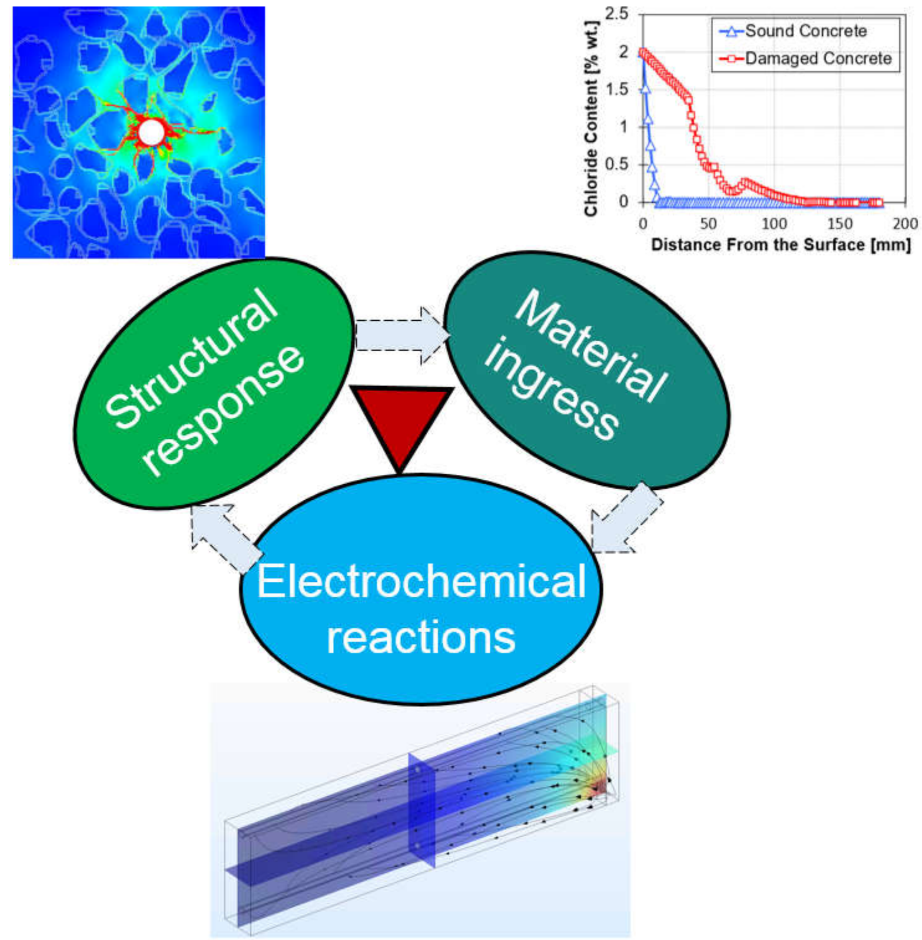
- Testing and simulation standards often treat **each form of damage in isolation**
- In practice there is a **coupling** of damage which **accelerates deterioration**
- The **benefits of new concrete systems** may be more apparent when studied **in light of coupled damage**
- The boundary conditions **are time-dependent, not stationary**



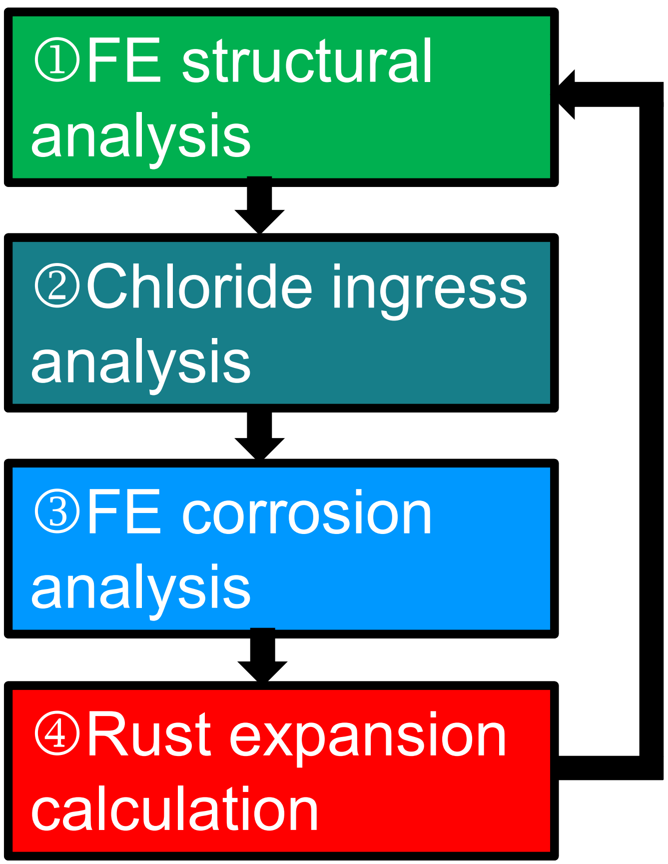


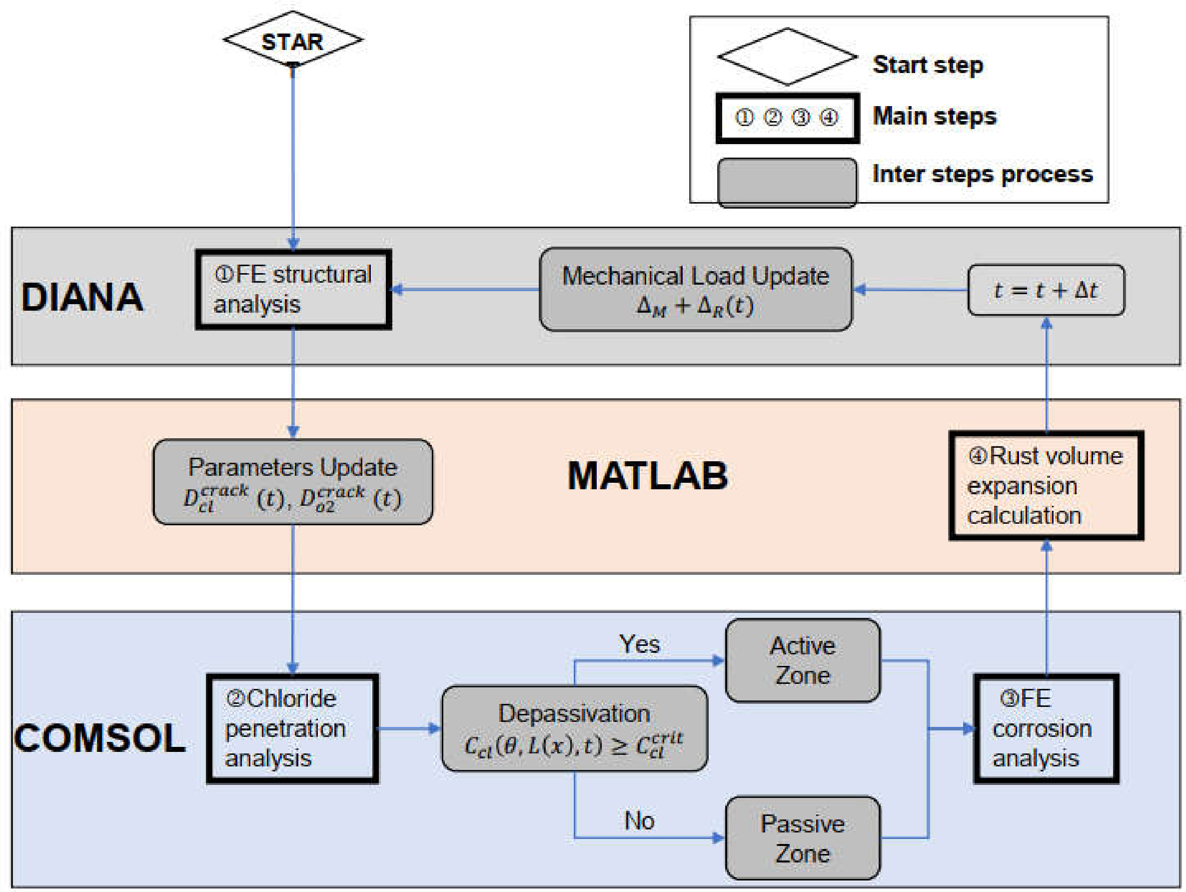
PROPOSED MODELING FRAMEWORK

- Consider **initial structure status**
- **Couple** material ingress with damage conditions
- **Time-dependent**: updates input parameters at each time step
- **Connect** all the stages in corrosion progress



PROPOSED MODELING FRAMEWORK

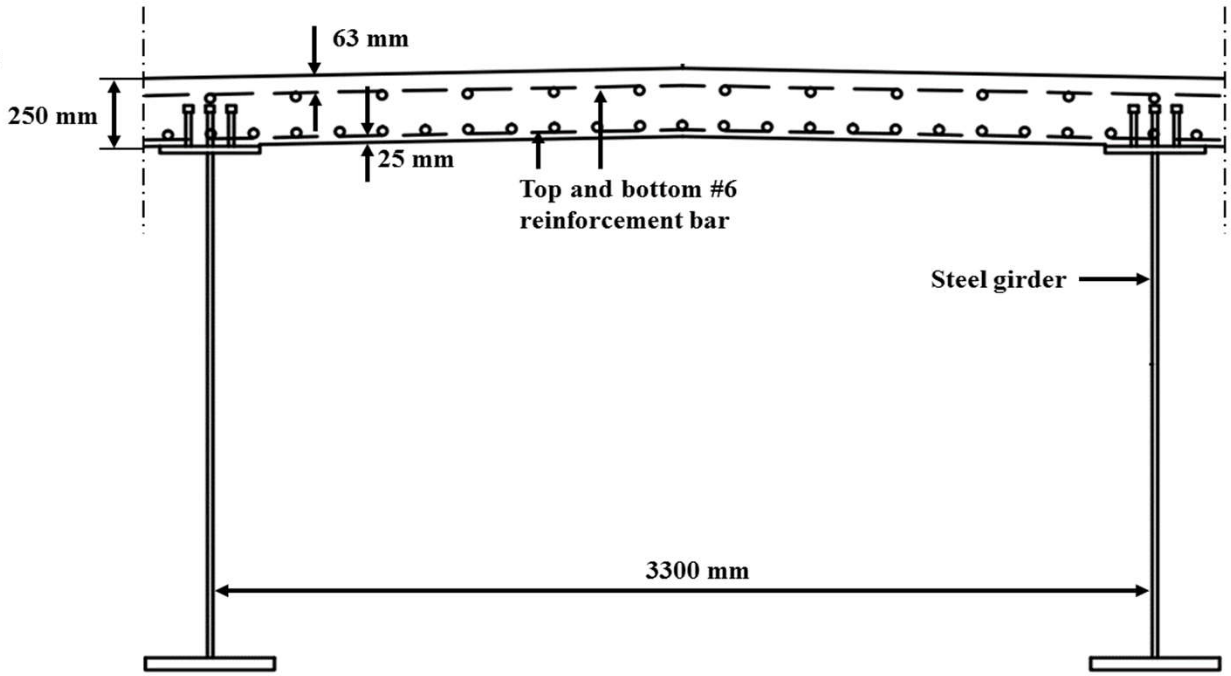




References: Fan et al. (2022).

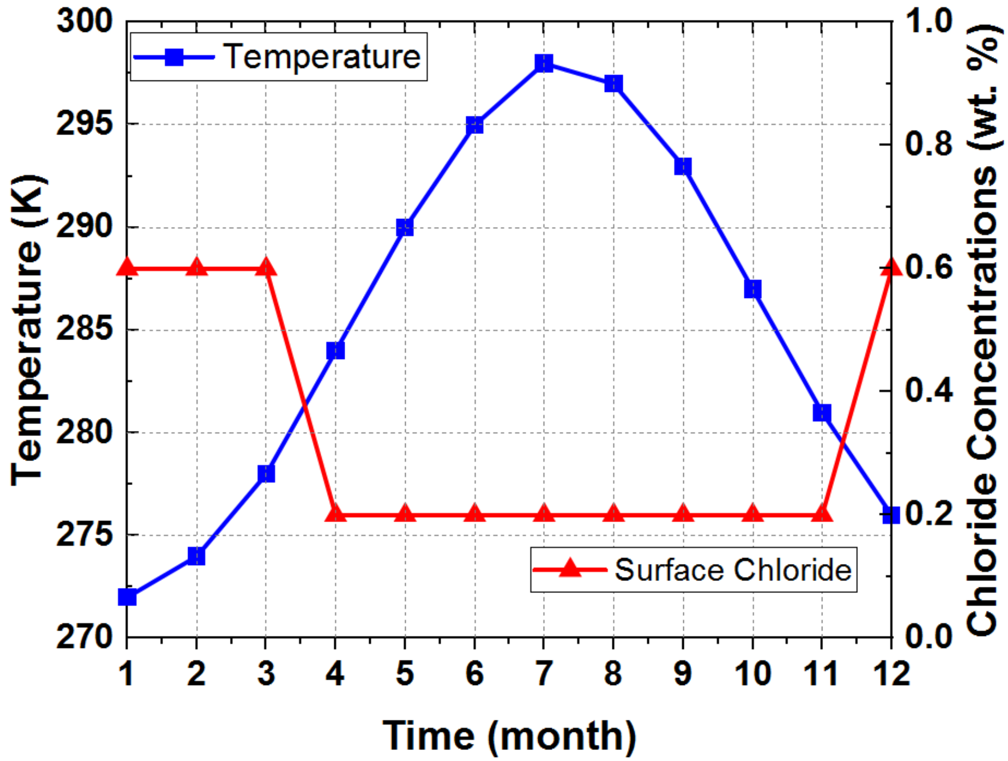
Case Study Example

- Comparison analysis **of UHPC and RC** bridge deck
- Subject to **realistic environmental conditions** in N



Environmental Conditions

- **Source chloride**: deicing salt; **Temperature varies**
- **Humidity** is constant (~70%) in NJ

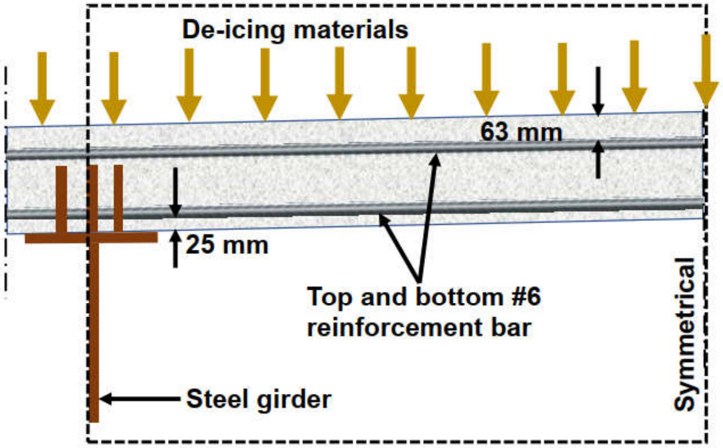


Source chloride profile of the deicing salt and temperature fluctuation

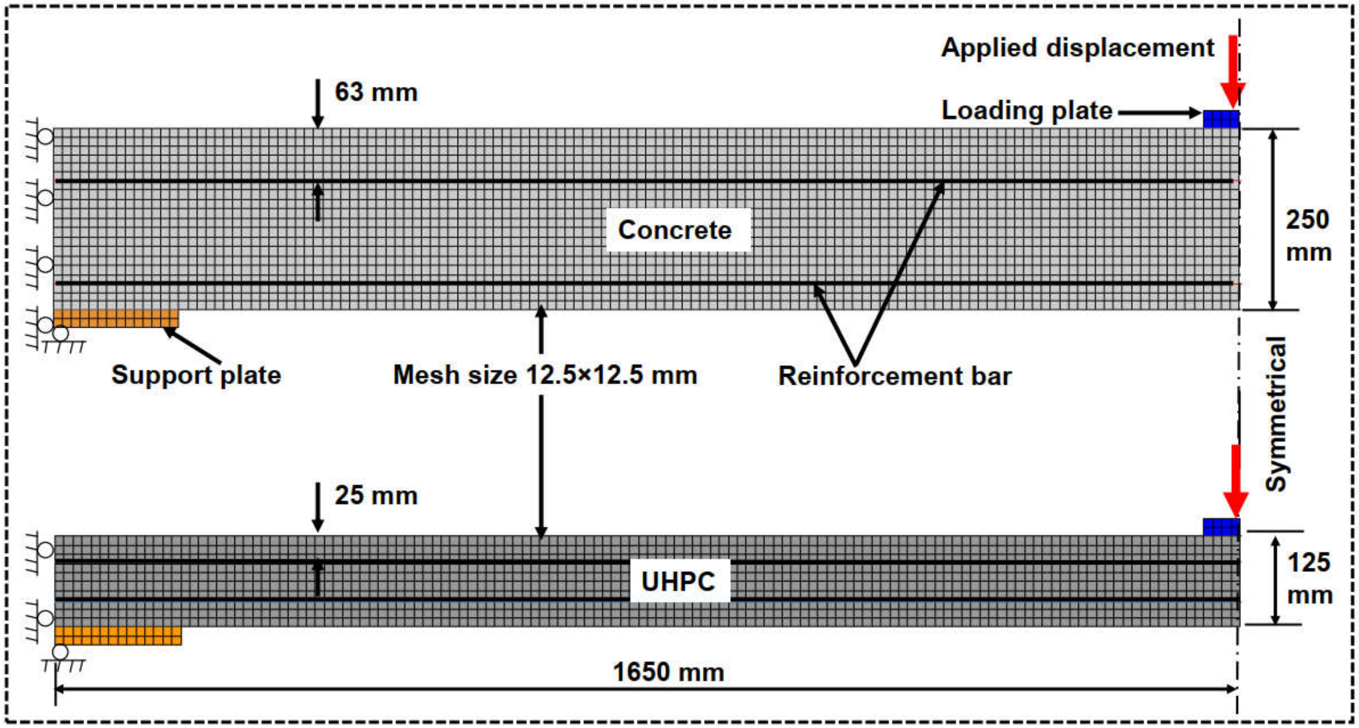
References: Cheung et al. 2009.

STRUCTURAL MODELING SET UP

- Symmetrical geometry
- Original deck thickness 250 mm



(a) Half span cross section of the original concrete bridge deck design



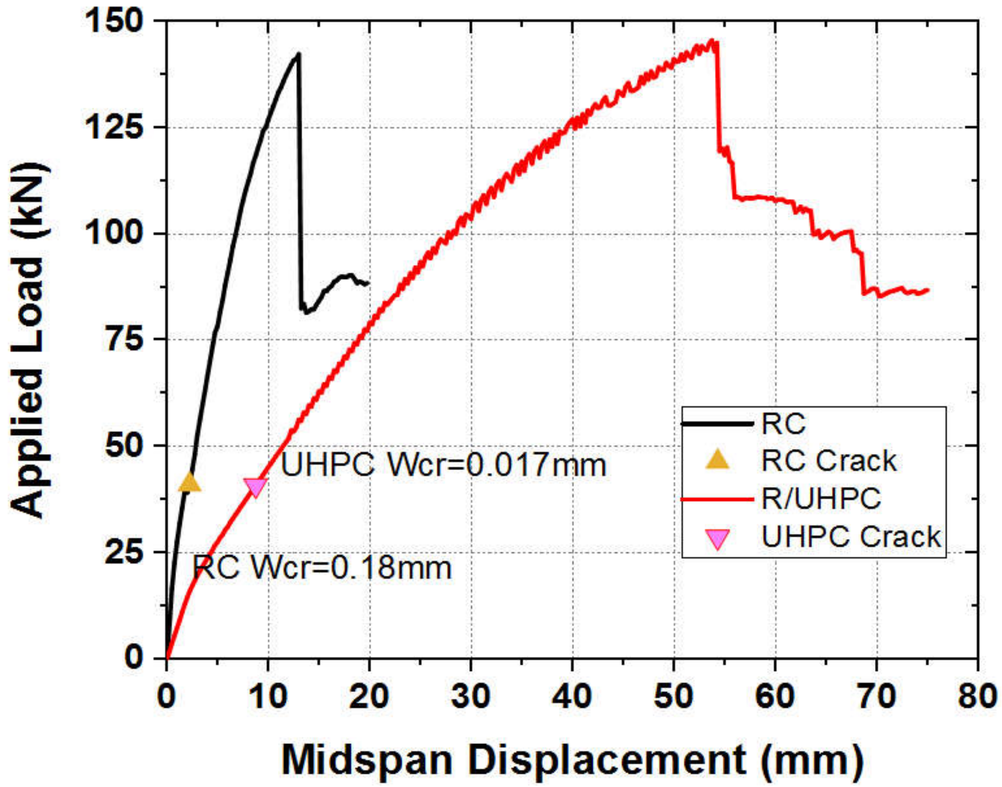
(b) Finite element modeling set up

Initial Cracking

- Load-deformation before corrosion

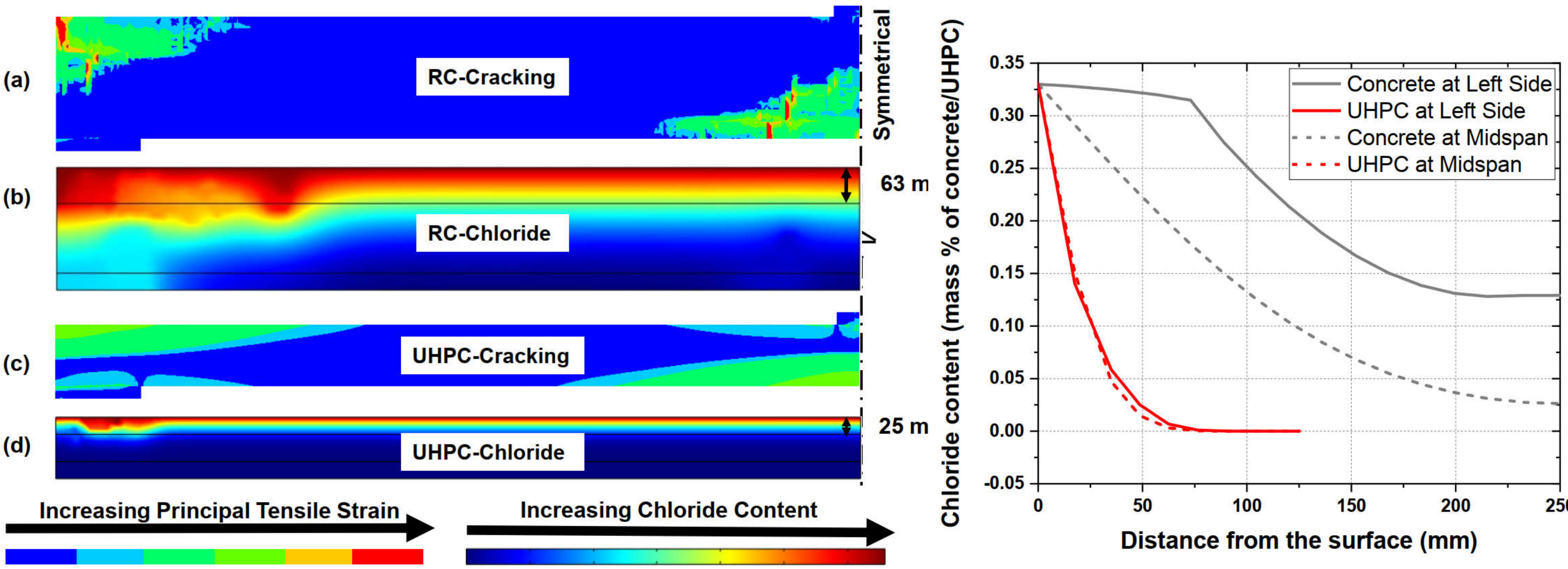
- **UHPC is half size**, redu from 250 mm to 125 mm

- **Cover depth** of UHPC was also reduced from 63 mm to 25 mm



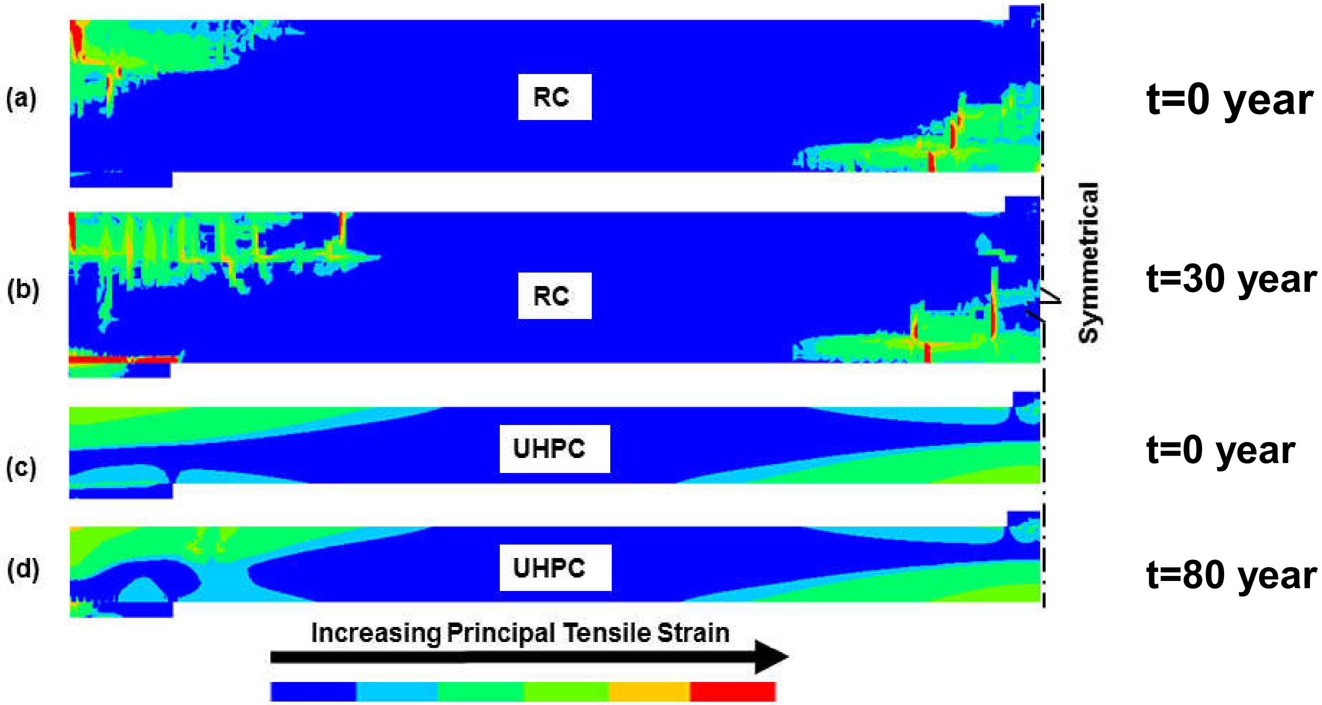
Impacts of Cracking on Chloride Profiles

- Damage conditions and chloride contour after **30 years** of de-icing exposure



DETERIORATIONS

- **Cracking patterns** before and after corrosion
- Distributed **fine cracks in UHPC**, localized **major cracks in RC**

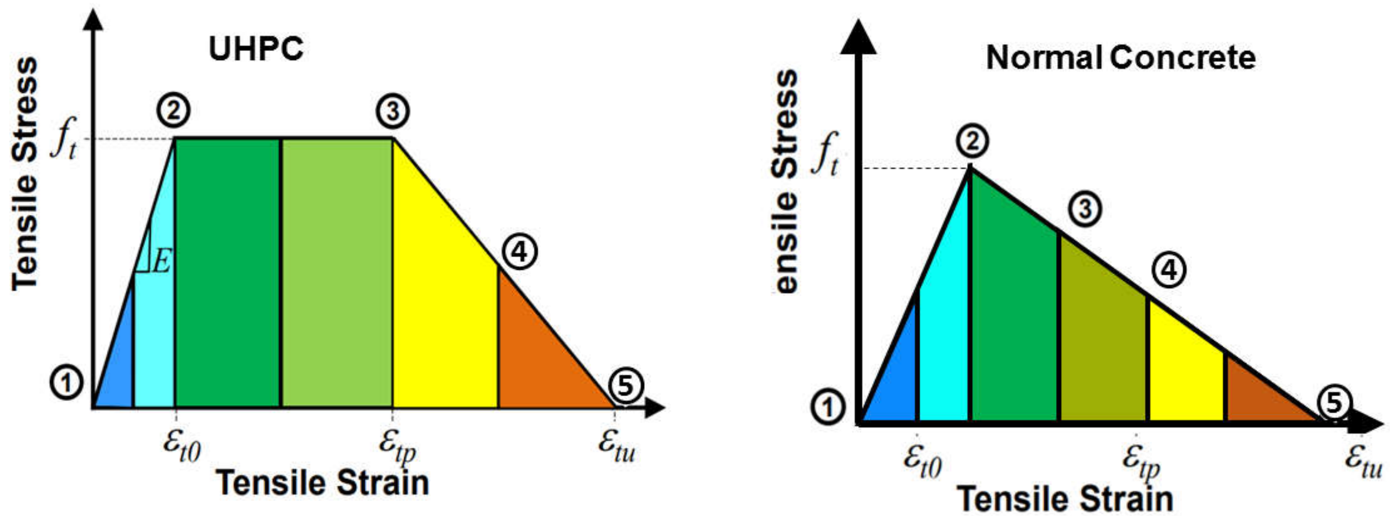


DETERIORATIONS

- Condition rating=% area in **severe×0**+% area in **poor×40**+%area in **fair×70**+%area in **sound×100**

- RC rate **79.1 after 30 year**

- UHPC rate **9 after 80 years**



Principal tensile strain contour of UHPC and normal strength concrete

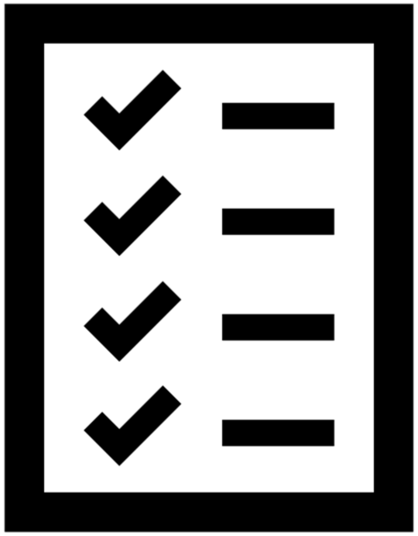
Takeaways of Numerical Modeling Framework

- The **multi-physics time-dependent numerical approach** is effective in **service life evaluation**

- UHPC bridge deck experienced **slower deterioration** under same traffic load and environmental conditions

- **UHPC becomes cost-effective** compared to RC in a 50 years service life period

Conclusions and Future Work



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CONCLUSIONS

- UHPC had the best durability performance between ductile concrete systems
- More cementitious materials in ductile concrete systems increases drying shrinkage
- Fibers help to improve the durability of ductile concrete systems
- There is a direct relationship between corrosion intensity and crack width in ductile concrete systems

CONCLUSIONS

- Ductile concrete systems have different chloride diffusion behavior
- Fibers affect the RCPT results in ductile concrete systems
- RCPT cannot reflect the corrosion performance of ductile concrete systems accurately
- The multi-physics time-dependent numerical approach is effective in service life evaluation

RECOMMENDATIONS

Modifications and improvements for testing corrosion behavior in ductile concrete systems are recommended in terms of:

- Changing specimen size
- Cracking method
- Brine solution
- Cover depth and
- Measurements techniques

Modifications for salt scaling testing of ductile concrete system are recommended as follows:

- Surface finishing
- Surface evaluation
- Rating criteria

FUTURE WORK

- More investigation are needed to evaluate the effect of fibers on RCPT results in ductile concrete systems.

- Evaluation of effect of cracking on RCPT results in ductile concrete systems

- Development a test method for salt scaling evaluation in ductile concrete systems

- Investigation of the applicability of resistivity test for evaluation of corrosion performance in ductile concrete systems