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WITH UTC-UTI

# Novel Concrete Materials to Enhance Durability of Transportation Infrastructure

Tran-SET

UTC UNDERGROUND TRANSPORTATION INFRASTRUCTURE

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## Self-Healing Microcapsules as Concrete Aggregates for Corrosion Inhibition in Reinforced Concrete

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Texas A&M University

Tran-SET

TEXAS A&M UNIVERSITY

# CHARACTERIZING AND UNDERSTANDING SELF-HEALING MICROCAPSULES EMBEDDED IN REINFORCED CONCRETE STRUCTURES EXPOSED TO CORROSIVE ENVIRONMENTS


**Reece Goldsberry**

**Jose Milla**

**Melvin McElwee**

**Ahmad Ivan Karayan**

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Tran-SET

Transportation Consortium of South-Central States

# Background



**Corrosion-induced deterioration of reinforced concrete can be modeled in three steps**

- Initiation Time ($T_i$)
- Time for appearance of cracking in the external concrete surface (Tc) since the Chloride Threshold Concentration ($C_T$) is reached.
- Time for development of spalls ($T_s$) and the Maintenance-Free Service Life ($T_{mf}$) is reached

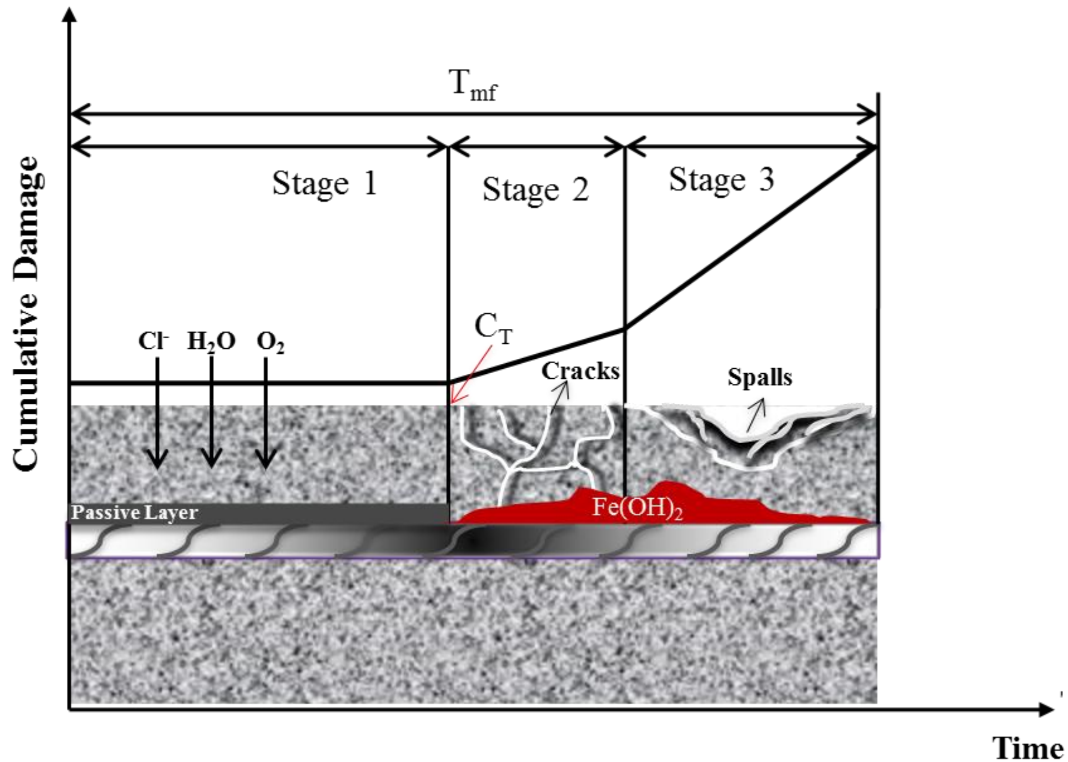



Image from NACE Conference, Vancouver, 2016

# Background

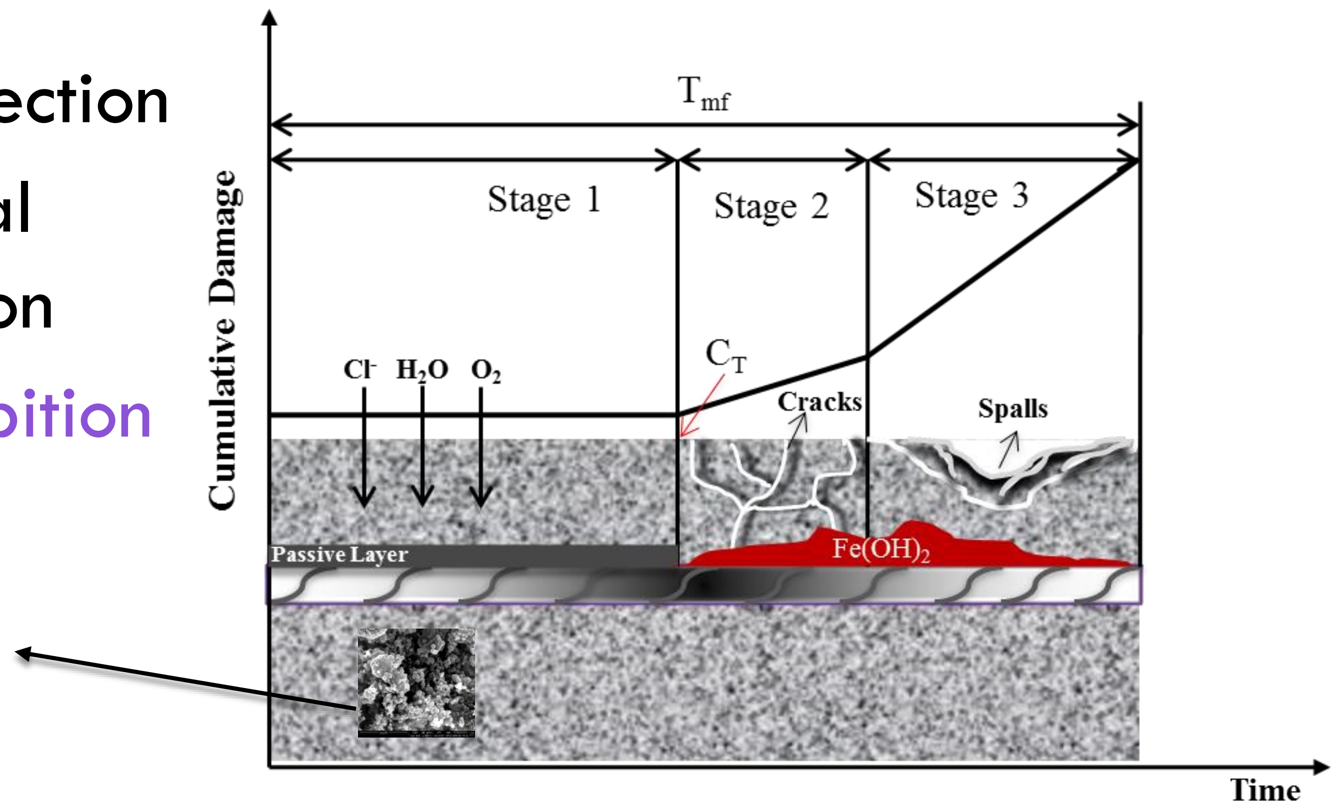


**Corrosion mitigation techniques in chloride-contaminated concrete**

1) Cathodic protection

2) Electrochemical chloride extraction

3) Corrosion inhibition mechanism with microcapsules to increase stage 1



# Background



- Microcapsules have been the most widely utilized delivery method for the self-healing concept due to
  - Its versatility in fabrication
  - The variety of applicable healing agents
- The corrosion inhibitor selected is calcium nitrate
- Calcium nitrates microcapsules will rupture during a cracking event and thereby release the core material when needed

# Corrosion Inhibition Mechanism



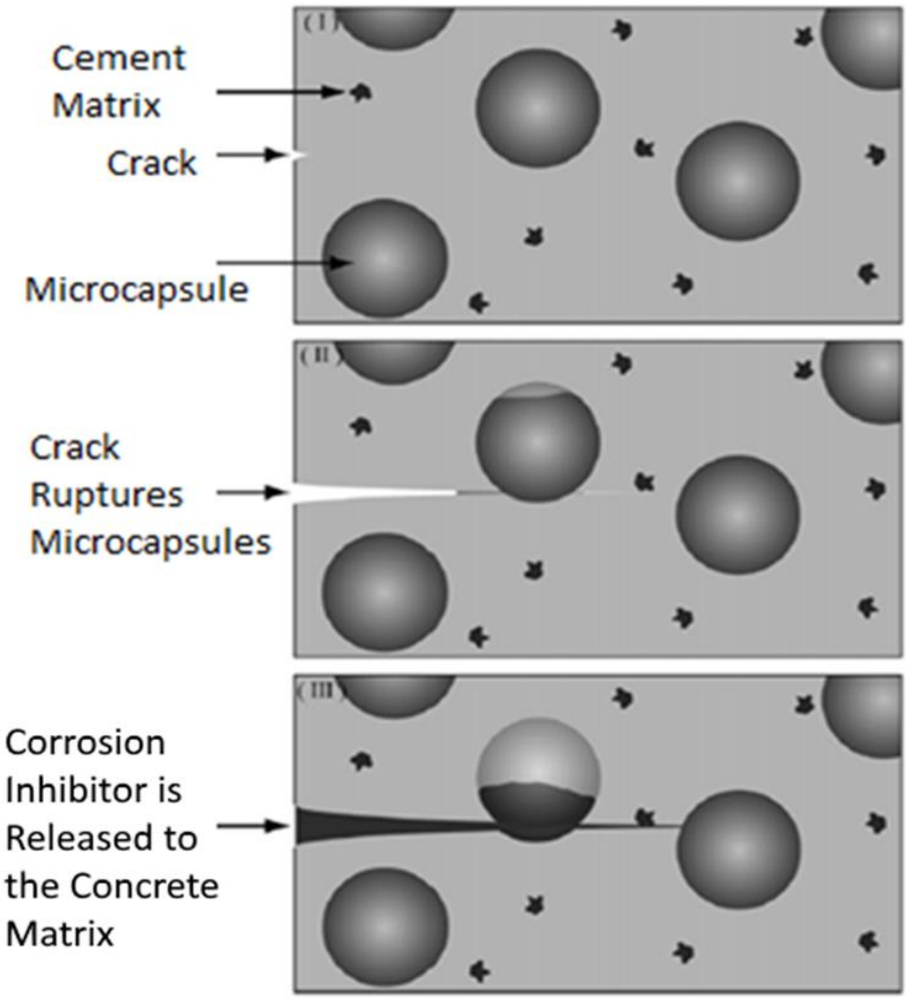



Image adapted from White et al. 2001

# Objectives



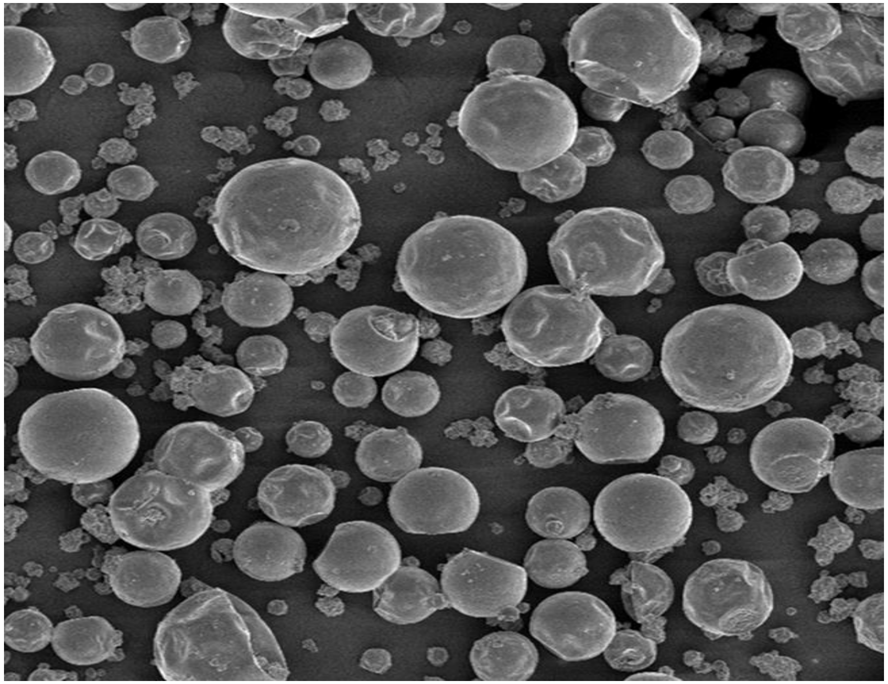
- Study the performance of microencapsulated calcium nitrate as a corrosion inhibitor
- Evaluate the influence of microcapsule concentrations (0.25, 0.50, and 2.00% by wt. of cement)
- Test for corrosion in continuous ponding and wet/dry cycles
- Performance evaluation based on short term experiments

# MATERIALS AND METHODS

# Microcapsule Preparation



The process is based on a water-in-oil suspension polymerization reaction of polyurea-formaldehyde



# Experimental Matrix



- Microcapsules embedded at varying concentrations to determine the minimal dosage required to mitigate corrosion considerably

| Sample ID | Corrosion Inhibitor | Concentration (% by wt. of cement) |
| --- | --- | --- |
| Control | N/A | N/A |
| CN-0.25 | Calcium Nitrate | 0.25 |
| CN-0.50 | Calcium Nitrate | 0.50 |
| CN-2.00 | Calcium Nitrate | 2.00 |

# Concrete Testing

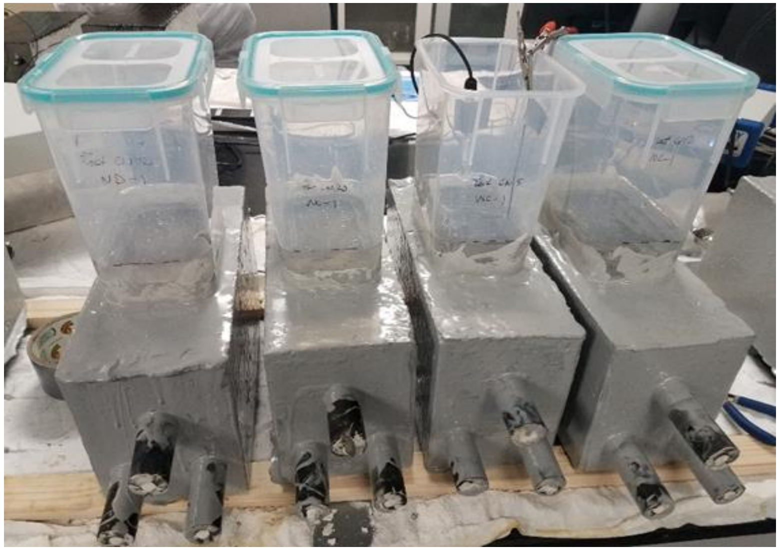


- Concrete cylinders (100 mm x 200 mm) were made for:
  - Compressive strength (ASTM C39)
  - Surface resistivity tests (AASHTO TP 95)

# Corrosion Characterization



- Concrete beams were made for corrosion testing (ASTM G109)
- Dimensions: 115 mm x 150 mm x 280 mm



# Corrosion Characterization

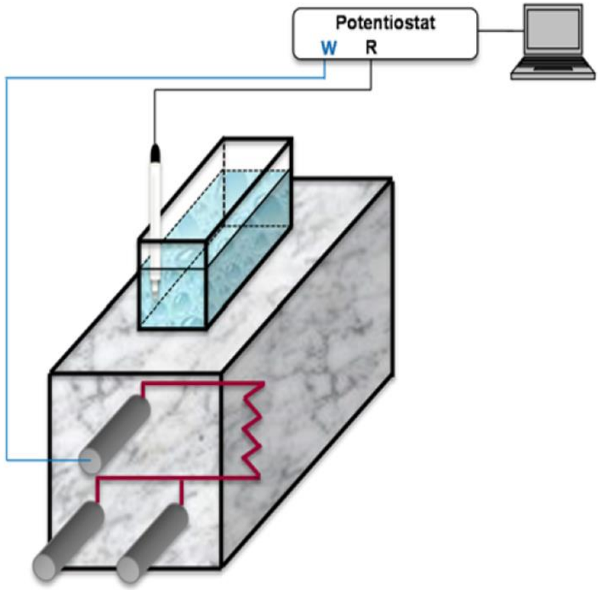


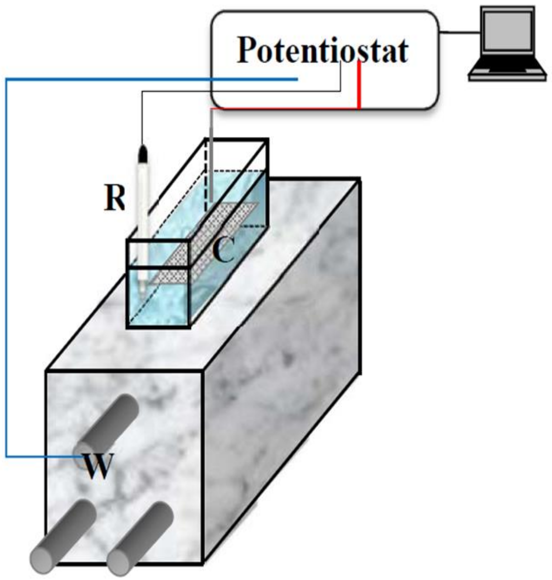
- Interfacial characterization of corrosion-inhibiting agents by exposing the concrete specimens to continuous ponding and wet/dry cycles
- Open circuit potential measurements
- Electrochemical impedance spectroscopy was performed in the frequency range from 10k – 0.01 Hz with the amplitude of 10 mV.

# Corrosion Characterization



- Traditional three-electrode configuration was used for EIS testing, consisting of:
  - Working electrode (anodic rebar)
  - Saturated calomel electrode (SCE) as the reference electrode
  - Platinum mesh wire as the counter electrode



# Corrosion Characterization



- The polarization resistance (Rp) from EIS was used to calculate the instantaneous corrosion rate
- For the continuous ponding, all the corrosion tests were performed every week for 85 days.
  - In the first ten days, measurements were taken every 2 days
- In the wet/dry cycles, the ponding well was filled with a 3 wt.% NaCl solution
  - Specimens were alternately exposed to 2-week periods with solution then 2 weeks without solution
- The corrosion testing was conducted at the beginning of the second week of ponding.

# RESULTS AND ANALYSIS

# Results

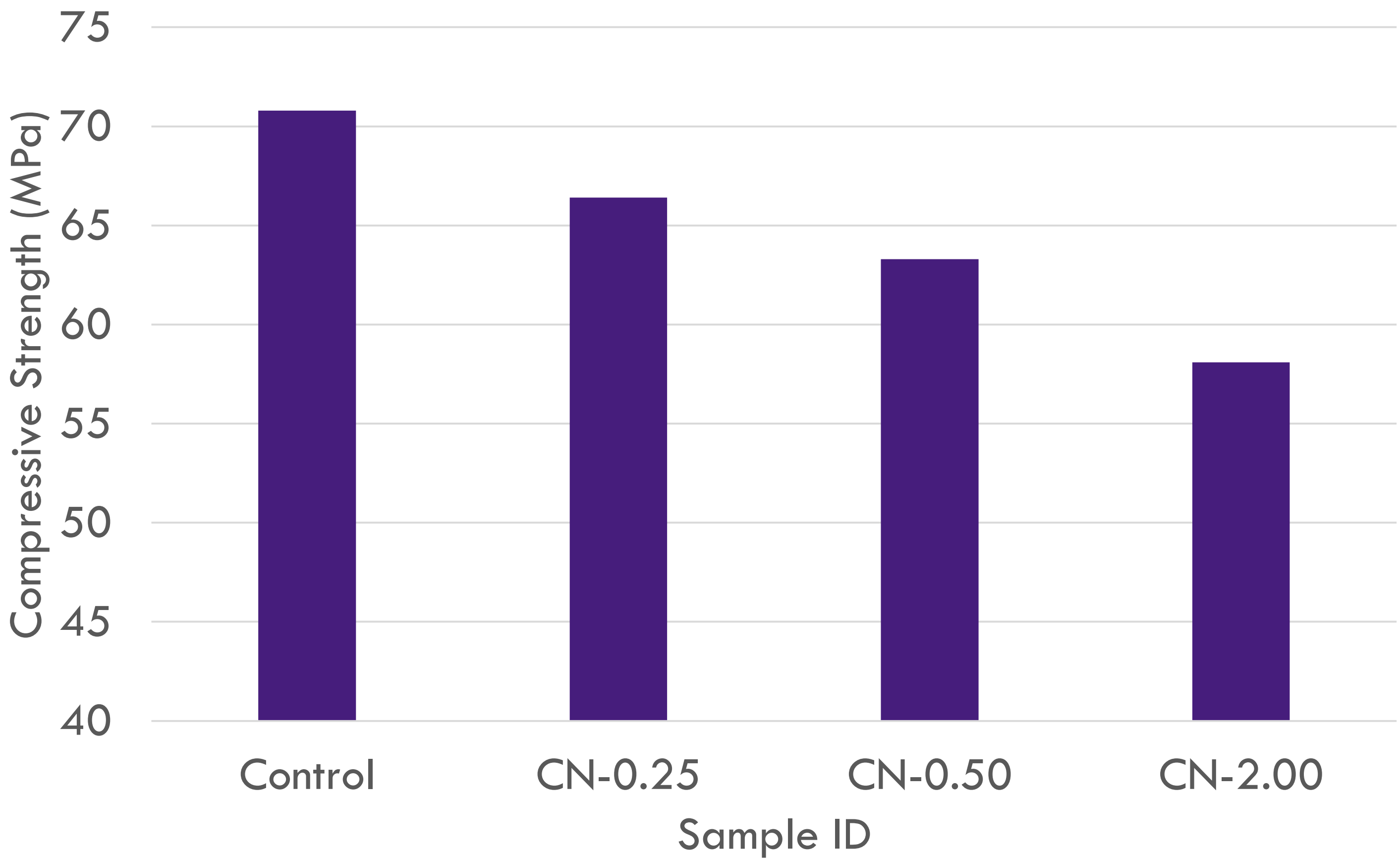


**Concrete Testing**

- An increase in microcapsule concentration has a negative impact on strength
- The highest microcapsule concentration (2% by wt. of cement) resulted in an 18% strength reduction
- Resistivity tests showed that the addition of microcapsules dropped the chloride permeability level from ‘Low’ to ‘Moderate’

# Compressive Strength





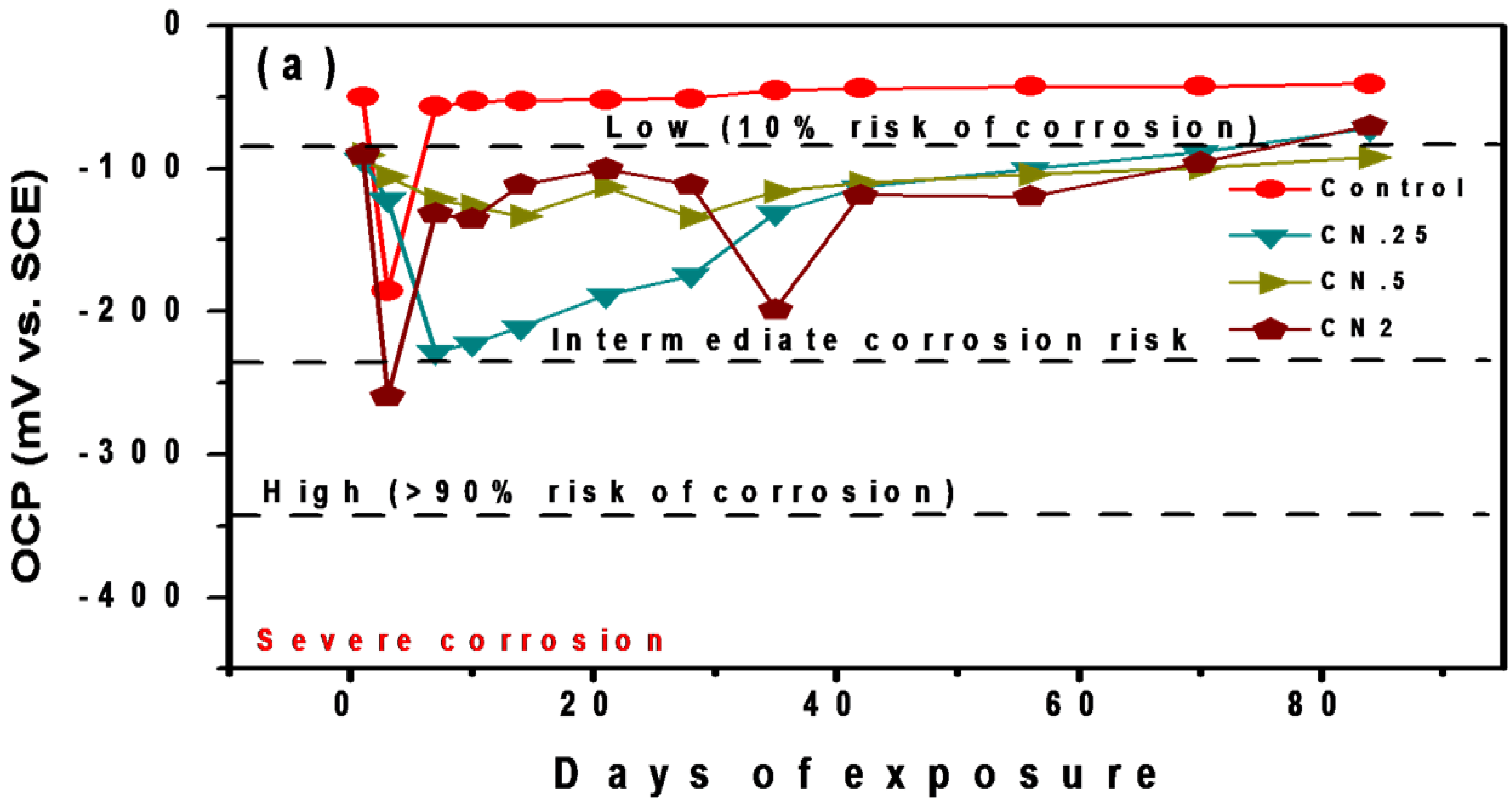
# Surface Resistivity



| Sample ID | Concentration (% by wt. of cement) | Surface Resistivity (kΩ-cm) | Chloride Penetrability |
|---|---|---|---|
| Control | N/A | 21.9 | Low |
| CN-0.25 | 0.25 | 20.1 | Moderate |
| CN-0.50 | 0.50 | 18.7 | Moderate |
| CN-2.00 | 2.00 | 15.3 | Moderate |

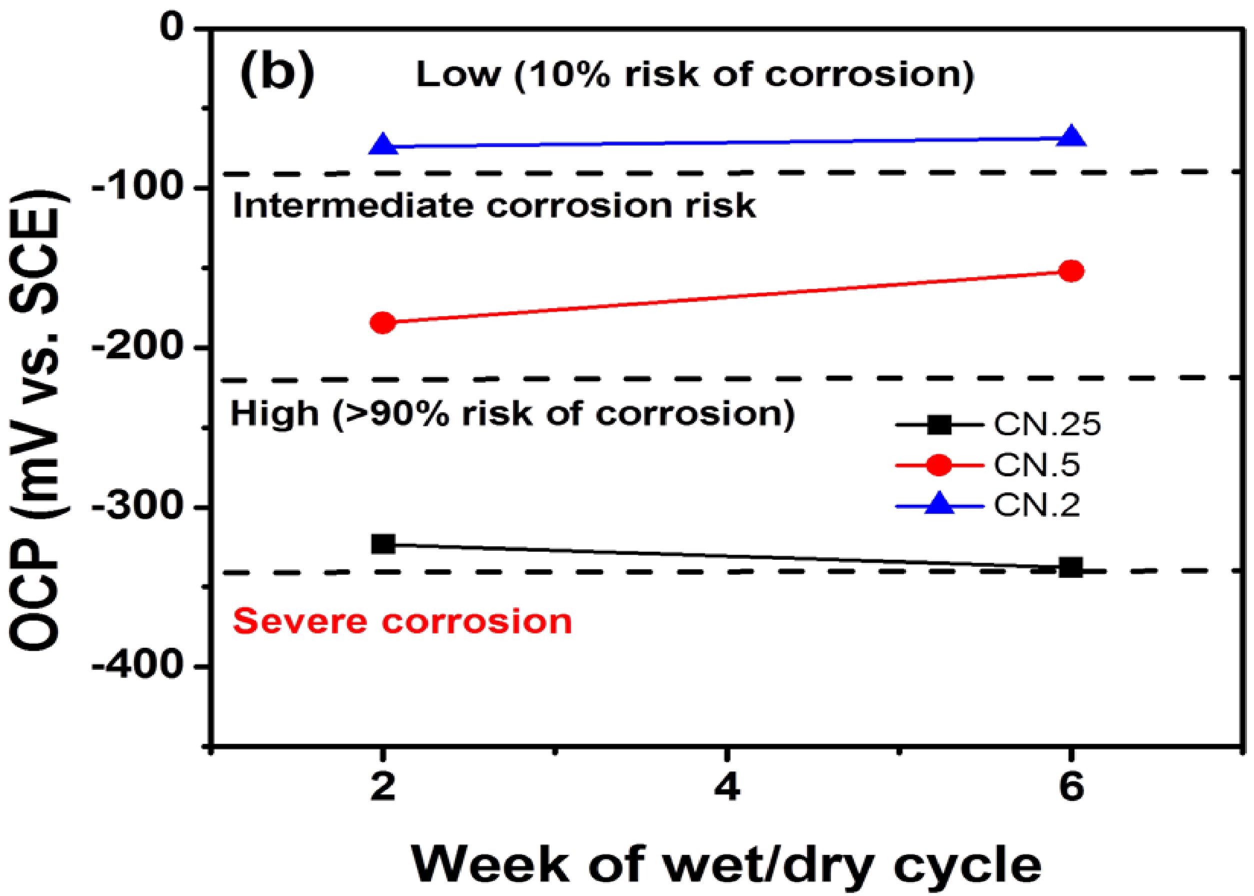
# Open circuit potential
# Continuous Ponding





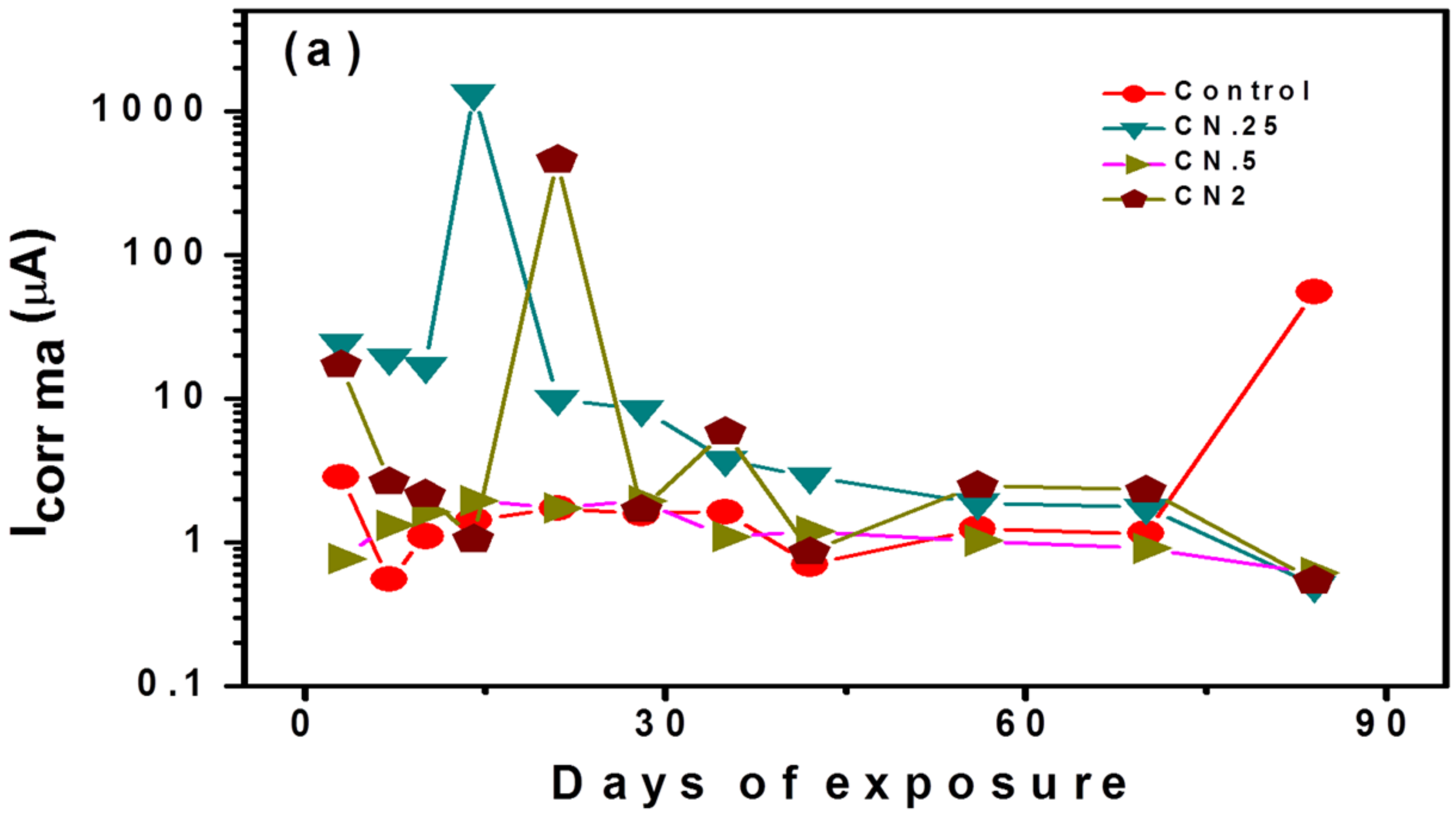
# Open circuit potential
# Wet/Dry Cycles





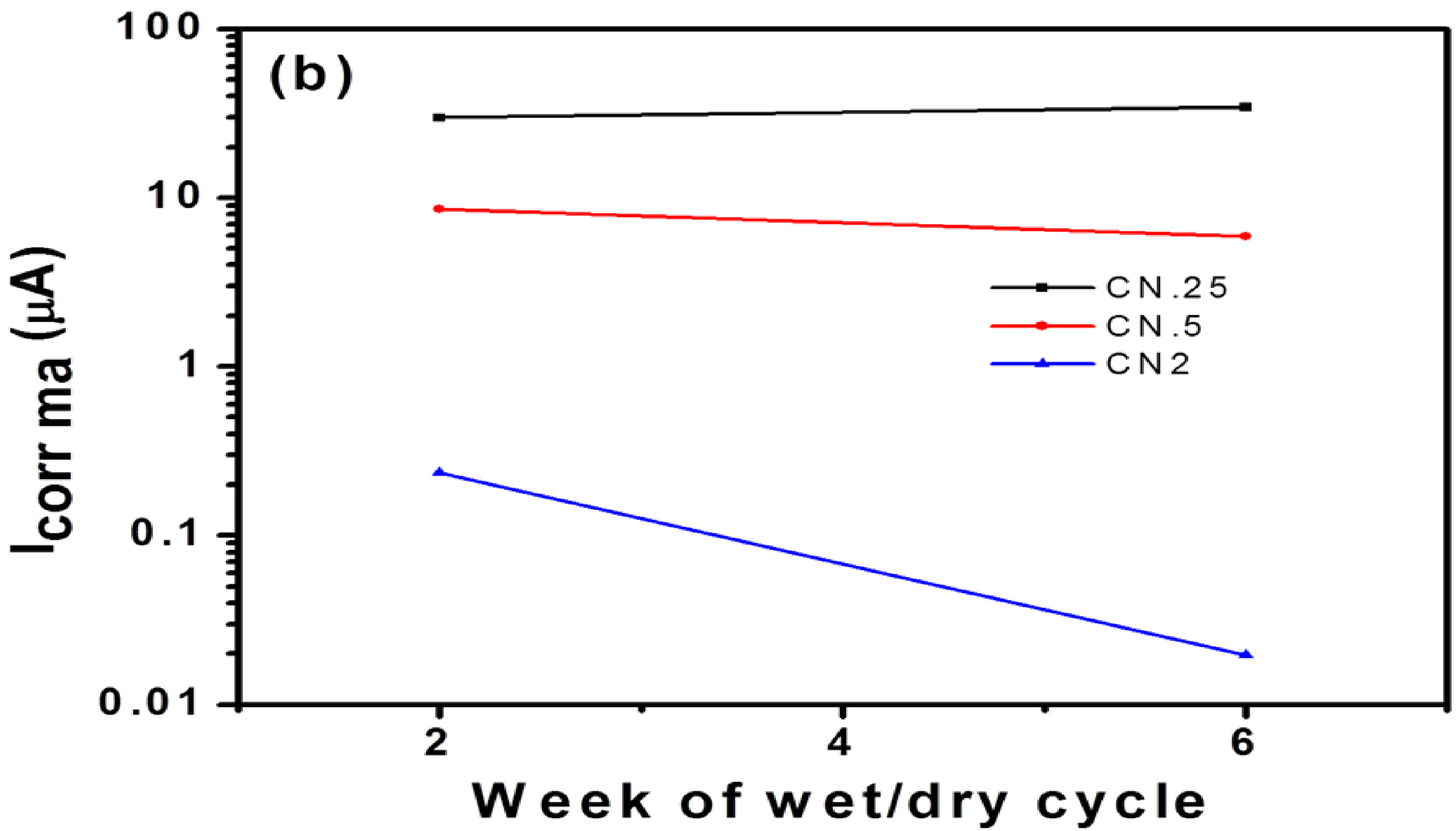
# Macrocell corrosion current Continuous Ponding





# Macrocell corrosion current Wet/dry cycle





# Conclusions



- The concentration of microcapsules added had a significant effect on the compressive strength of concrete
- Surface resistivity tests indicated that a slight increase in chloride penetrability was attributed to the addition of microcapsules.

# Conclusions



- The exposure of the concrete specimens (continuous ponding vs. wet/dry cycles) had a significant influence on the results
- For the continuous ponding, there was a passivation-activation-repassivation process.
- The highest magnitude of activation was found in the sample that had the highest microcapsule concentrations (2%).

# Conclusions



- For the wet/dry cycles, the sample with the smallest microcapsule concentration has the most active corrosion
- The best performance is achieved at the highest microcapsule concentration (2%).
- New testing is ongoing for short-term results and interfacial characterization

# QUESTIONS?

Thank you!

# JOINT TRAN-SET WEBINAR SERIES

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## Evaluating the Use of Recycled and Sustainable Materials in Self-Consolidating Concrete for Underground Infrastructure Applications


**Dr. Mehran Mazari**

California State University - LA


UTC UNDERGROUND TRANSPORTATION INFRASTRUCTURE

CAL STATE LA

# Evaluating the Use of Recycled and Sustainable Materials in Self-Consolidating Concrete for Underground Infrastructure Applications

**Mehran Mazari, Ph.D.**
**Assistant Professor, Department of Civil Engineering**
**California State University Los Angeles**
**Los Angeles, CA**
**July 11, 2018**

UNIVERSITY TRANSPORTATION CENTER
FOR UNDERGROUND TRANSPORTATION INFRASTRUCTURE

COLORADO SCHOOL OF MINES
EARTH ENERGY ENVIRONMENT

CAL STATE LA

LEHIGH UNIVERSITY

# Acknowledgment

## UTC-UTI Director:
**Marte Gutierrez**
**Colorado School of Mines**

## Project Staff:
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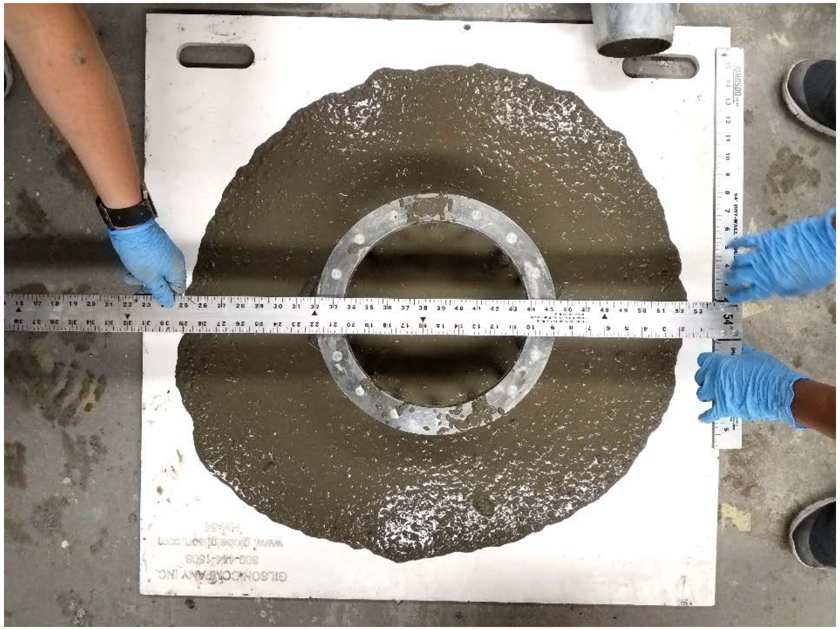
**Tona Rodriguez (Co-PI)**

## Research Assistants:
**Hector Cruz**
**Jason NG**
**Francisco Ojeda**
**Daniel Marquez**

# Outline

1. Introduction
2. Literature Review
3. Problem Statement
4. Research Objectives and Scope
5. Research Methodology
6. Results and Discussion
7. Project Status



# Introduction

## Definition of Self-Consolidating Concrete (SCC)

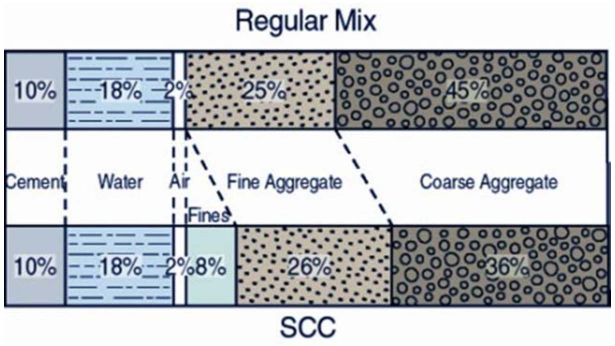
**Compared to Conventional Vibratory Concrete (CVC)**

**High workability, flowability, passing ability and forming around reinforcement, smooth finished surface**

**Specific mix proportioning as well as using admixtures:**
**- viscosity modifying admixture (VMA),**
**- high range water-reducing (HRWR),**
**- super-plasticizers (SP)**

**SCC**

Richard-Hulin et al. 2011



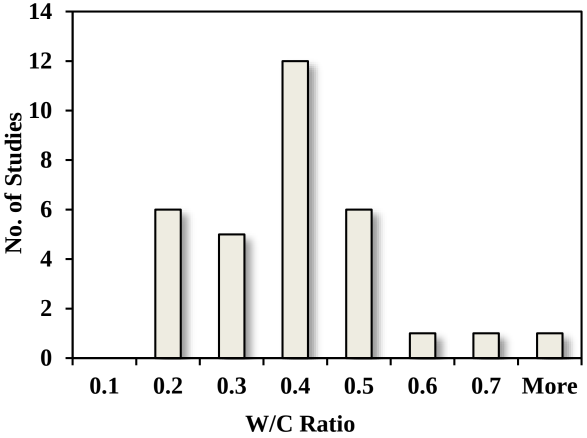

Traditional Concrete

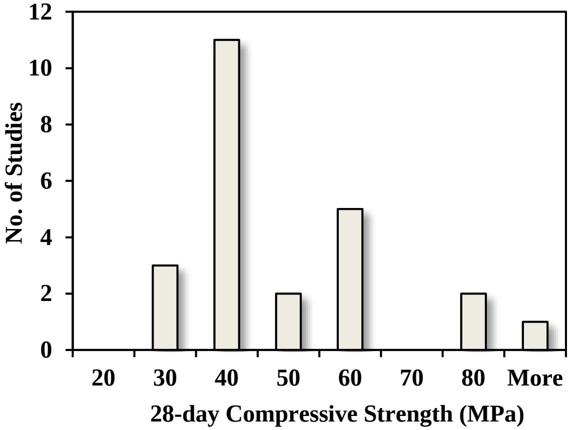
**CVC**

Self-Compacting Concrete

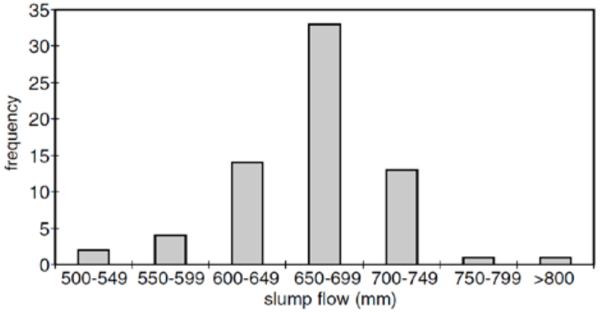
# Literature

- Distribution of the Water/Cement ratio and 28-day compressive strength for SCC mixes across the literature




- Distribution of slump flow of SCC across the literature



# Scope of Work

- Phase I
  - **Documentation and Information Search**
- Phase II
  - **Experimental Investigations**
    - Fresh Concrete Properties
      - Workability
      - Rheology
      - Air Content
    - Early-Age Concrete Properties
      - Time of Setting
      - Heat of Hydration
    - Hardened Concrete Properties
      - Mechanical
        - ✓ Compressive/Tensile Strength
        - ✓ Modulus of Elasticity
      - Visco-Elastic
        - ✓ Drying Shrinkage
  - **Data Analysis, Simulation and Model Development**
  - **Draft Final Report**

→

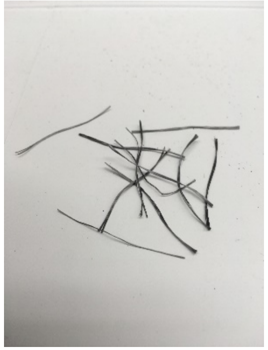
- **Sustainable Infrastructure Materials (Extending the Life)**
- **Avoiding Micro-Cracks (Extending the Life)**
- **Improved Load Bearing Capacity and Durability**
- **Improved Workability**

# Fibers

### Steel MacroFibers

### Synthetic MicroFibers

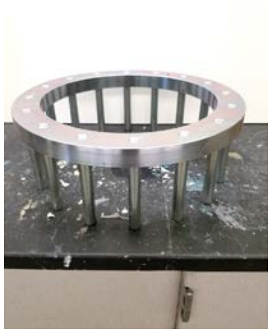
### Synthetic MacroFibers



### Recycled Tire Fibers

# Laboratory Evaluations

- Estimating fresh properties of fiber-reinforced SCC
  - **Filling ability: Slump flow** (ASTM C1611)
  - **Passing ability: J-Ring** (ASTM C1621)
  - **Static Segregation resistance: Column Segregation Test** (ASTM 1610)
  - **Air Content of Freshly Mixed Concrete by the Pressure Method** (ASTM C173)
- Drying and Plastic Shrinkage
- Estimating Hardened Properties
  - **Compressive Strength** (ASTM C39)
  - **Split Tensile Strength** (ASTM C496)
  - **Modulus of Elasticity** (ASTM C469)
  - **Flexural Beam Strength** (ASTM C1609)

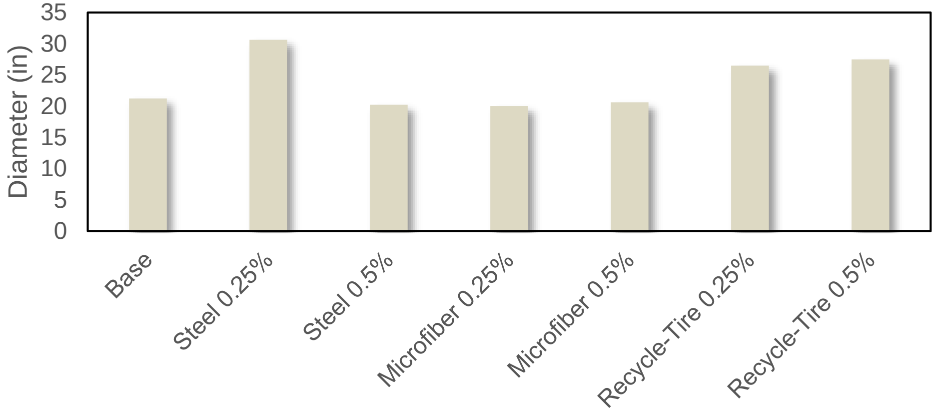





# Fresh Properties – Passing Ability by J-Ring (AASHTO T345, ASTM C1621)

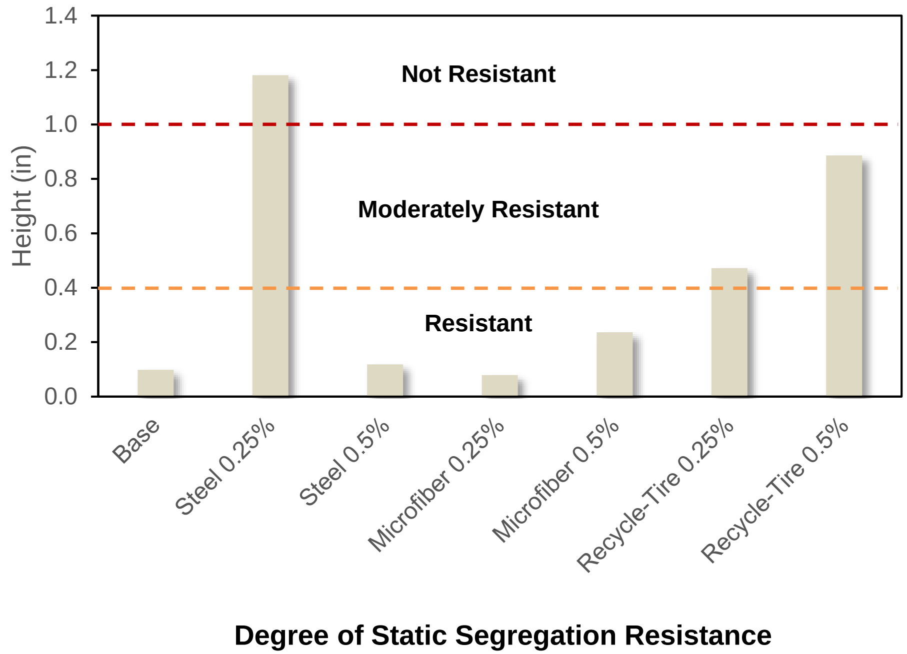
Slump Test

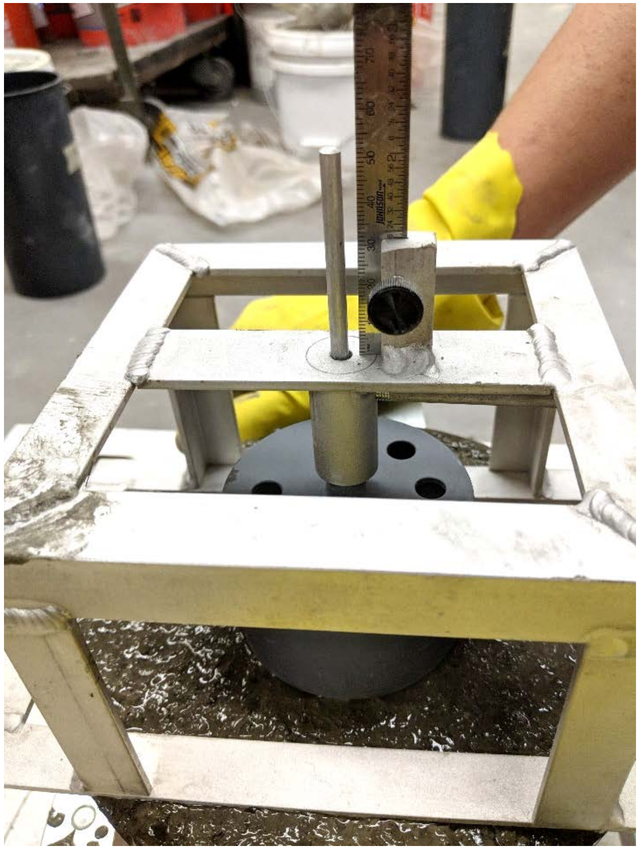
(a) Steel Fiber 0.5% (b) Steel Fiber 0.25 (c) Micro Fiber 0.25% (d) Micro Fiber 0.5% (e) Recycled Tire 0.25% (f) Recycled Tire 0.5%



# Fresh Properties – Static Stability
## (ASTM C1712)

### Higher Static Penetration = Higher Segregation



# Fresh Properties – Visual Stability Index, VSI (AASHTO T351)

Stable SCC Mix

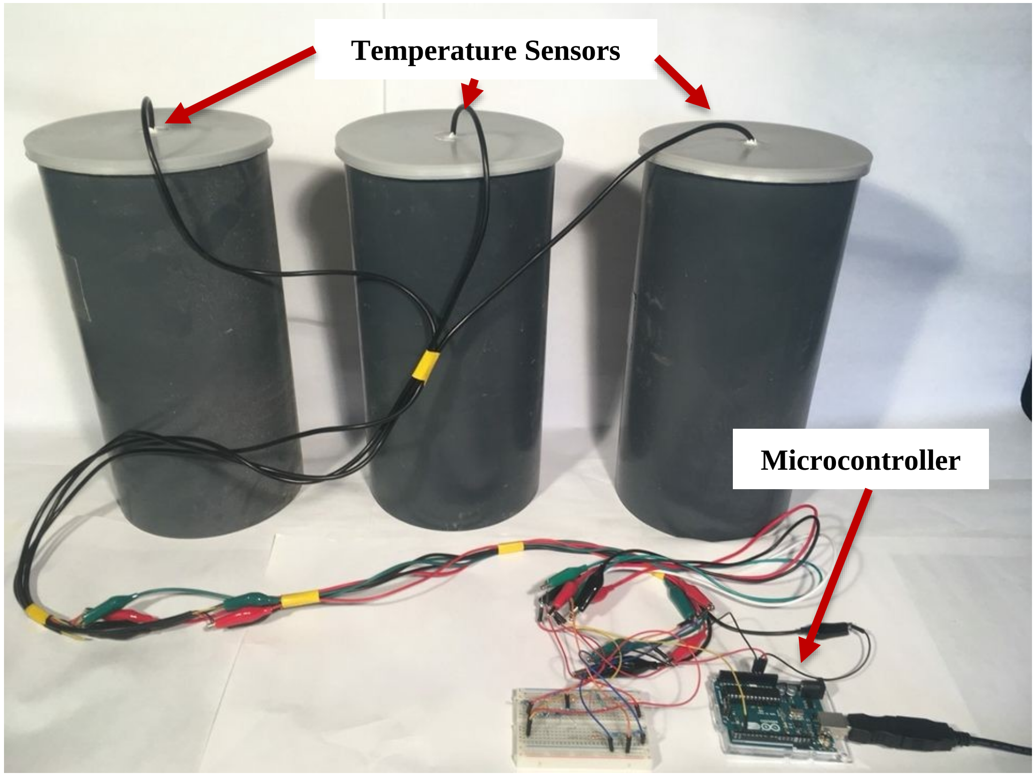
Bleeding

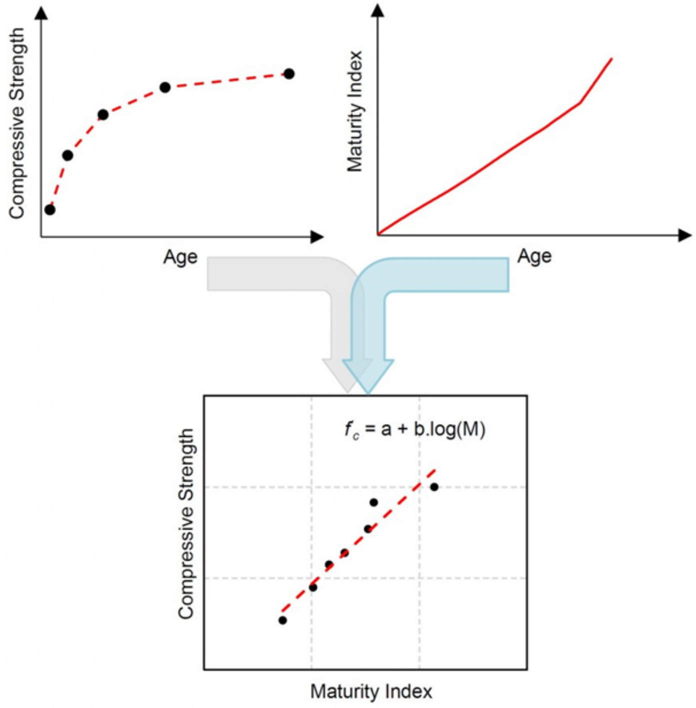
Segregation

# Maturity Index

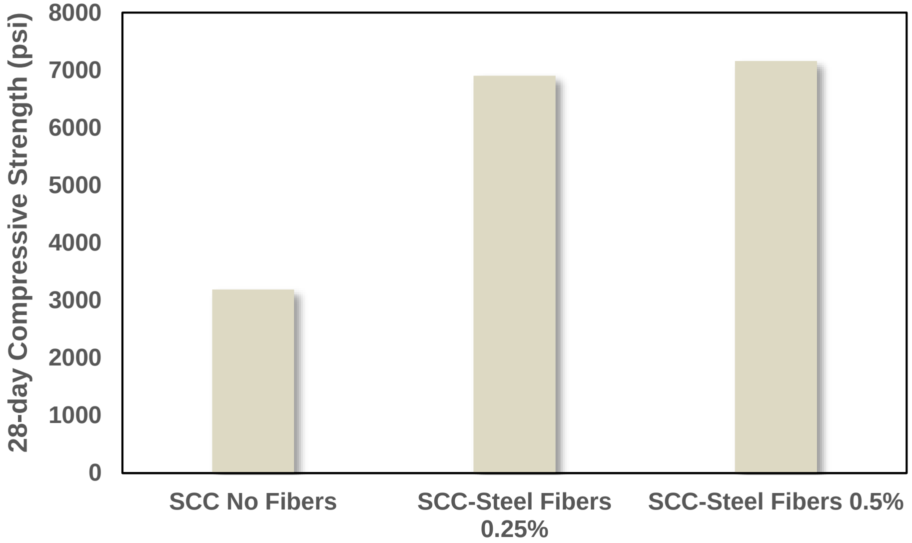
- **Estimating maturity of SCC specimens and predicting strength based on curing temperature and maturity index**

$$M = \sum_{0}^{t} (T - T_o) \cdot \Delta t$$

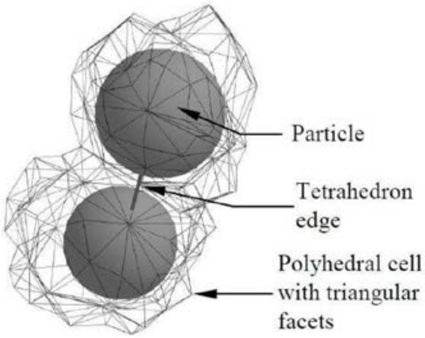


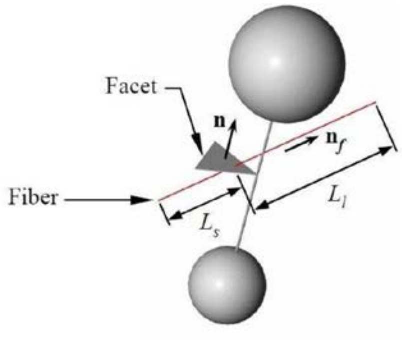
# Preliminary Results – Compressive Strength

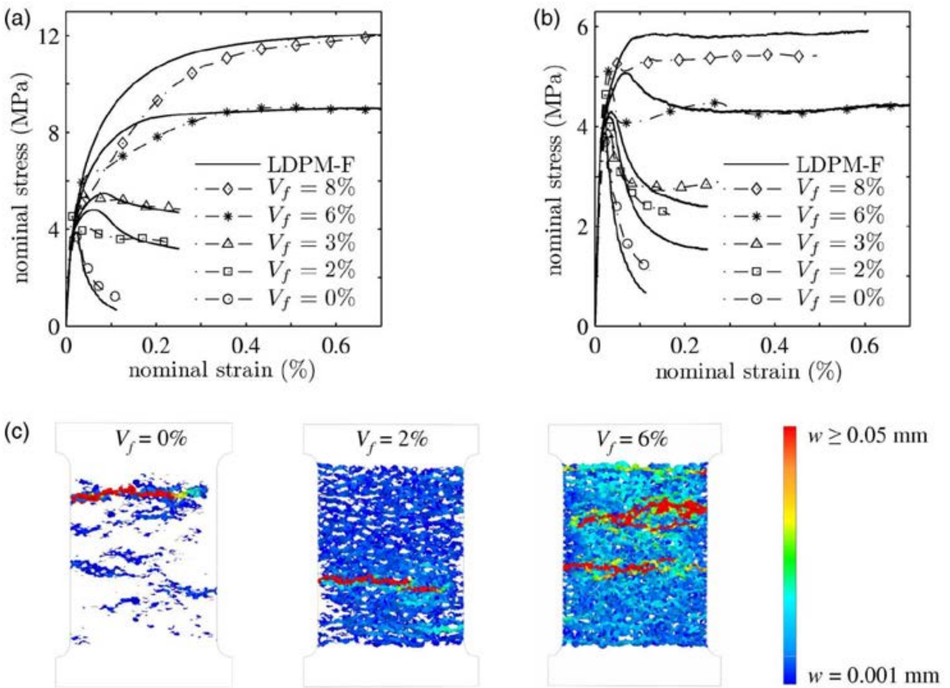


# Simulating the Response of Fiber-Reinforced SCC




Cusatis et al. 2015




Cusatis et al. 2015

# Summary

- Work is in progress in Phase II
  - Design of fiber-reinforced SCC mix proportioning
  - Selection of recycled fiber types and non-cementitious materials
  - Preparing laboratory samples
    - Fresh properties
      - Passing ability, filling ability, segregation, slump flow
    - Hardened properties
      - Compressive strength, split tensile strength, modulus of elasticity, drying shrinkage
    - Maturity
  - Developing analytical models
  - LDPM simulations

# New ACI Certificate

## ACI Self-consolidating Concrete Testing Technician Certification

- **ASTM C1610**: Standard Test Method for Static Segregation of SCC Using Column Technique
- **ASTM C1611**: Standard Test Method for Slump Flow of SCC
- **ASTM C 1621**: Standard Test Method for Passing Ability of SCC by J-Ring
- **ASTM C1712**: Standard Test Method for Rapid Assessment of Static Segregation Resistance of SCC Using Penetration Test
- **ASTM C1758**: Standard Test Method for Fabrication of a Test Specimen with SCC


ACI, 2018

# Thank You

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# Use of ECC in Shear Keys, Closure Pours, and Culvert Repairs

**Dr. Celik Ozyildirim**
Virginia DOT

VDOT

VTRC
Virginia Transportation Research Council

VDOT
Virginia Department of Transportation

*We bring innovation to transportation.*

# USE OF ECC IN SHEAR KEYS, CLOSURE POURS, AND CULVERT REPAIRS

H. Celik Ozyildirim, Ph.D., P.E.

July 11, 2018

# Outline

- ECC
- VDOT Applications
  - Shear keys
  - Closure pours
  - Culvert repairs

# ECC (engineered cementitious composite)

- ECC is a mortar mixture with PVA (polyvinyl alcohol) fibers.

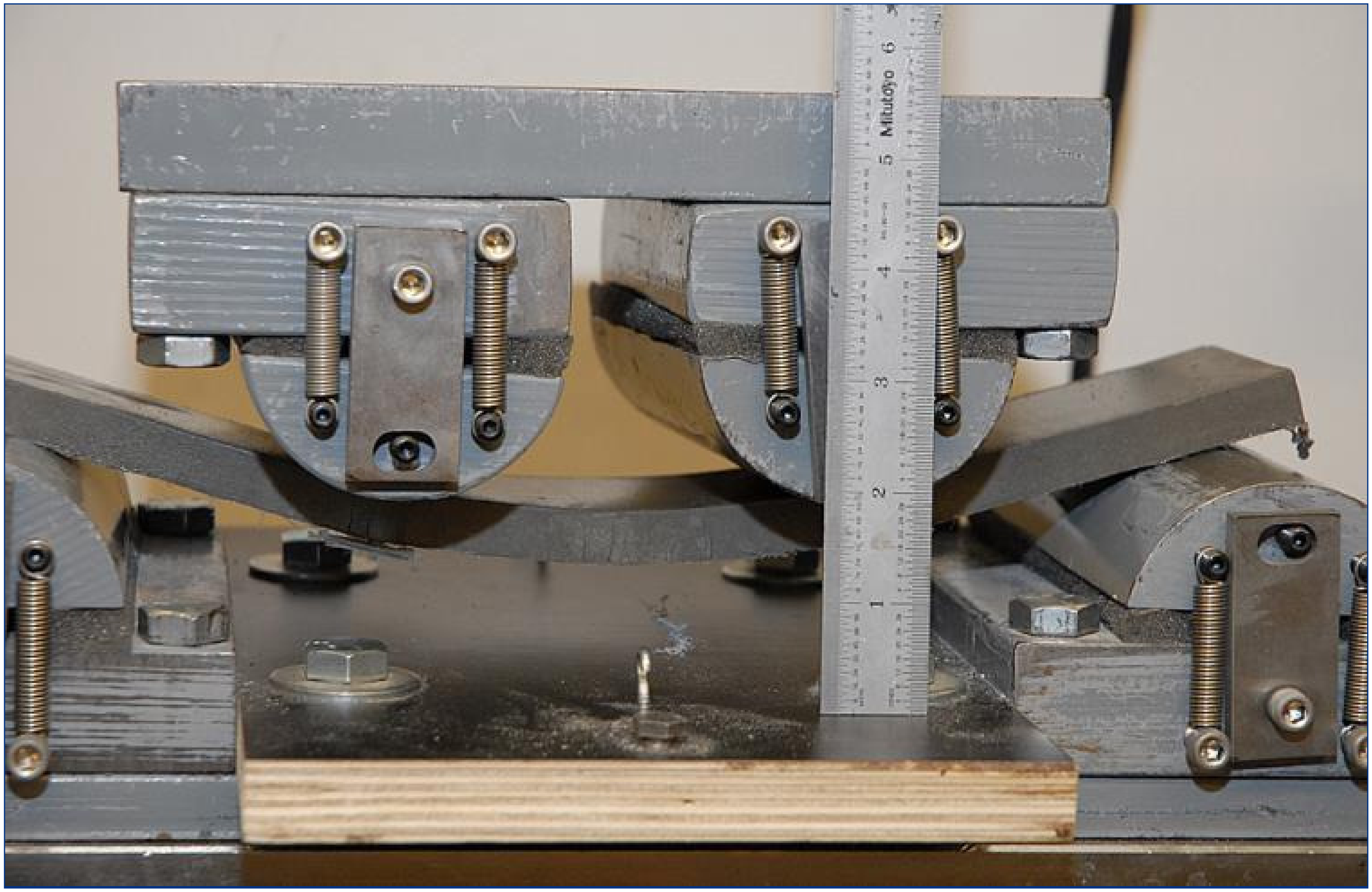
- ECC was developed by Dr. Victor Li from the University of Michigan.

# Typical ECC Mixture (lb/yd$^3$)

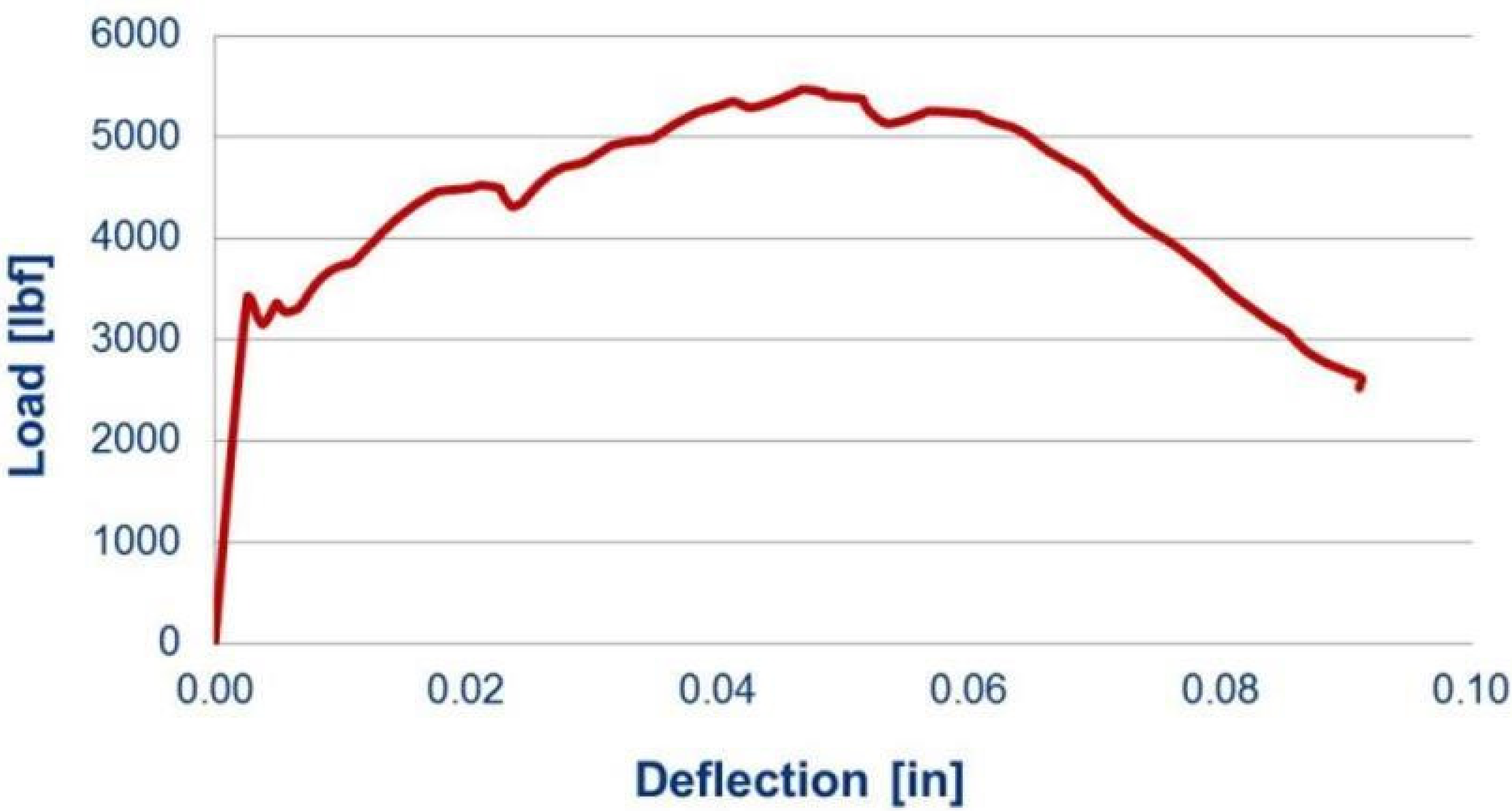
| | |
|---|---|
| Portland cement (Type I/II) | 961 |
| Class F fly ash | 1153 |
| Water | 571 |
| Mortar or concrete sand | 676 |
| Fibers (PVA) | 40-44<br>(1.8 to 2%) |
| Max w/cm | 0.27 |

Contains HRWRA; other admixtures such as workability retaining, shrinkage reducing, retarding, accelerating, viscosity modifying can be added.

# ECC



# Flexure Test - ECC with 2% (44 lb/yd$^3$) PVA fibers deflection hardens; stronger after the first crack

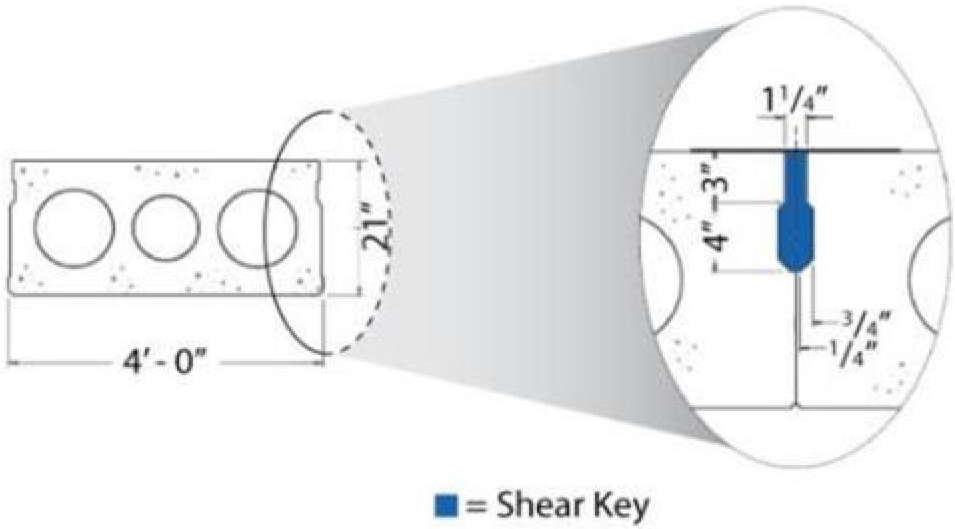


# ECC

## Deflection


## Tight cracks (<0.1 mm)

# Shear Keys




Transfer the load between beams and seal joints

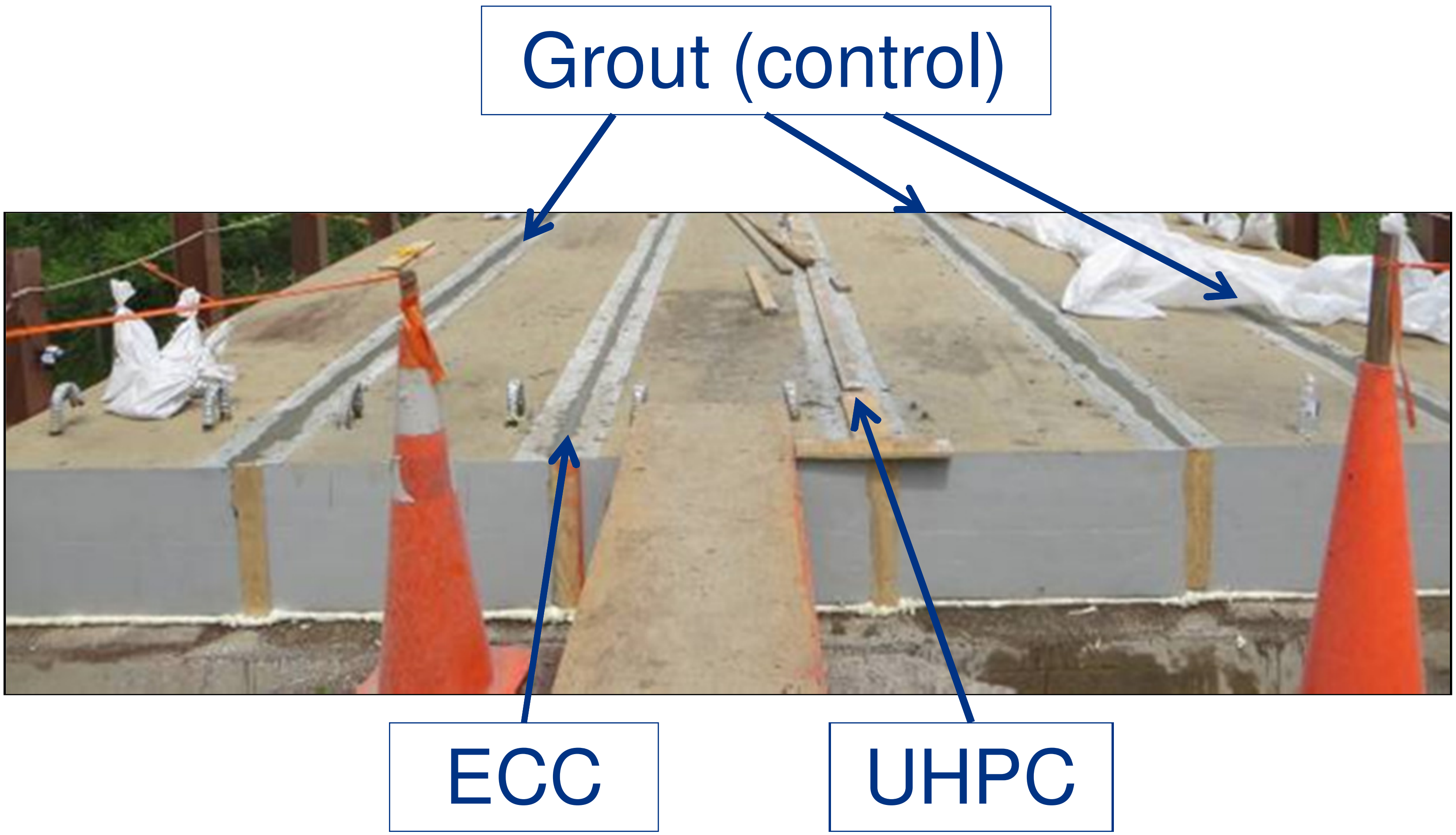
# Route 645 Bridge: Shear Keys, 2013

# Mixing

# Self- consolidating ECC with high workability is used in Shear Keys


Slump flow ranges from 18 to 21 inches

# Route 645: Shear Keys



# Route 645: ECC

- Self consolidating
- Easy to place with wooden trough
- Held shape

# Route 645 - Shear Keys

**Non-shrink grout**

**UHPC**

**ECC with PVA fibers**

**After 3 months, only ECC did not leak**

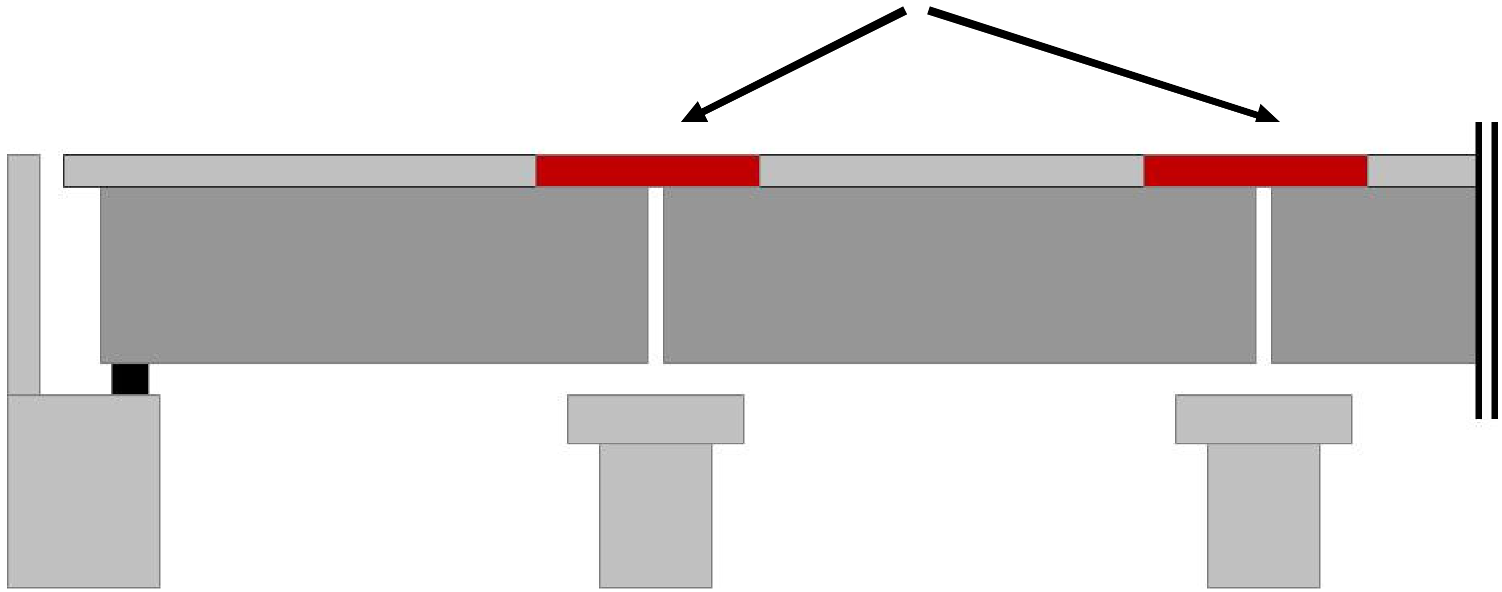
# Route 630: Shear Keys, 2014


# Route 630: Shear Keys

Easy placement of ECC. No consolidation.

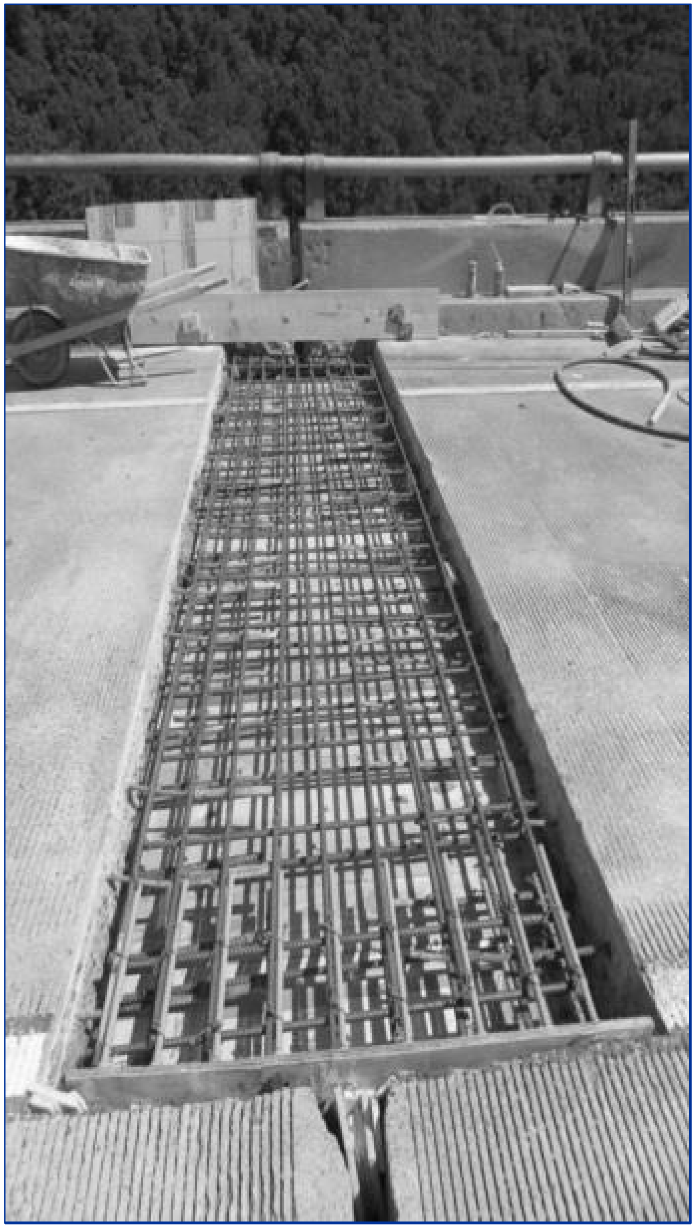
# Closure Pour (Link Slab), 2014

- Eliminate joints
- Place closure pour



# Closure Pours: I-64 over Dunlap Creek

# Joint Closure Pour



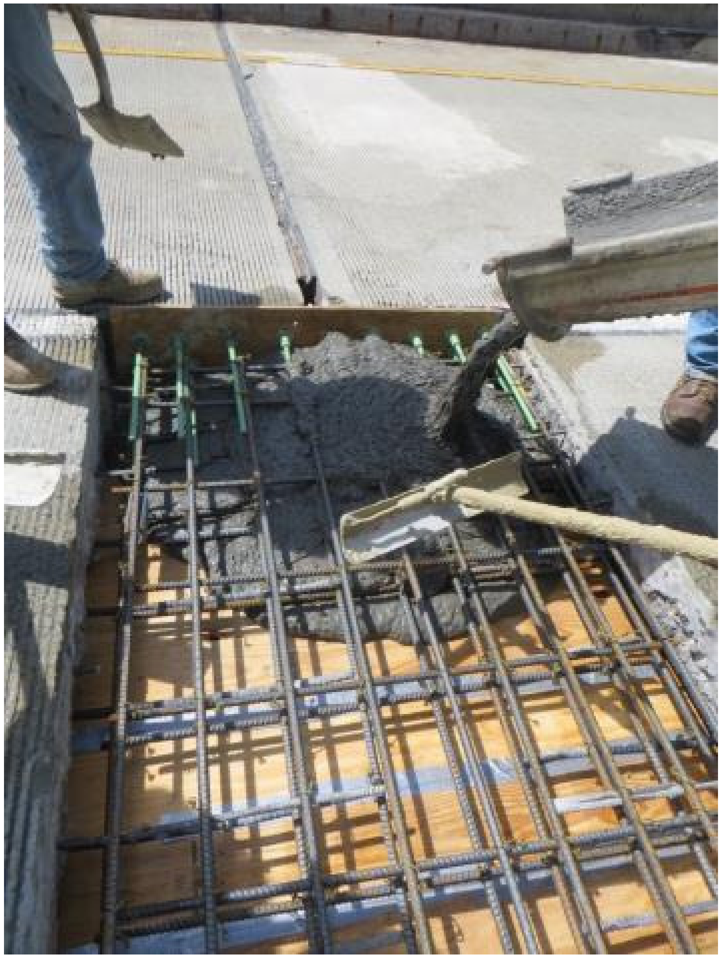
**Dimensions:**

- 16 feet long
- 4 feet wide
- 8-10 inches deep
- 2-3 $yd^3$

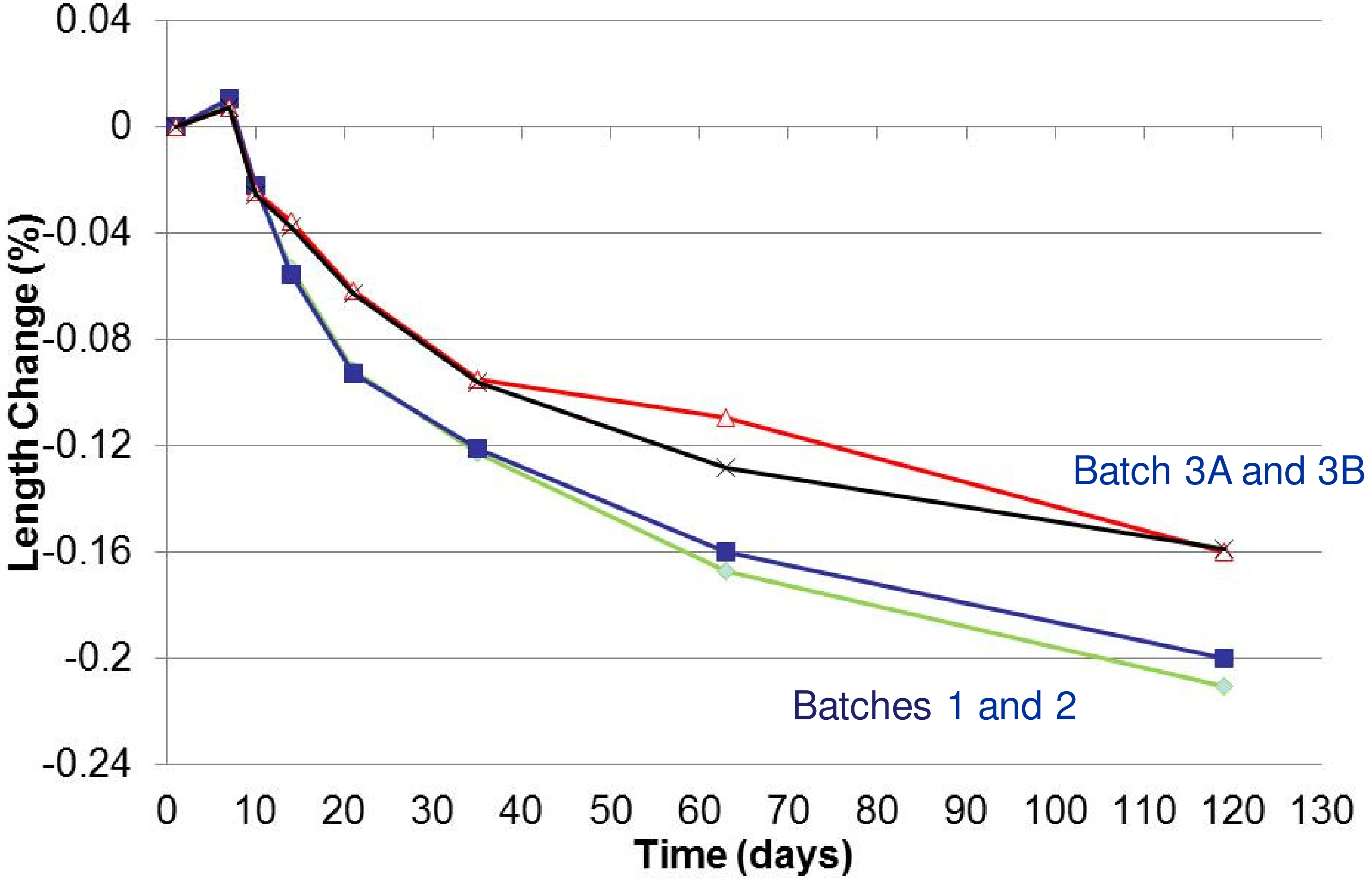
# ECC in RMC Trucks

Fibers added manually without the bags

# ECC in Closure Pours



# ECC - Shrinkage



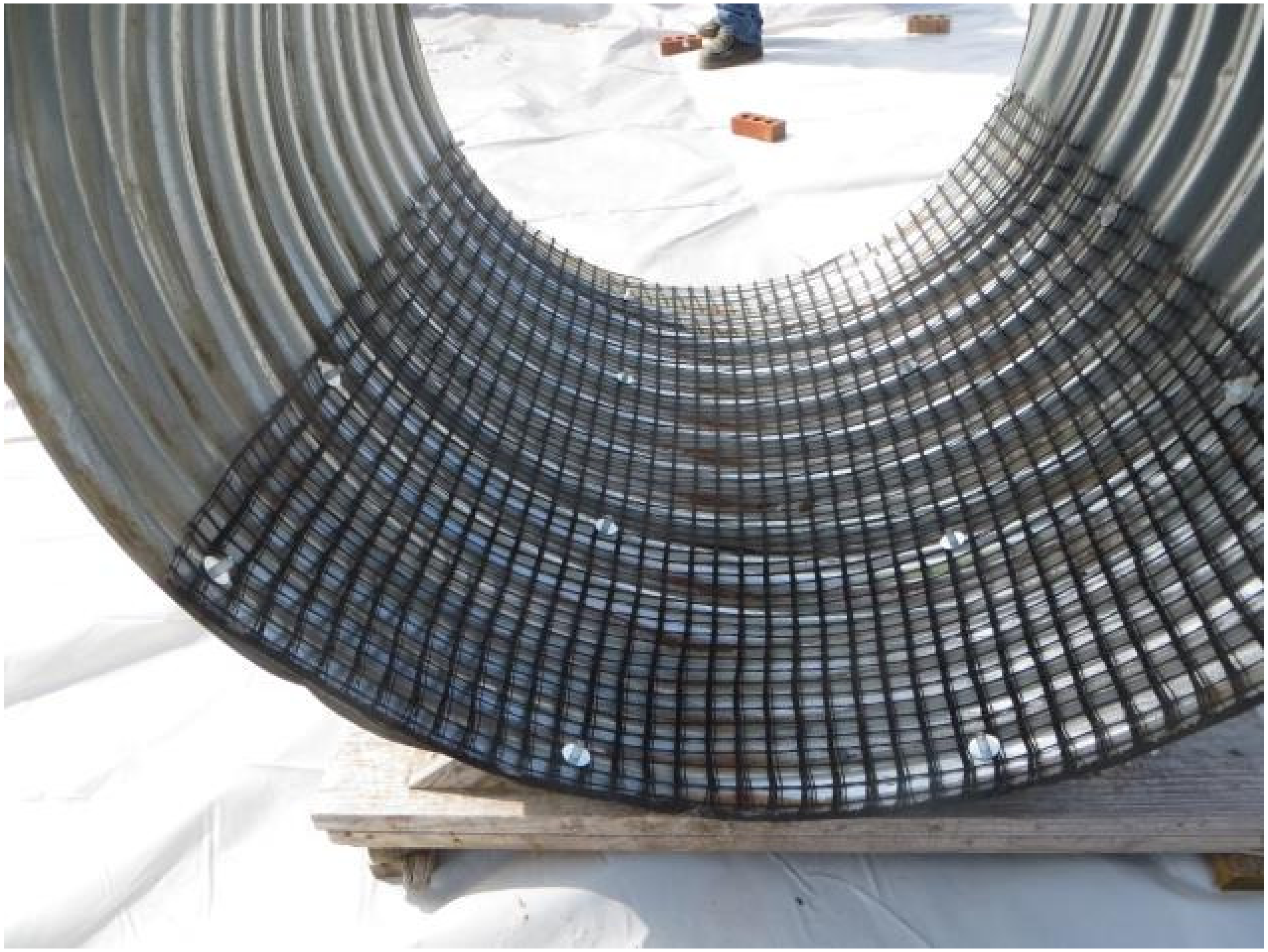
# Crack Survey

# Crack Survey

# Culvert Repair

Corrugated metal pipe (CMP) culverts made of galvanized steel are subject to abrasion and corrosion mainly in the inverts.

# Geogrid and Spacers



# First Application, 2017

## 6-ft section of a 70-ft long culvert

# High Workability  (slump flow)

# Manual Placement

Wet mix flowing down on the sides

# Completed

# Remaining Section Paved by Spraying

# Trailer Pump

# Wet Mix

ARNING
OT REMOVE OR
E THIS EQUIPMENT
OUT ALL SAFETY
DS IN POSITION

# Completed

# Stiff ECC mixture

# Stiff mix

# Vibrator

# Route 774

# Completed

# Conclusions

- ECC can be prepared with locally available materials including mortar or concrete sand.
- ECC deflection hardens and exhibits tight cracks.
- Mortar mixer and RMC trucks both can be used for mixing ECC.
- ECC is self-consolidating (for shear keys, and closure pours).
- Stiff ECC is easily sprayed with a trailer pump.

VTRC
Virginia Transportation
Research Council

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# Thank you.

# Questions?