RECLAMATION

Managing Water in the West

Protocol for Measuring the Performance of Reinforcing Steel Corrosion Mitigation Technologies for Concrete Repairs

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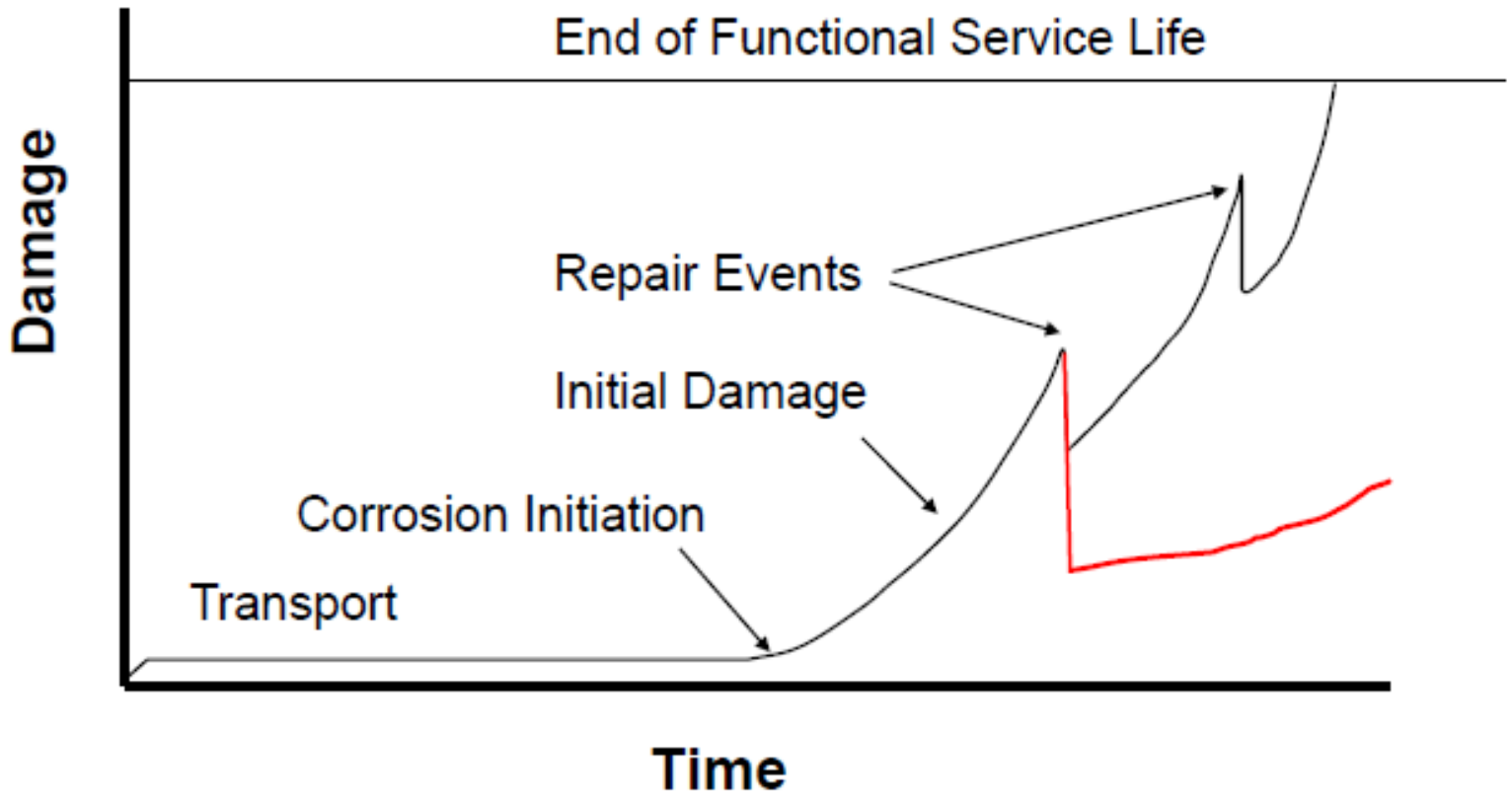
U.S. Department of the Interior
Bureau of Reclamation

Key scenario:

- An existing reinforced concrete structure has some corrosion damage evident or imminent. Spall repairs are obvious but what technology(ies) does one use to repair the spall and to minimize the frequency and quantity of subsequent repairs on the whole structure?
- Designers and owners are approached by dozens of product suppliers without much standardized testing or independent guidance.
- There is a strong feeling of paralysis or doubt on every product / technology.


End of Functional Service Life
Damage
Repair Events
Initial Damage
Corrosion Initiation
Transport
Time

13 Goals of Vision 2020

1. Mechanism for industry cooperation
2. Speed process of document creation
3. Create repair code
4. Performance based specifications
5. Improve repair material properties
6. Worker friendly materials and methods
7. Performance modeling system
8. Industry strategic research plan
9. Increase industry professionals
10. Better contract documents
11. Owner education tools
12. Condition assessment standards
13. Special repair systems

Develop a means for predicting repair system performance to help ensure the use of proper materials, design details and installation methods based upon predictive models validated by experience..

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Strategic Overview

Vision 2020 Objective:

- **Develop a test protocol which can be used to evaluate the effectiveness of reinforcement corrosion mitigation techniques for existing structures**
  - **Should be a flexible testing program that would properly evaluate the performance of current corrosion mitigation options while allowing for future innovations**

Goal and Objective

- Program goal is to develop data needed to validate a protocol for evaluating products that mitigate corrosion in reinforced concrete.
  - Products evaluated under similar conditions
  - Aid to accelerate the development of new technologies
- Both topical surface treatments and patching repair technologies are used.
- Program is close to completion
- DOES NOT GRADE TECHNOLOGIES – Simply allows for generating test data using a relevant, consistent, repeatable process

History of the Project

- 2003 - Vision 2020
- Industry Experts Suggest "Test Protocol to Measure Performance of Corrosion Prevention and Mitigation Technologies for Existing Concrete Structures"
- 2008 Organizational meetings
- 2009 Draft
- 2010 ACI Foundation Funds through SDC
- BOR Administering Contract for Phase 1

Expert Panels 2008

TAMPA FL July 2008

- Peter Emmons (Structural Group)
- Leandro Etcheverry (WP Moore)
- Yash Paul Virmani (FHWA)
- Alberto Sagues (U. of South Florida)
- Matt Miltenberger, Mukul Dehadbrai (Tourney Consulting)
- Daryl Little (US Bureau of Reclamation)
- Bill Hartt (Florida Atlantic U. - Hartt & Assoc.)
- Jack Bennett (J.E. Bennett Consultants)
- Paul Noyce (Electrotech)
- Jacques Marchand (U. of Laval)
- Kelly Page (ICRI/Repair Council)
- Tony Nanni (U. of Miami - ACI TAC)
- Fred Goodwin (BASF Construction Chemicals)

Chicago IL Sept. 2008

- P. Emmons (Structural Group)
- P. Tourney (Tourney Consulting)
- D. Little (Bureau of Reclamation
- K. Page (ICRI)
- J. Marchand (SEM Laboratories & U of Laval)
- F. Goodwin (BASF Construction Chemicals)
- A. Saguez (U of South Florida)
- A. Nanni (U of Miami and ACI TAC)

Primary Authors

M. Miltenberger (Tourney Consulting)

J. Marchand (U. of Laval / SEM Labs.)

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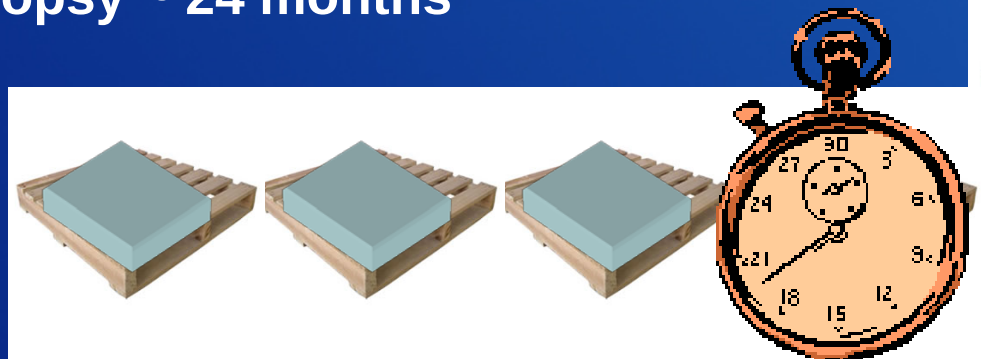
What is in the Protocol?

- Pallet size specimen
  - Small enough for handling and controlled conditions
  - Large enough to properly evaluate
- Relevant results for an array of concrete materials and treatment options
- Repeatability and reproducibility evaluation prior to evaluation scale-up
  - 100 repeatability slabs
- Corrosion initiation in ~ 1 year
- Treatment effectiveness in ~ 6 months by monitoring
  - 3 non-proprietary topical (surface applied) treatments
  - 3 non-proprietary repair (integral) options
- Eventual autopsy ~ 24 months



Evaluation of Test Protocol

- Concrete cover, 0.75 and 1.50 inches
- Water-to-cement ratios, 0.40, 0.50, 0.60
- Effectiveness of various end bar protection techniques
- Methods to accelerate corrosion
- Test corrosion mitigation mechanisms
  - Various mechanisms
  - Ability to reduce corrosion rates

Evaluation Material Types

- Integral
  - Applied within the repair material
    - Reinforcing steel coatings
    - High-performance repair materials
    - Repair materials with containing corrosion inhibitors
    - Polymer concrete
    - Discrete galvanic cathodic protection anodes
- Surface Applied
  - Applied to surface of concrete
    - Penetrating sealers
    - Coatings
    - Chemical corrosion-inhibitors
    - Combined mechanism products

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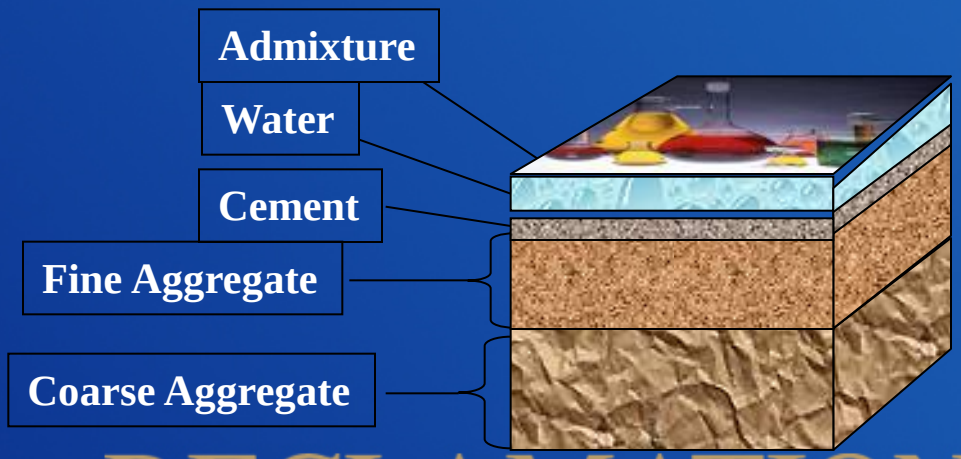
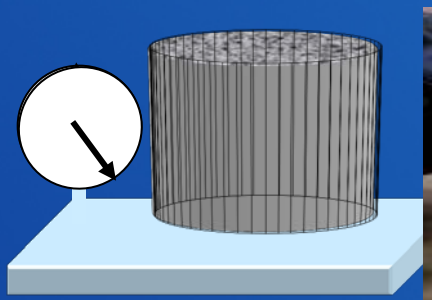
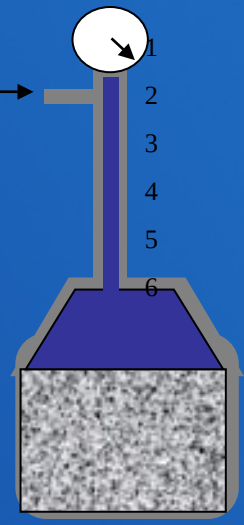
Materials (continued)

- Cement
  - ASTM C150 I/II 564 lb/yd^3
- Aggregate
  - Fine Aggregate ASTM C33
  - Coarse Aggregate ASTM C33 Gradation No. 67 Limestone
- Admixtures
  - Air entrained 6%+/-1
  - Type A water reducer
- Slump 5-8 inches



Materials (continued)





- Report
  - Density ASTM C138
  - Slump ASTM C143
  - Air Content ASTM C231
  - Temperature ASTM C192
- Cast
  - C39 Compressive Strength 21 4x8”
  - ASTM C1202 RCP 12 4x8”
  - ASTM C1556 Cl^- Diffusion 6 4x8”
  - ASTM C642 Density, Absorption Voids 2 4x8”
  - BS1881 Water Absorption 4 3x6”

U.S. DEPARTMENT OF THE INTERIOR

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1902

- 17 Western States
- 600 Dams and Reservoirs ***~RECREATION~***

- Largest Wholesaler of Water
  - 31M people
  - Irrigation to 10M acres of farmland
  - 60% of nations vegetables & 25% of fruits and nuts

- Second Largest producer of Hydroelectric Power
  - 58 Power Plants
  - 40 Billion kw hours of electricity
  - Nearly $1 Billion in revenue
  - To 6M homes

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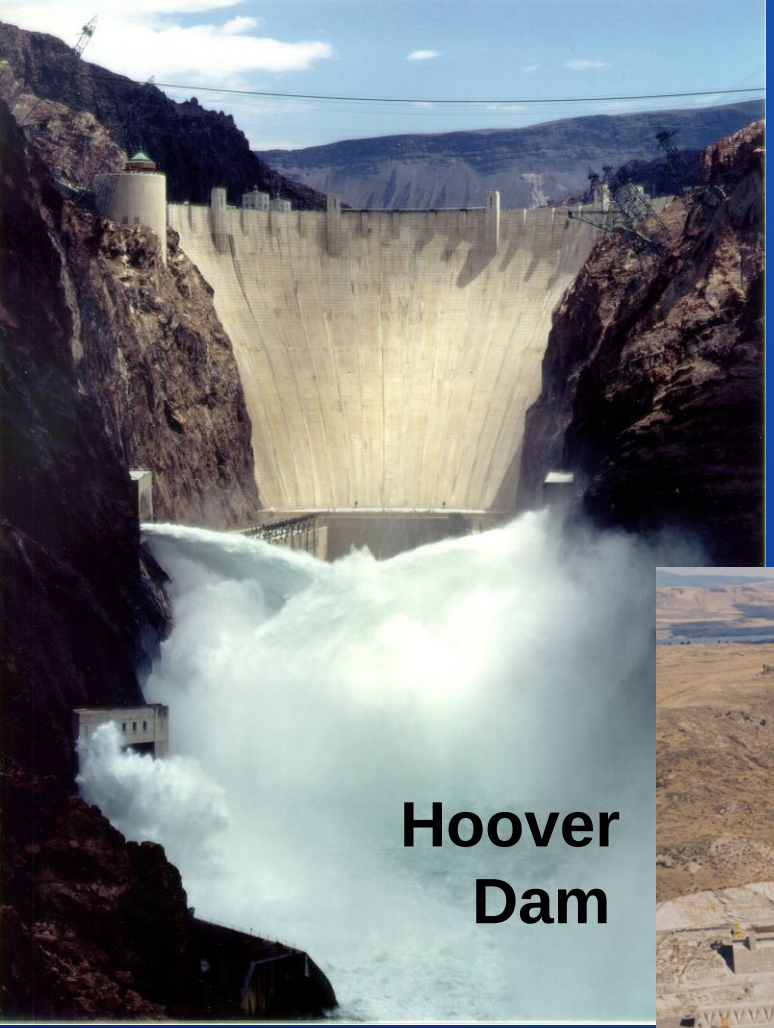

Hoover Dam

Grand Coulee Dam

Civil Engineering

Geotechnical

Environmental Resources

Water Resources

654

330 engineers,
134 scientists,
135 technical support,
55 administrative support

Infrastructure Services

Laboratory

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Contract No. R10PC80497

- 2010 ACI Foundation Funds through SDC
- Funds acceptable through authority of the Contributed Funds Act
- BOR to Administer Project Phase 1
- First step – Turn proposed protocol into a statement of work for a competitive bidding process
- Determined suitable for a small business set-aside
- Awarded to Tourney Consulting Group, LLC Kalamazoo, MI using a competitive bidding process in September 2010.

Contract Committee

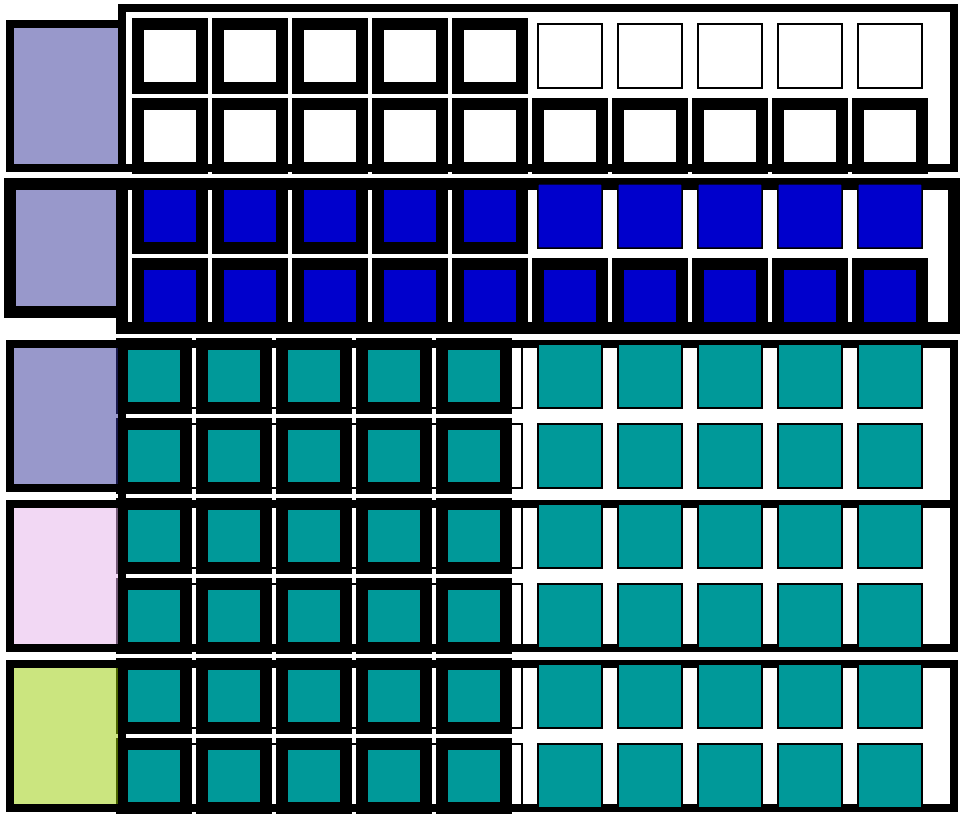
- SDC charged with forming a committee to determine
  - Specific technologies and number of technologies to use
  - When to apply/use corrosion mitigation technologies
  - Answer other questions as they come up
  - Review documents produced as a result of this work

Specimen Types

- **Slabs**
  - **Monolithic slabs for Surface Applied techniques**
  - **Hot spot slabs for Integral techniques**
- **Materials**
  - **Three W/C ratios**
    - **0.4, 0,5, and 0.6**
  - **Two Reinforcement cover depths**
    - **0.75 in. and 1.5 in.**
  - **Three Reinforcing bar end treatments**
    - **Cement paste with calcium nitrite**
    - **10% H2SO4 pickle (ASTM G 109)**
    - **0.1N Hot NaOH**

Batch Castings

		Quantity of Specimens		
Batch No.	W/C	0.75" Cover	1.5" Cover	Type (Comment)
1	0.4	5	15	Repair (15 hotspot + 5 plain)
2	0.6	5	15	Repair (15 hotspot + 5 plain)
3	0.5	10	10	Topical
4	0.5	10	10	Topical
5	0.5	10	10	Topical



100 total slabs

20 slabs per 4 yard batch of concrete

- Group of 20 slabs with W/C 0.4
- Group of 20 slabs with W/C 0.6
- Group of 60 slabs with W/C 0.5

60 Surface Applied slabs

30 with 1.5 in cover

30 with 0.75 in cover

40 Integral Repair Slabs

10 with 0.75 in cover

30 with 1.5 in cover

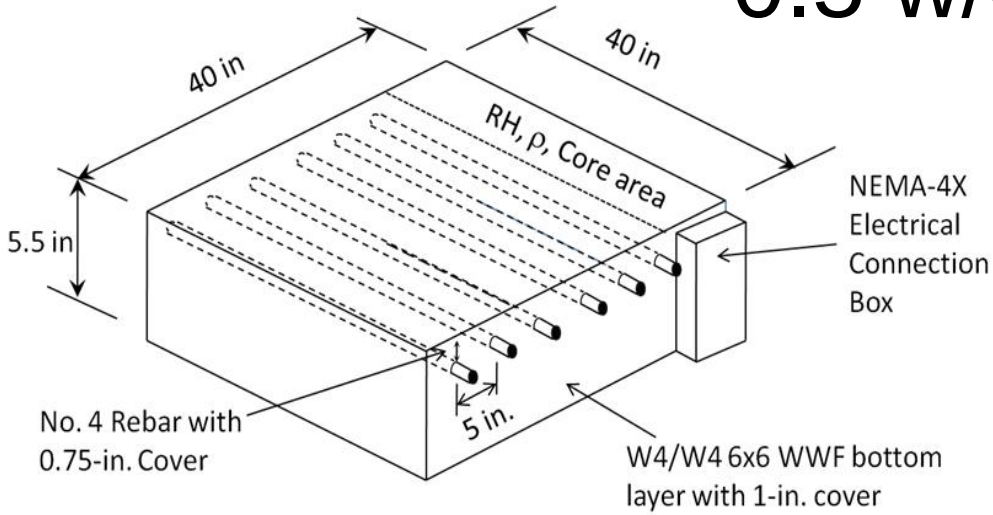
3 End Treatments: Drill, tap, and install 1/4x20SS machine screw in end of bar, remove surface rust.

Clean 4” to SSPC SP15. Coat with .5 W/C cement paste with ¼ of mix water consisting of 30% CaNO3 solution. Cover paste with heat shrink tubing. After casting and wiring, cover end with epoxy.

Per G109 -cover 4”-8” with electroplaters tape, pickle end 4” in 10% H_2SO_4 10-15 min., rinse, wire brush to SSPC SP15, cover end 5” with neoprene tubing, fill with epoxy. After casting and wiring, cover end with epoxy.

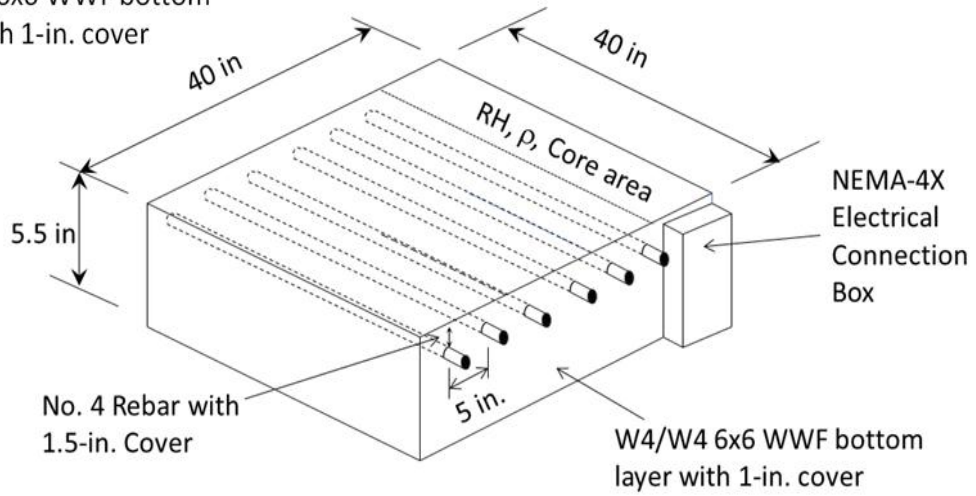
Cover 4”-8” with electroplaters tape, clean end 4” soak in 120F 0.1N NaOH 8 hr., rinse, cover end 5” with neoprene tubing, fill with epoxy. After casting and wiring, cover end with epoxy.

Monolithic Slab – Topical Treatment 0.5 w/c



30 slabs with ¾-inch cover

30 slabs with 1.5-inch cover

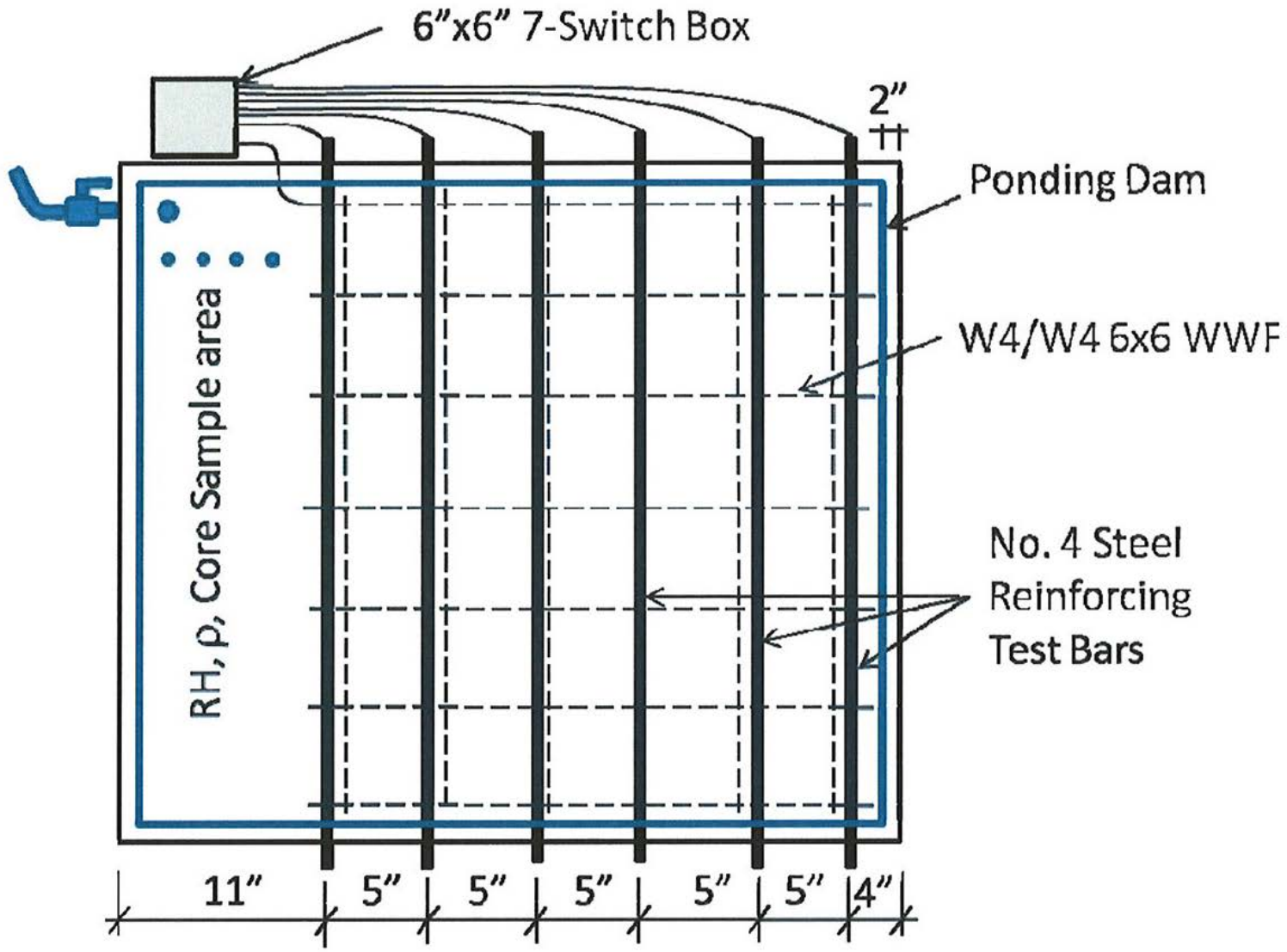


30x36” W4/W4 6x6” WWF with 1” bottom Cover

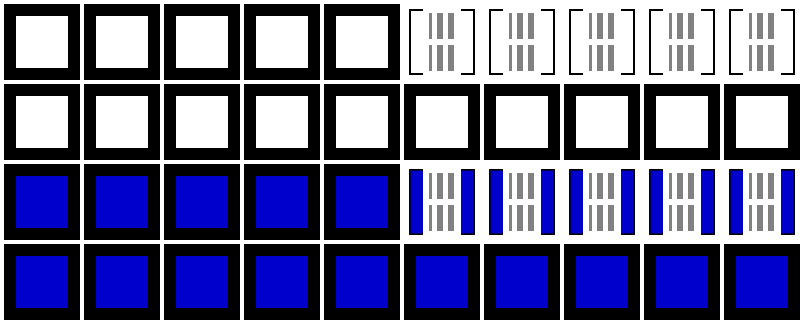
#4 Steel Reinforcing Test Bar

For RH, Resistivity, Cores
4 SS Resistivity Pins

NEMA 4 Connection Box



Top view of plain concrete specimens



Batch 1 – “Repair”

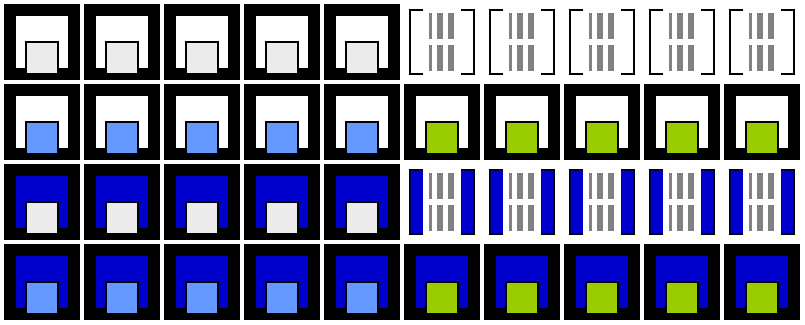
Batch 2 – “Repair”

Group of 20 slabs with W/C 0.4

Group of 20 slabs with W/C 0.6

5 Plain Slabs of Both W/C and ¾” Cover

Cast Monolithically With Discontinuous Reinforcing Steel to Compare W/C effect on Cl^- Ingress



100 total slabs

20 slabs per 4 yard batch of concrete

- Group of 20 slabs with W/C 0.4
- Group of 20 slabs with W/C 0.6

40 Integral Repair Slabs

10 with 0.75 in cover

30 with 1.5 in cover

Construct Remaining 30 Slabs (15 from batch 1 and 2) with 1 ½" Cover and 9"W x 20"L x 3"D Blockout Form Extending Below FRP Bars.

Place Concrete Around Blockout

Place 3 Different Types of Concrete Inside Blockout Area for Both W/C.

5 Plain Concrete Depressed Cover 8" W X 15" L X 1" Deep Depression

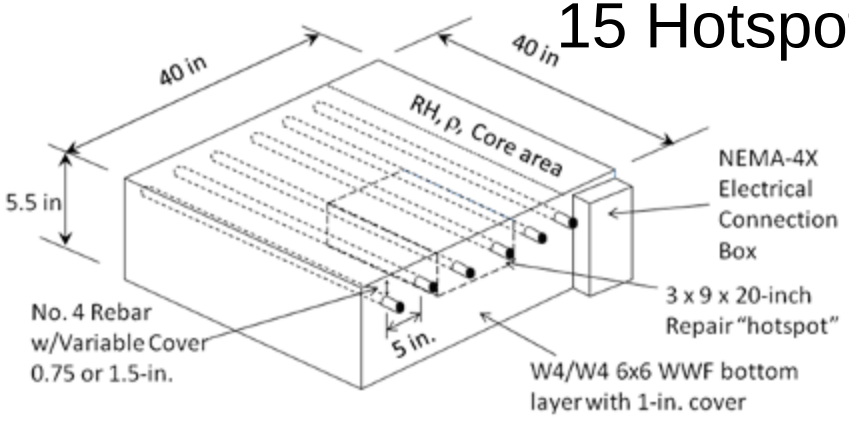
5 High W/C Ratio Concrete >0.75

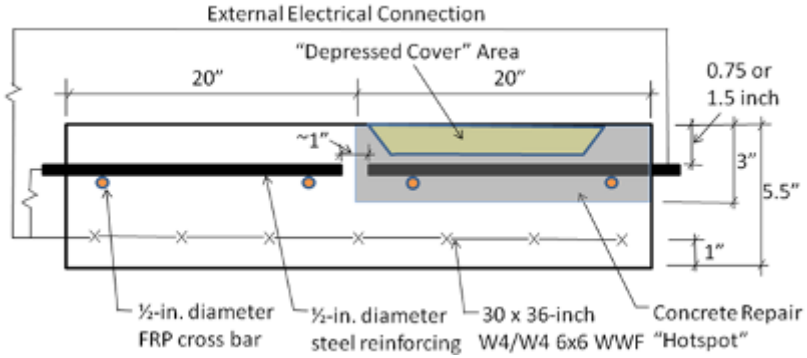
2 ft^3 of W/C 0.4 mixed with 14.6 lbs Water &

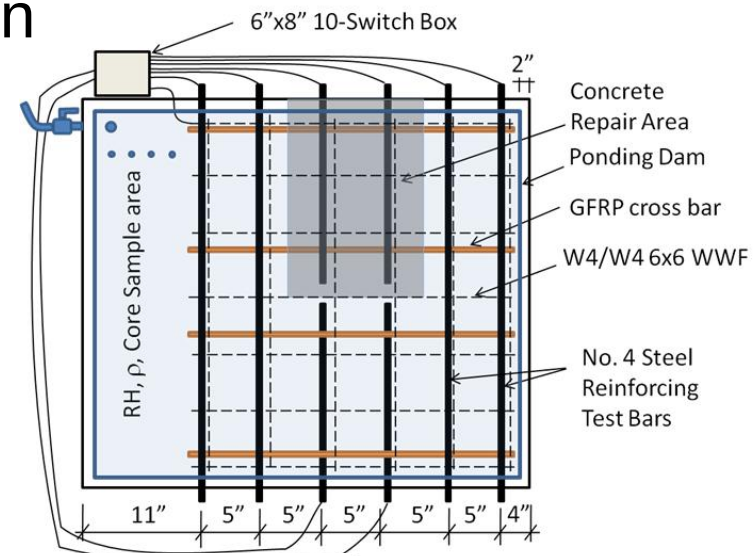
2 ft^3 of W/C 0.6 mixed with 6.3 lbs Water

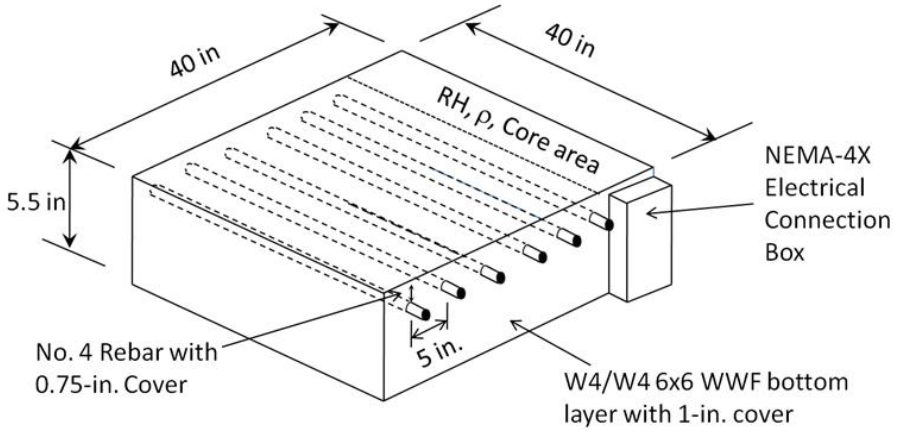
5 Chloride Spiked Concrete (2 ft^3 of Each W/C Mixed With 3 lbs $CaCl_2$)

Repair Area Slab
15 Hotspot, 5 plain









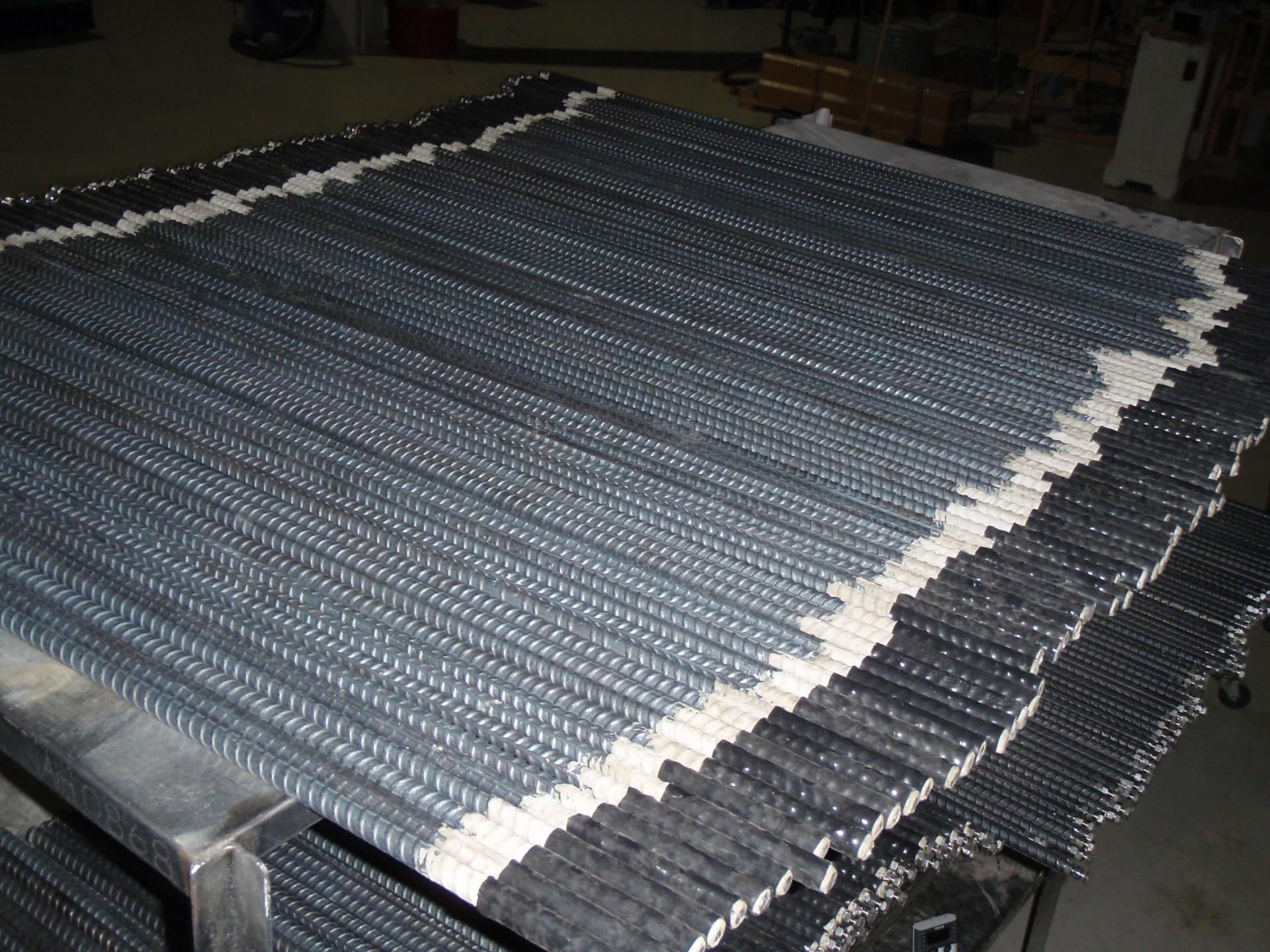
9"x20"x3"D Removable Blockout

30x36" W4/W4 6x6" WWF with 1" bottom Cover
27" FRP Cross Bar

#4 Steel Reinforcing Continuous Bar
6 20" #4 Steel Reinforcing Discontinuous Bar
Nylon Zip Ties Join FRP and Test Bars

For RH, Resistivity, Cores
4 SS Resistivity Pins

NEMA 4 Connection Box

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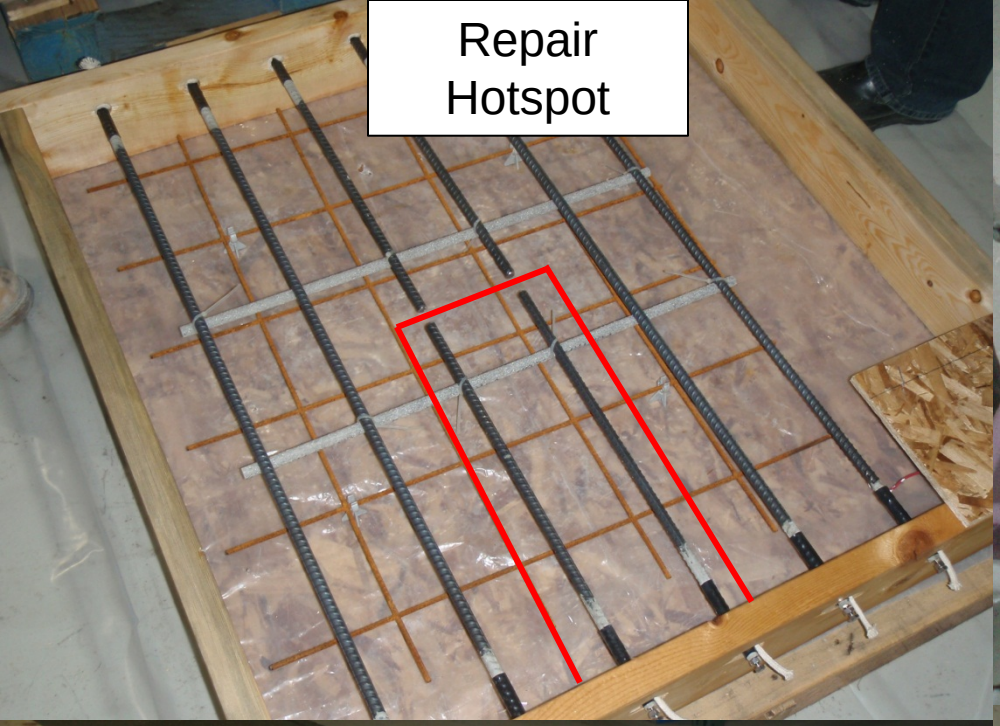

Repair
Hotspot

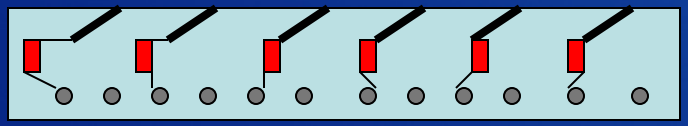

Depressed Cover

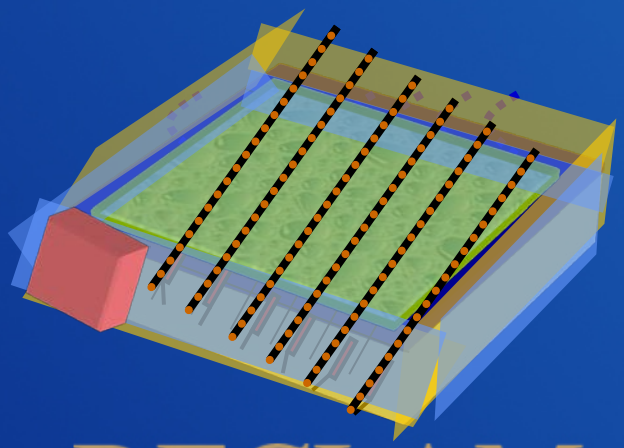
Mixture Characterization

- Fresh Properties
- Compressive Strength (ASTM C39)
- RCP (ASTM C1202)
- Chloride Content (ASTM C1152)
- Bulk Diffusion (ASTM C1556)
- Density, Absorption, and Voids (ASTM C 642)
- Water Absorption (BS 1881)
- STADIUM® Transport Properties

Next Steps

- Bull Float, Tool Edges, Float, & Light Broom Finish
- Cure Slabs With Blanket or Burlap &Plastic for 7 Days
- Dry Slabs One Week
- Connect Individual Reinforcing Bars to WWG With 1.0 ± 0.1Ω 1 Watt Shunt Resistor With >AWG 16 Stranded Copper
- Connections and Test Points Inside NEMA 4 Box
- Coat Sides of Slabs, Ends & Connections With Epoxy
- Adhere 2” Dam to Slab Perimeter with Neutral Cure Silicone
- Pond with 5.0 ± 0.1% NaCl Each 2 Weeks
- Dry Other 2 Weeks <70% RH
- Repeat Until Corrosion Onset





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4
5
KOMATSU


G4
G3
G2
6
7

Test Procedure

Outcomes

- Time to Corrosion and Variation
  - 180 bars ¾” cover W/C 0.5
  - 180 bars 1 ½” cover W/C 0.5
  - 30 bars ¾” cover W/C .4
  - 30 bars ¾” cover W/C .6
- Cl^- Threshold when corrosion is initiated
- Current when corrosion activity is sustained vs time to corrosion
- Repeatability of time to corrosion
- Batch to batch variation for each mix and cover
- Conditioning period prior to treatment vs depth of cover
- Water content vs time to corrosion
- Variability of macrocell corrosion measurements
- Determine minimum lot size for treatment evaluation
- Macrocell corrosion current vs
  - Temperature
  - Internal RH
  - Cl^- contamination level for corrosion
  - Electrical resistance vs other variables
- Effectiveness of different Hot Spot techniques for evaluation of internal treatments
- Effectiveness of different reinforcing bar end treatments
- Ability of program to evaluate different GENERIC corrosion mitigation treatments

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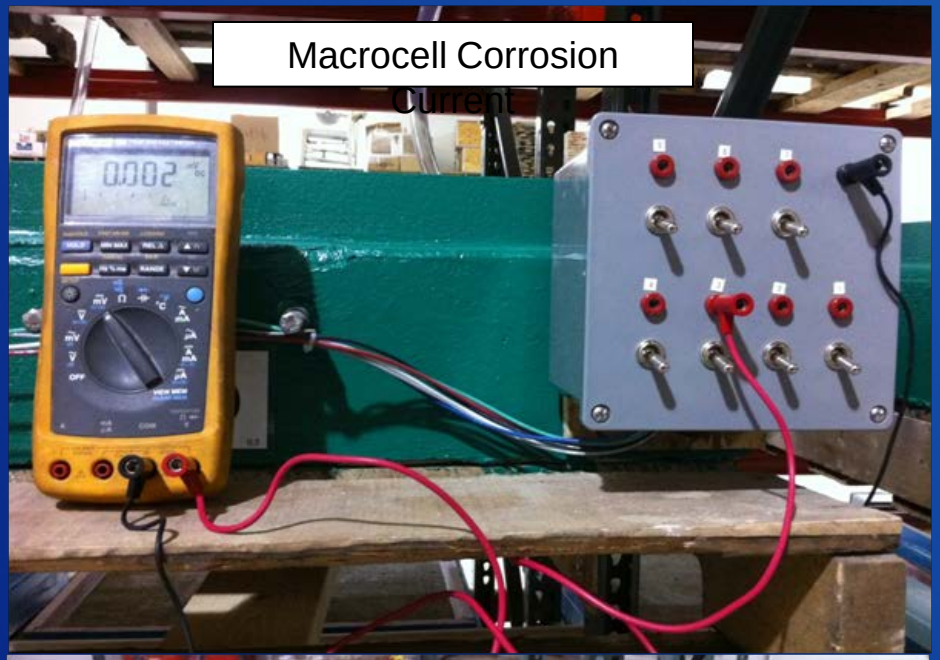
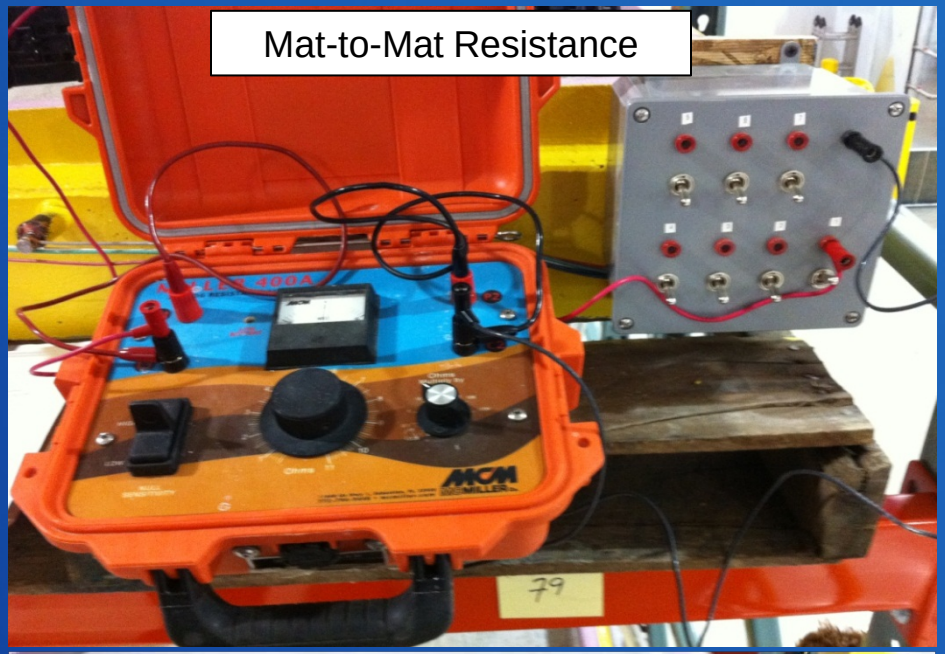
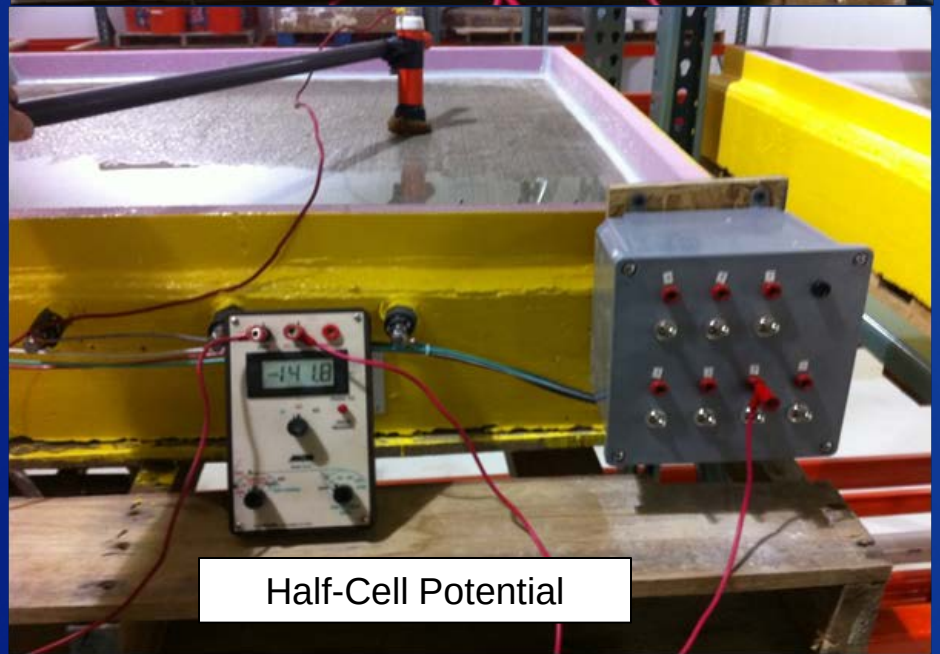
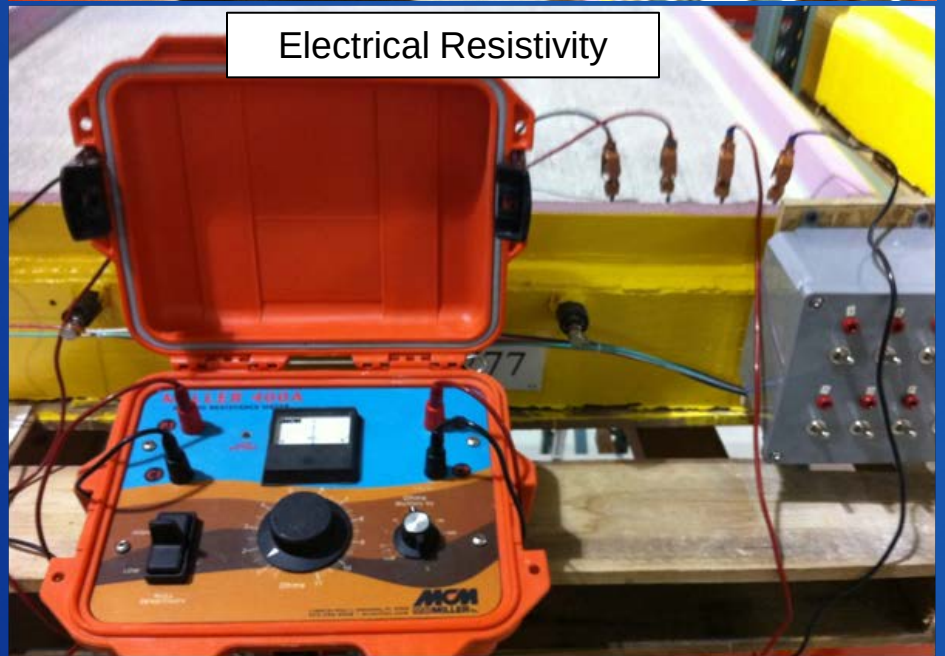
Corrosion Monitoring









Summary after about 6 months (4/11)

Corrosion Condition Summary (Surface Repair Slabs)

Surface Treatment Slabs 0.75" Cover					
Batch No.	Specimen ID	No. of Slabs	Cycle	Corrosion Initiation	Bars Corroding
1	0.40 w/c	5	6	100%	95%
2	0.60 w/c	5	6	90%	88%
3	0.50 w/c	10	5	82%	78%
4	0.50 w/c	10	5	88%	80%
5	0.50 w/c	10	4	85%	80%

Surface Treatment Slabs 1.5" Cover					
Batch No.	Specimen ID	No. of Slabs	Cycle	Corrosion Initiation	Bars Corroding
3	0.50 w/c	10	5	0%	0%
4	0.50 w/c	10	5	0%	0%
5	0.50 w/c	10	4	0%	0%

Product Selection

Patch Repair Treatments:

- Rebar Coatings
- Galvanic Anodes
- Mortars with Inhibitors

Electrochemical Treatments:

- Cathodic Protection
- Chloride Extraction
- Electro-Phoresis

Surface Treatments:

- Silane Sealers
- Epoxy/Resin Coatings
- Corrosion Inhibitors (Several Chemistries)
- Elastomeric Membranes
- Silicates

Surface Treatment Program

Surface Treatment:

- Allow slab to dry for a minimum of 1 week
- Do not repair hotspot (or eliminate?)
- Clean and prepare surface using abrasive technique (shotblasting)
- Install 3 grout-filled potential wells with caps for membrane & coating series
- Photo document preparation
- Apply surface treatment/coating according to manufacturer instructions
- Allow treated surface to remain dry for at least one week prior to ponding
- Reinstall dams
- Resume cyclic ponding and monitoring

Monitoring:

- Macrocell current between top and bottom mat across 1-ohm shunt
- Microcell corrosion current in and adjacent to hotspot (quarterly)
- Corrosion potential map of surface
  – ~12-inch grid or potential wells @ end of wet cycle)
- Internal temperature and RH
- Internal electrical resistivity (4-pin measurement)

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Batch Castings

		Quantity of Specimens		
Batch No.	W/C	0.75" Cover	1.5" Cover	Type (Comment)
1	0.4	5	15	Repair (15 hotspot + 5 plain)
2	0.6	5	15	Repair (15 hotspot + 5 plain)
3	0.5	10	10	Topical
4	0.5	10	10	Topical
5	0.5	10	10	Topical

Topical Mitigation Treatment Timing

Corrosion Mitigation should be applied when:

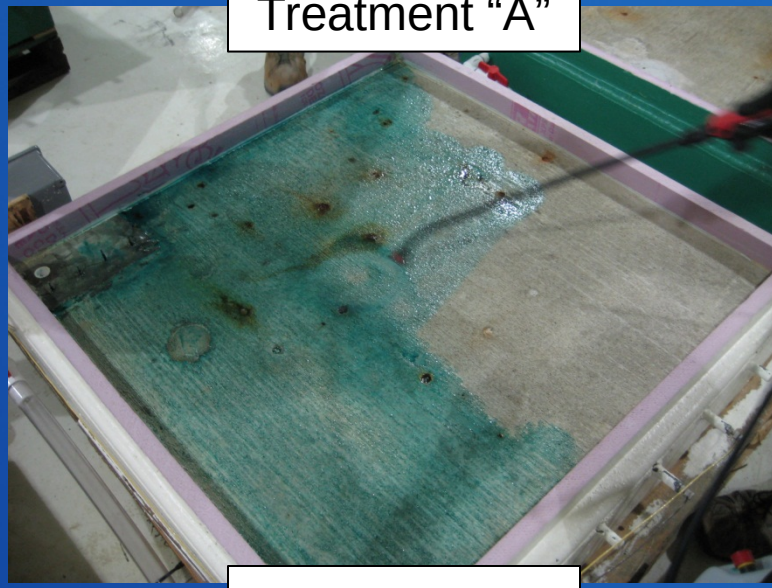
- 750 Coulombs is reached on average; and
- At least half the rebar have reached ≥ 750 C; or
- Any single rebar has exceeded 5000 C
- Before Cracking

Treatments Applied – 0.75” Cover Topical Slabs – Applied June 2011

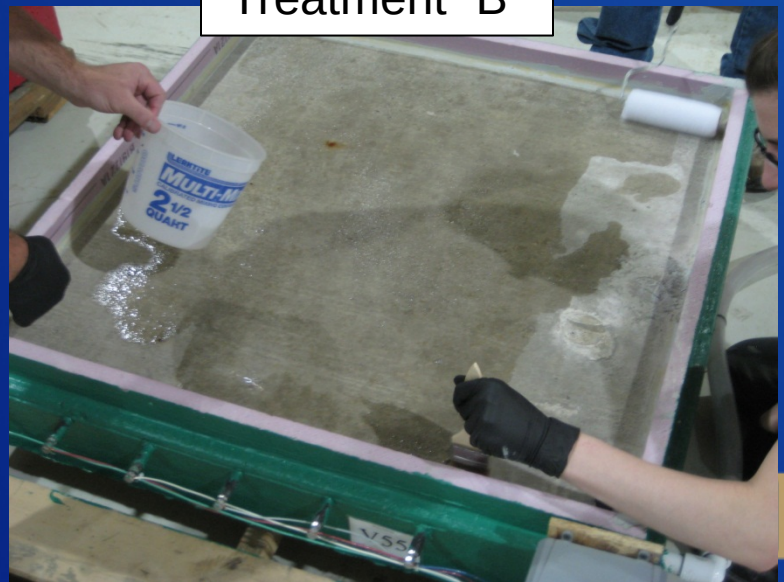
Topical Treatments

- **A – Inhibitor – Calcium Nitrite**
- **B – Sealer – 40% silane**
- **C – Membrane Urethane/Epoxy Coating**

Treatment “A”



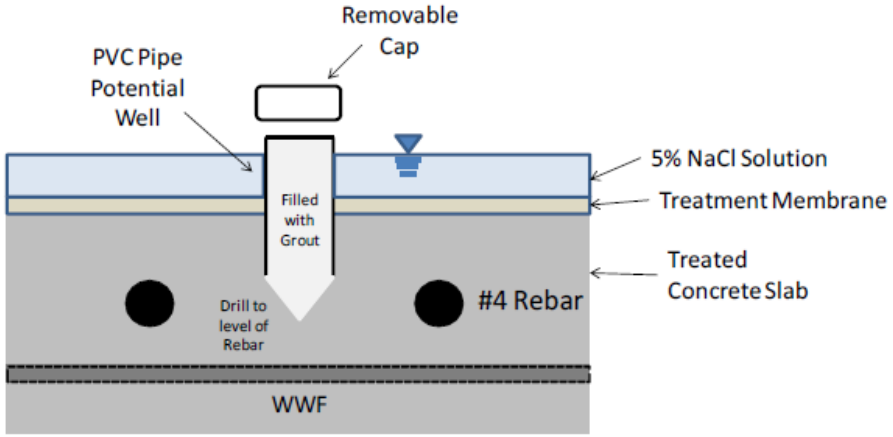
Treatment “B”

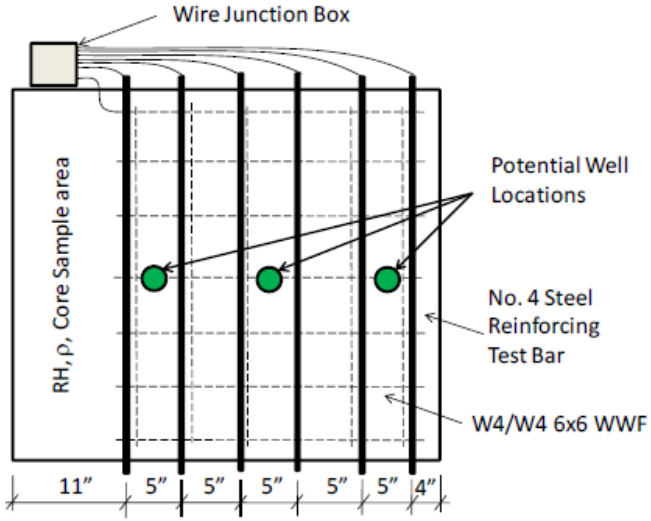


Treatment “C”

Potential Well Construction

Potential wells were installed to enable half-cell potential measurements beneath the membrane





Each potential well functions for measuring two rebar

RECLAMATION

Treatments Applied - .75 inch cover

- Testing Recently Completed

of Slabs per Treatment

Batch #	Control	Topical Treatment			TOTAL
		A	B	C	
1 (0.40 w/c)	3	2	-	-	5
2 (0.60 w/c)	3	2	-	-	5
3 (0.50 w/c)	4	2	2	2	10
4 (0.50 w/c)	4	2	2	2	10
5 (0.50 w/c)	4	2	2	2	10

Batch #'s 1, 3, & 5 treated on June 7, 2011
Batch #'s 2 & 4 treated on June 21, 2011

Destructive Analysis Of .75 Inch Cover Slabs

- For slabs in batches 3 – 5
- One of each slab type – Control and treatment
- Results in December

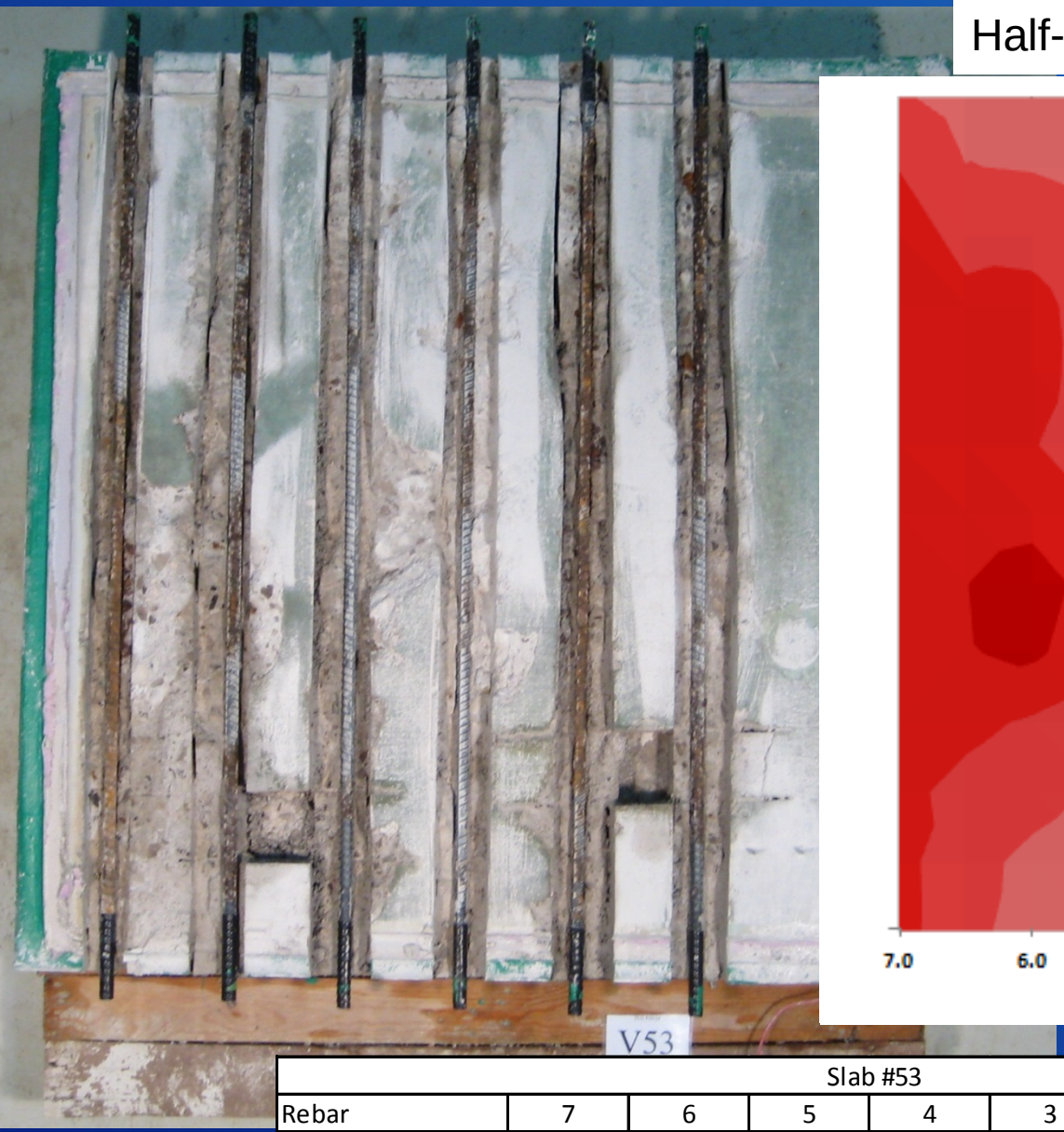
Destructive Analysis

- Two slabs autopsied
  - Slab 46 with low macrocell corrosion rate
  - Slab 53 with high macrocell corrosion rate
- Tests performed
  - Macrocell
  - Corrosion potential map
  - Chloride profile at most negative and positive corrosion potential site
  - Degree of corrosion
  - Exam of end treatments
- Findings
  - Good correlation between corrosion damage macrocell current
  - Potential mapping identifies high damage to reinforcing bars
  - Average total macrocell corrosion for applying repairs is valid

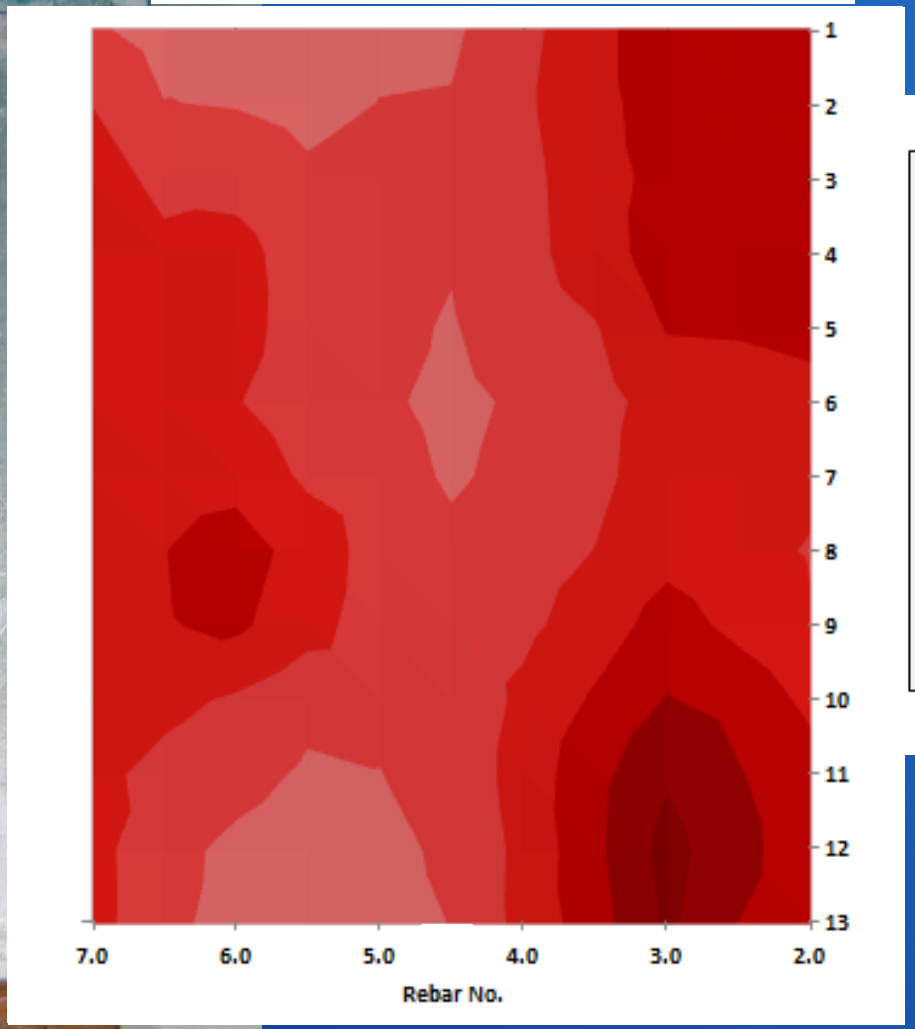
Destructive Analysis – Slab #53

- Batch #3
- 0.50 w/c
- 0.75” Cover
- Treated w/ CNI

ATION



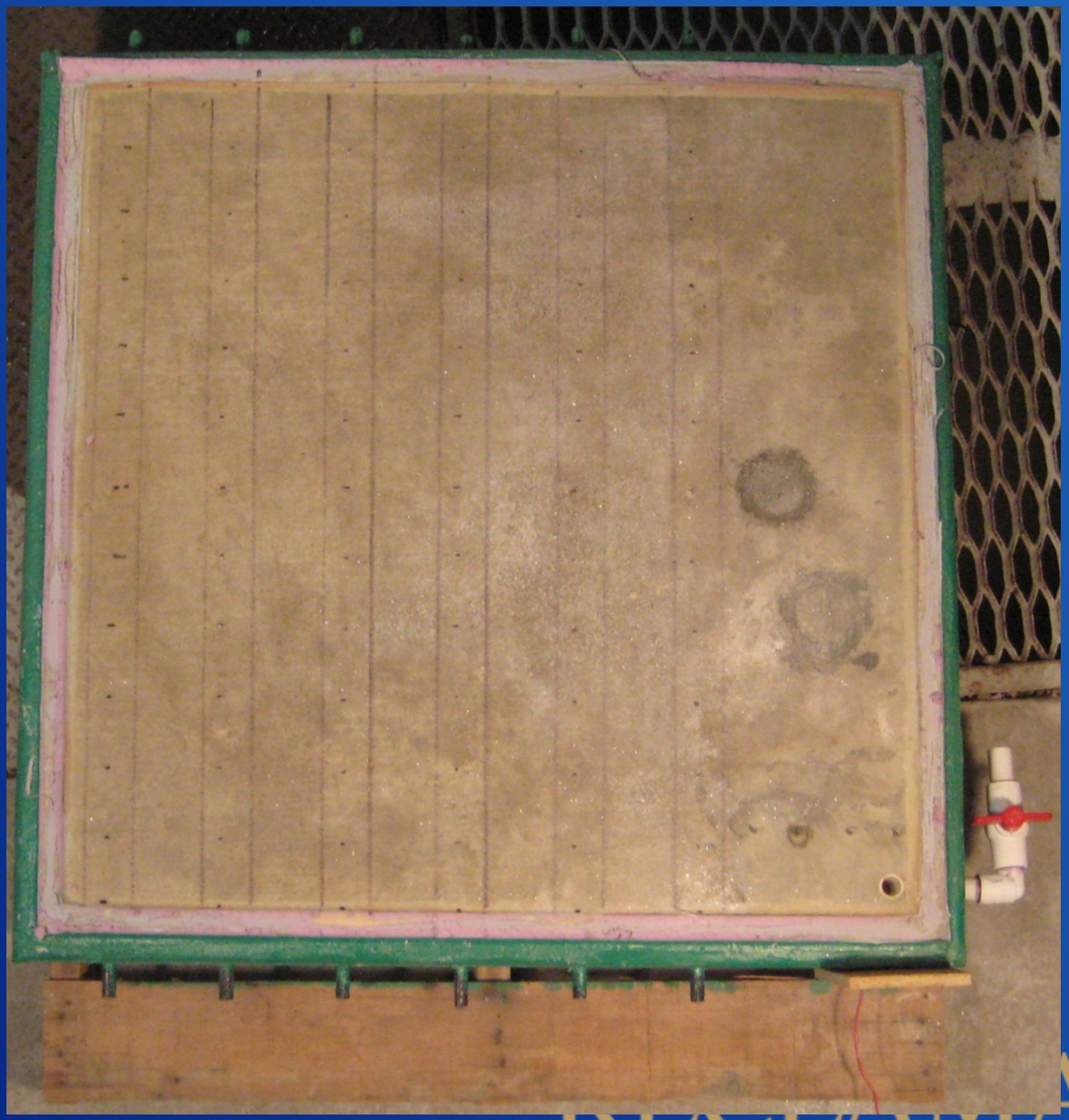
Half-Cell Potential, -mV CSE_{77}



Slab #53								
Rebar	7	6	5	4	3	2	Average	Total
Integrated Current (Coulombs)	10128	34483	656	0	10669	35106	15174	91042
Half-Cell Potential (mV CSE_{77})	-514	-562	-428	-395	-529	-508	-489	-

Destructive Analysis – Slab #46

Batch #3
0.50 w/c
1.5” cover
No treatment
- Autopsy prior to treatment to quantify level of corrosion at time of treatment



Topical Treatment – 1.5 inch Cover

Batch Castings

		Quantity of Specimens		
Batch No.	W/C	0.75" Cover	1.5" Cover	Type (Comment)
1	0.4	5	15	Repair (15 hotspot + 5 plain)
2	0.6	5	15	Repair (15 hotspot + 5 plain)
3	0.5	10	10	Topical
4	0.5	10	10	Topical
5	0.5	10	10	Topical

Topical Slab Treatment Criteria

Corrosion mitigation should be applied when:

Level 1)

- 750 Coulombs is reached on average; and
- At least half the rebar have reached ≥ 750 C; or
- Any single rebar has exceeded 5000 C

Level 2) (Batch #5 Only)

- 1500 Coulombs is reached on average

Treatments started in May 2012

Topical Slab Treatment – 1.5-inch cover

Topical Treatments (Suggested based on Autopsy results)

- A - Calcium Nitrite Inhibitor (Do not retest)
- B - 40% Silane Sealer (*Test at 2 levels of corrosion activity)
- C - Urethane/Epoxy Coating Membrane

# of Slabs per Treatment (Better Statistics)

Batch #	Control	Topical Treatment			TOTAL
		A	B	C	
1 (0.40 w/c)	-	-	-	-	-
2 (0.60 w/c)	-	-	-	-	-
3 (0.50 w/c)	3	-	3	3	10
4 (0.50 w/c)	4	-	3	3	10
5 (0.50 w/c)	4	-	6*	-	10

First slab in Batch #3 autopsied to quantify corrosion

Patch Repair Program

Patch Repair:

- Concrete removal and patch repair using abrasive blast prep.
- Photo document patch preparation
- Reinstall dams as necessary
- Resume cyclic ponding and monitoring

Monitoring:

- Macrocell current between top and bottom mat across 1-ohm shunt
- Corrosion potential map of surface (~12-inch grid)
- Galvanic current (anode series only)
- Microcell corrosion rate (NDT) in and adjacent to hotspot (quarterly)

Hot Spot Treatments

Batch Castings

		Quantity of Specimens		
Batch No.	W/C	0.75" Cover	1.5" Cover	Type (Comment)
1	0.4	5	15	Repair (15 hotspot + 5 plain)
2	0.6	5	15	Repair (15 hotspot + 5 plain)
3	0.5	10	10	Topical
4	0.5	10	10	Topical
5	0.5	10	10	Topical

Hot Spot Repair Criteria

Corrosion mitigation should be applied when:

- 500 Coulombs is reached on average outside the hot-spot

Six slabs to be used for autopsies – 2 each at 500 C, 1000 C and 2000 C average or when testing is complete.

Hot Spot Treatments

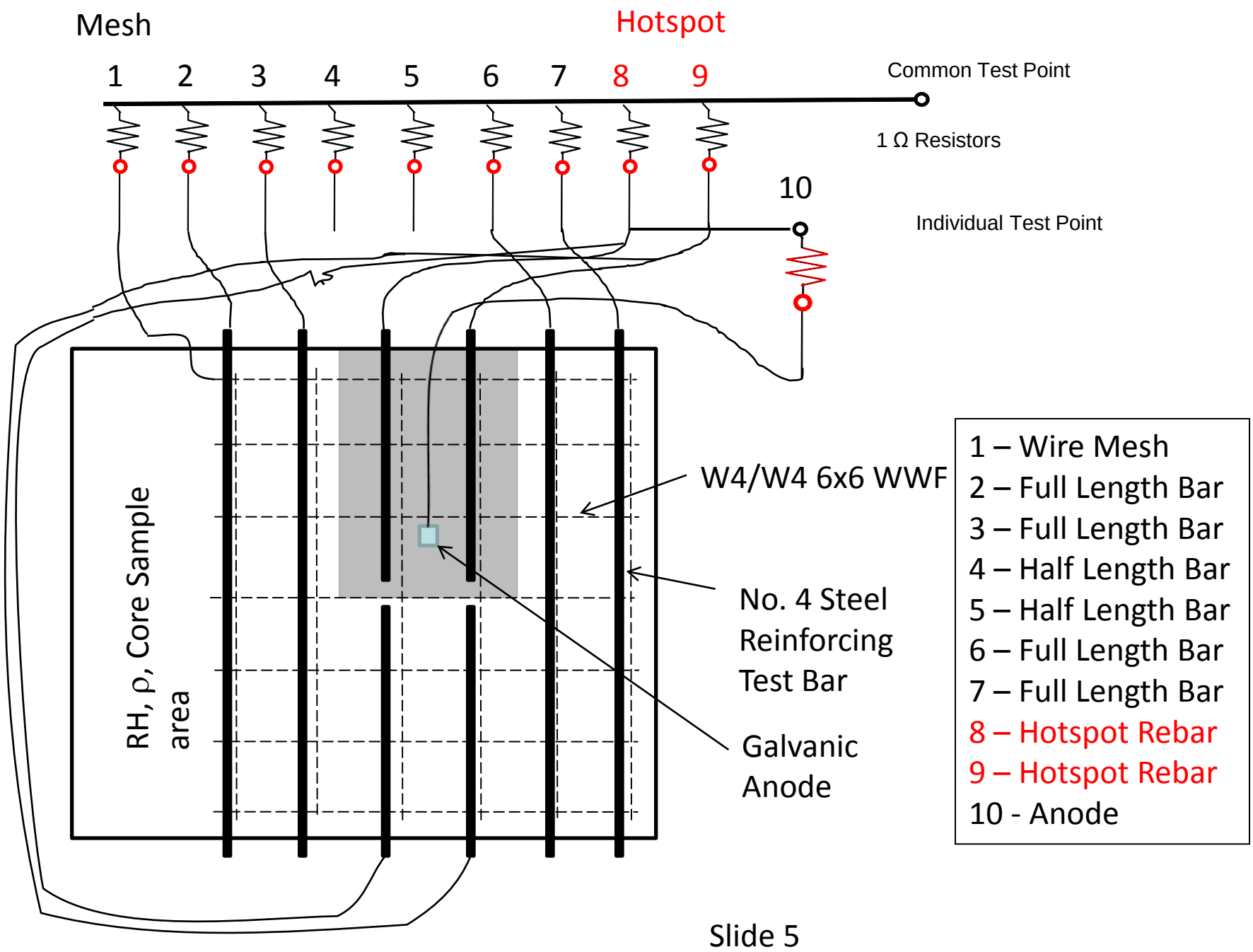
Repair Treatments

- D – Repair Mixture, 0.40 w/c, 6.5 SK, Type I/II Cem (No SCMs), pea gravel
- E - Rebar coating (Same repair mixture)
- F - Galvanic anode (Same repair mixture)
- G – 40% Silane (Same repair mixture)

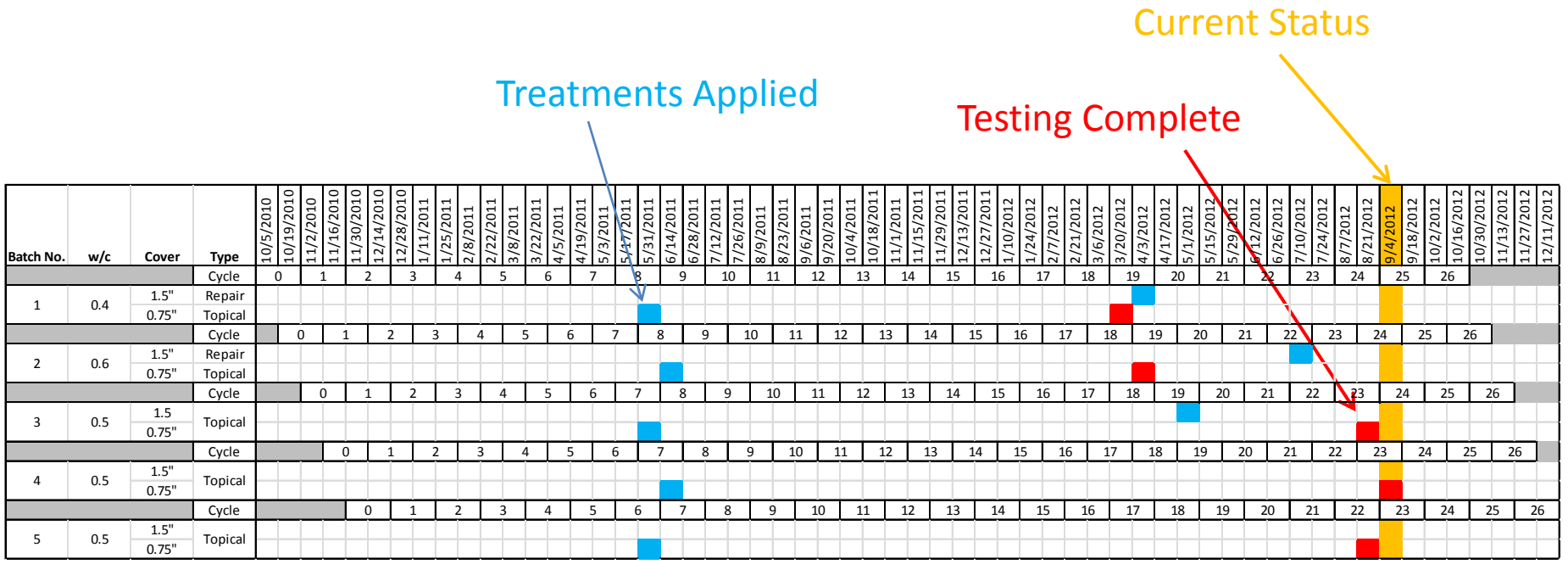
Quantity of Patch Repair Treatment Slabs							
Batch No.	**Specimen ID**	**No. of Slabs**	**D**	**E**	**F**	**G**	**Autopsy**
1	0.40 w/c (Chloride)	5	3	3	3	3	3
	0.40 w/c (High w/c)	5					
	0.40 w/c (Low Cover)	5					
2	0.60 w/c (Chloride)	5	3	3	3	3	3
	0.60 w/c (High w/c)	5					
	0.60 w/c (Low Cover)	5					

Repair Treatments

- D – Repair Mixture
- E - Rebar coating (Same repair mixture)
- F - Galvanic anode (Same repair mixture)
- G – 40% Silane (Same repair mixture)


Mesh
Hotspot
1
2
3
4
5
6
7
8
9
Common Test Point
1 Ω Resistors
10
Individual Test Point
RH, ρ, Core Sample area
W4/W4 6x6 WWF
No. 4 Steel Reinforcing Test Bar
Galvanic Anode
1 – Wire Mesh
2 – Full Length Bar
3 – Full Length Bar
4 – Half Length Bar
5 – Half Length Bar
6 – Full Length Bar
7 – Full Length Bar
8 – Hotspot Rebar
9 – Hotspot Rebar
10 - Anode

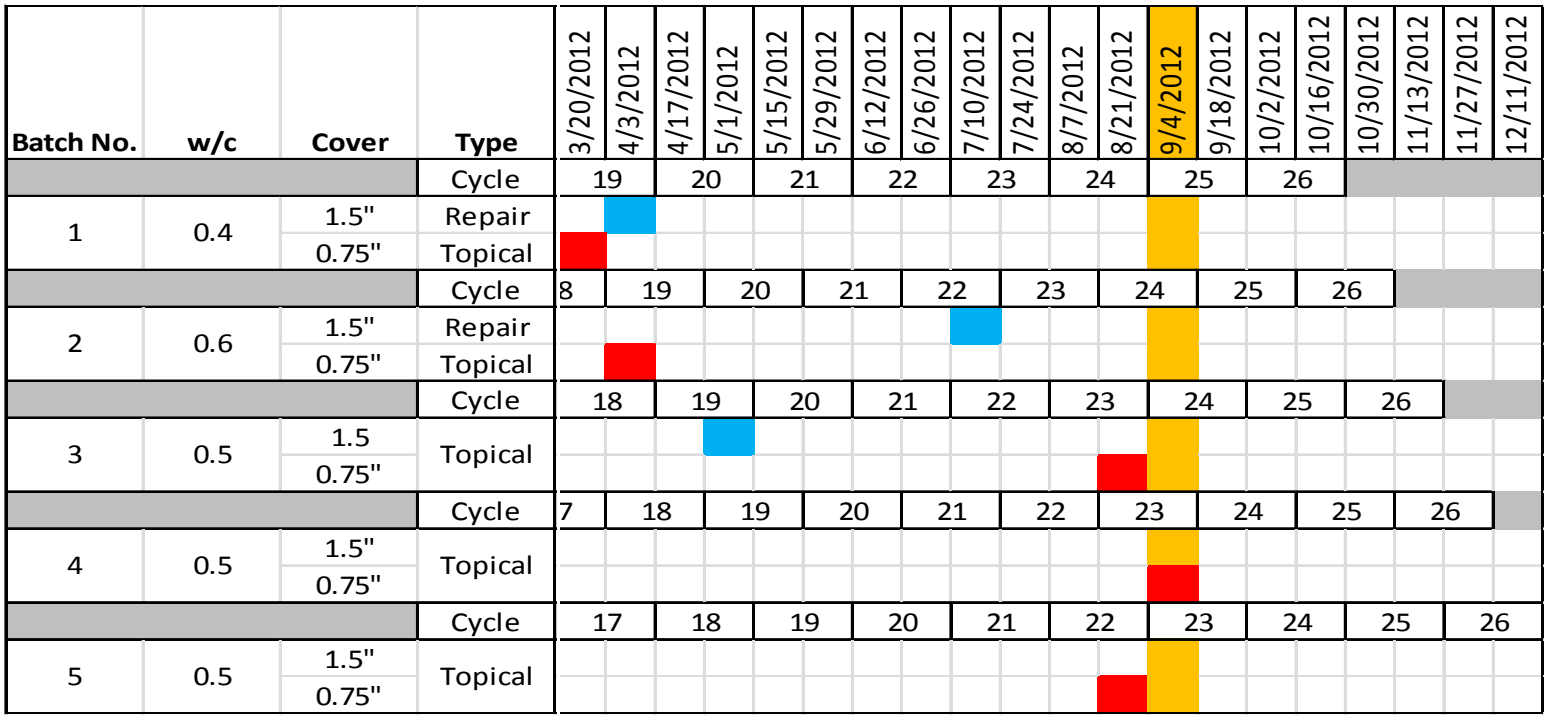
Project Timeline



- Batch #1 cast 10/5/10 commissioned 11/2/10 (14 day intervals between batches)
- Topical Treatments Applied
  - 0.75” Cover Slabs (Batches 1-5)
  - 1.5” Cover Slabs (Batch 3, as criteria is met)
- Repair Treatments Applied
  - 1.5” Cover Slabs (Batch 1-2, as criteria is met)
- Current Status
  - Batch #1 in 25th wet cycle
- Project completion not to exceed 30 months (2 full years of ponding)

Project Timeline

Current Status



- Repair Treatments Applied
  - 1.5” Cover Slabs (Batch 1-2, as criteria is met)
  - 50% of repair slabs have been treated or destructively analyzed

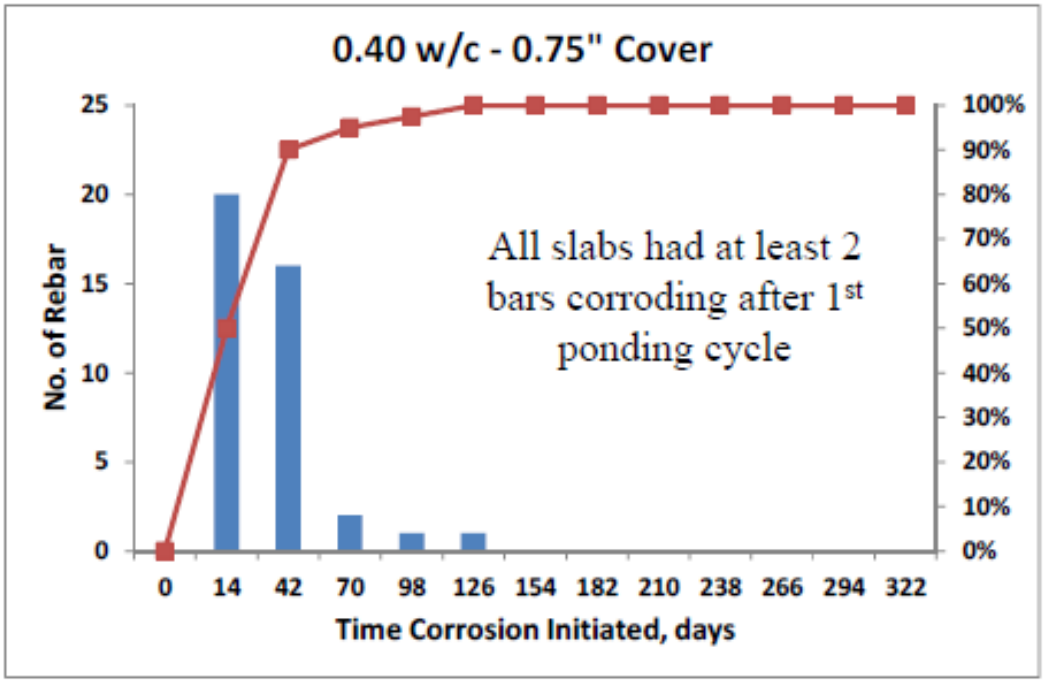
- **USBR has started the write up of the final released protocol for distribution and use in commercial assessments and specifications. Expected release in early 2013.**

Notes for Future Discussions

- Make depressed cover for hotspots ¼ inch less than nominal cover – 3/8 inch cover worked well.
- Rebar End conditioning – cement paste and shrink wrap seem best
- 1-inch cover with ½ inch MSA seems like the best choice for topical and hot spot repairs
- Include corrosion potential mapping
- Move ponding dams in from the edge to prevent damage to ends of rebar
- Do treatments at different corrosion levels

Concrete Cover

- 0.75” Cover – Corrosion initiation too quickly
- 1.5” Cover – Too long for accelerated test?



Thank you!!

Questions?

RECLAMATION