Optimizing System Preservation in Waterfront Concrete Construction

Tried and Emerging Technologies

Maryland Ready Mix Concrete Association

Baltimore, MD

March 2018

MDOT MARYLAND DEPARTMENT OF TRANSPORTATION

Significant Influences on End of Service Life of Marine Structures

- ✓ Design/Materials Specification for Durability
- ✓ Construction/Pile Driving to Avoid Damage
- ✓ In-Service/Repair of Deteriorating Members

Assessment Tools
Baseline Condition and Ongoing Asset Management

In Service

- Timber: Microscopy and Mechanical Testing

✓ Concrete: Petrography

Preventatives

✓ Mix Design: Ion Transfer Modeling

✓ Pile Driving: Embedded Technology for Monitoring Geotechnical Capacity and Pile Integrity

Definitions

- **Life Expectancy**: duration in number of years remaining for an in-water structure before the allowable live load deteriorates to a value that is critical to current or forecast operational logistics (Pre-collapse, sub-operational, operational and HLAs).

- **Design Service Life**: *maintenance-free* (maint <= 1% construction cost) target duration in number of years in advance of the deterioration of the allowable live load to an operationally critical value; **75-125⁺** yr min new structures and repairs

Facility Acquisition

- Maryland Port Authority 1956
  - Harbor Field City Airport➔570 ac Dundalk
  - Private Terminal Acquistions ➔ Locust Point, Hawkins Point Railroad Piers and Clinton Street, Fairfield Piers
- Maryland Port Administration 1971
  - Construction of Marginal Wharves
  - Harbor Tunnel Dredge Material ➔Seagirt 1989
  - Seagirt Channel Dredge Mat'l ➔ Masonville 2014

Marine Structure Inventory

- Piers
  - 532,000 sf timber (circa 1923)
  - 784,000 sf concrete (circa 1940- 2014)

- Marginal Wharves
  - 7,800 lf timber (circa 1930)
  - 4,400 lf concrete and steel (circa 1930 - 2014)

12 yr Maintenance and Reconstruction Costs

Contract #	Expenditure ($M)	Title	Material	Type
512912, 515000	8.1	AWSR3-4	Concrete	Repair
511006	2.47	DMT HLA	Concrete	Targeted
509915	1.5	SLP HLA	Concrete	Targeted
506921,	1.18	AWDR1-3	Concrete	Repair
513017	.52	DMT Crane Bm	Concrete	Repair
513015	.23	DMT A Row	Concrete	Repair
512901	22	FMT3	Concrete	Reconstr
502009	24	DMT 5/6	Timber	Reconstr
513003	22	DMT4	Timber	Reconstr
512015	5.37	DMT 1 – 3	Timber	Targeted
510015	1.65	DMT HLA	Timber	Targeted
504518	1.8	FMT3/4	Steel	Targeted
	$92.93M			

12 yr Maintenance and Reconstruction Summary

Expenditure ($M)	Proportion of Maintenance Budget (%)	Contract Type/Material
66.0	71%	Reconstruction
14.1	15%	Repair
12.8	14%	Targeted reconstruction
36.3	39%	Concrete
54.9	59%	Timber
1.8	2%	Steel

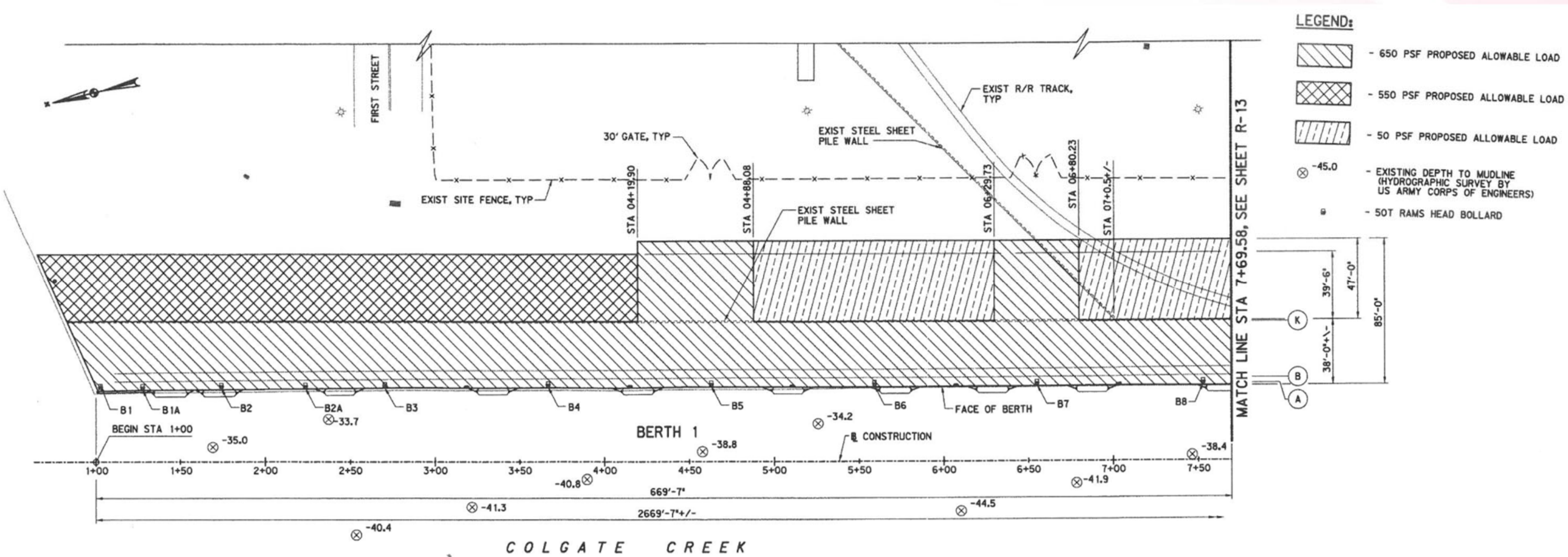
Timber Structures Inventory

	DMT 1-4, 7-10	NLP3	NLP6	SLP9	Hawkins Pt	Cambridge
Yr of Constr	1930	1930	1927	1958	1960	1963
Age (yrs)	**83**	**83**	**86**	**55**	**53**	**50**
Type	Wharf	Pier	Pier	Wharf	Pier	Wharf
Wharf Length (lf)	6,261			1,200		350
Pier Area		300,000	165,000			
Bulkhead Length (lf)		1438				
10 yr Tonnages	11,129,986	138,244		17,609	N/A	
Status	Load Restricted	Load Restricted	Condemned	Converted to Public Use		Converted to Public Use; Reconstruction Pending
Remedial Investment ($M)	50	0.50				2.75

Targeted Reconstruction

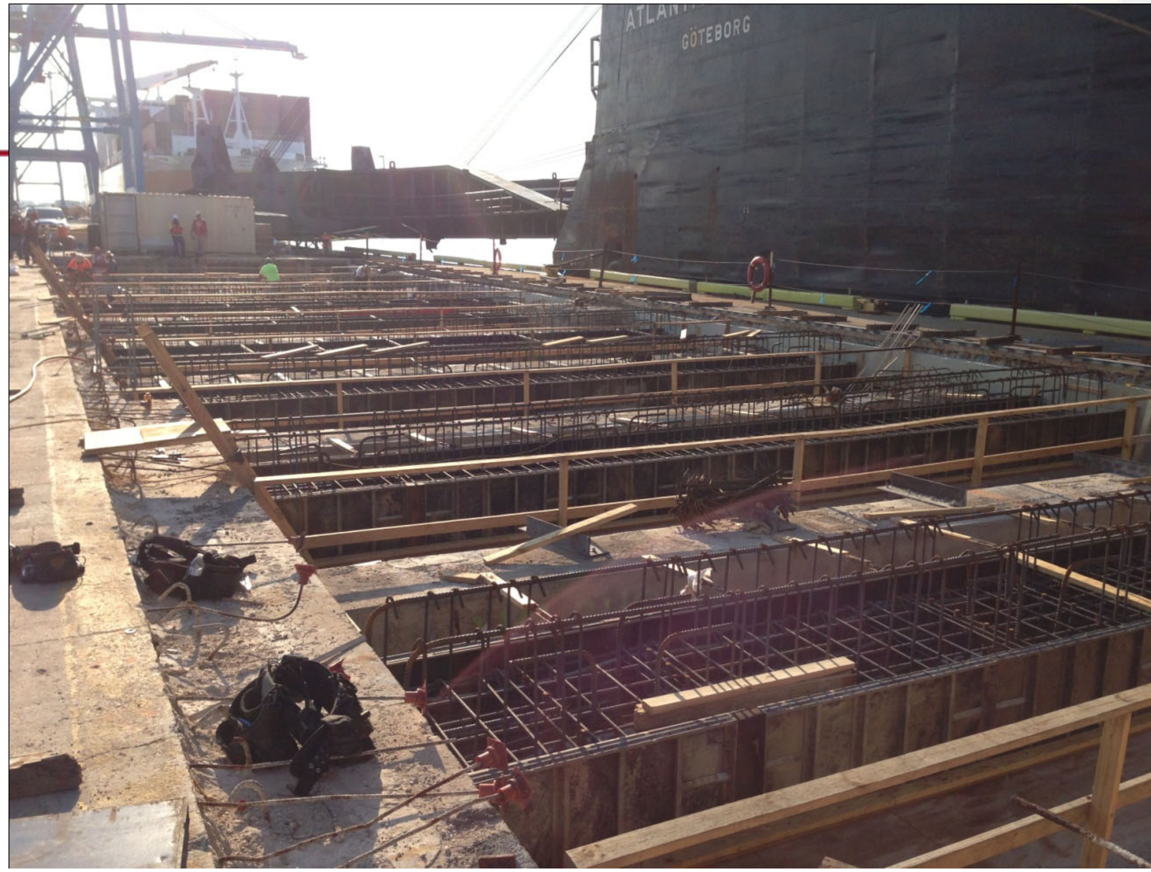
- A marine facility rehabilitation consisting of a combination of super- and substructure repairs, replacements and reconstruction in targeted areas resulting in upgraded load capacity to meet precise operational geometric and load demand. While extended life expectancy and zeroing of maintenance costs prevail for upgraded elements, continued vigilance and maintenance costs are associated with unrepaired structural members that remain within and adjacent to the upgraded footprint.

Operational Restoration - Targeted Reconstruction



Targeted Reconstruction Logistics

Adjacent vessels



Targeted Reconstruction Logistics

Overhead ramps

Targeted Reconstruction Logistics

Adjacent cargo

Targeted Reconstruction Results

Abandon deteriorating and weak elements in place

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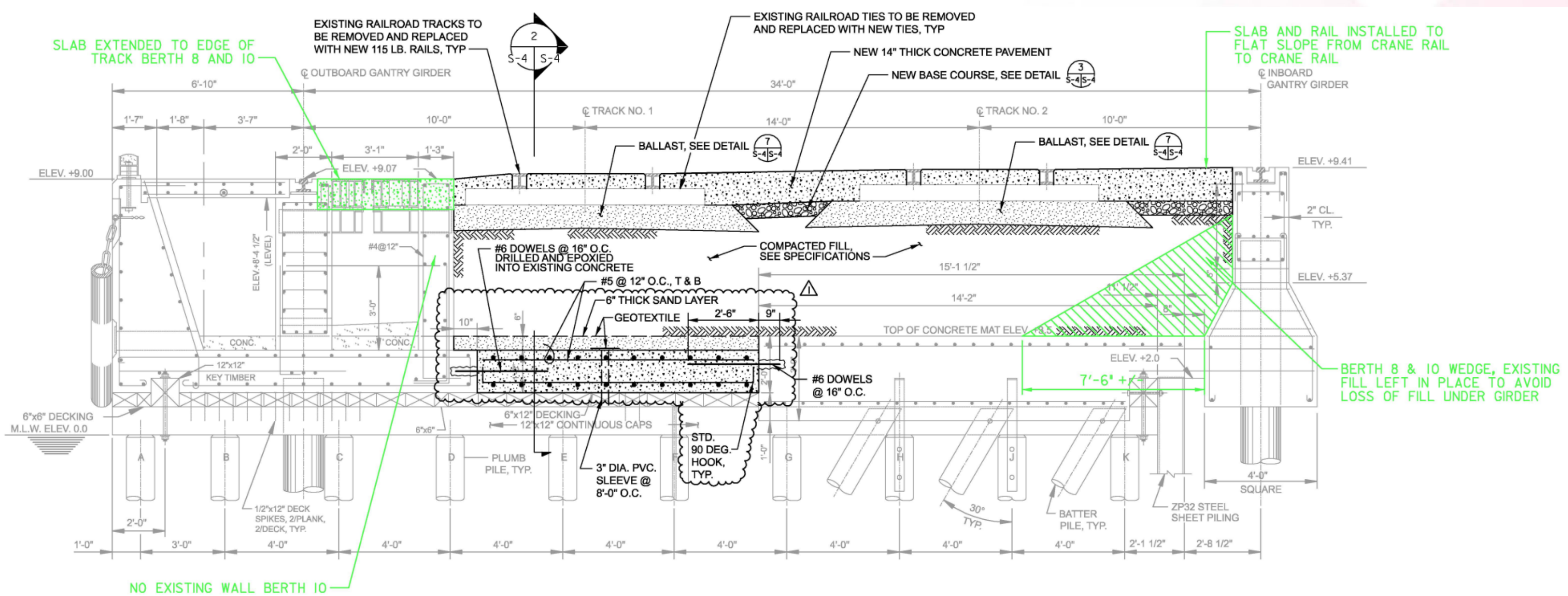
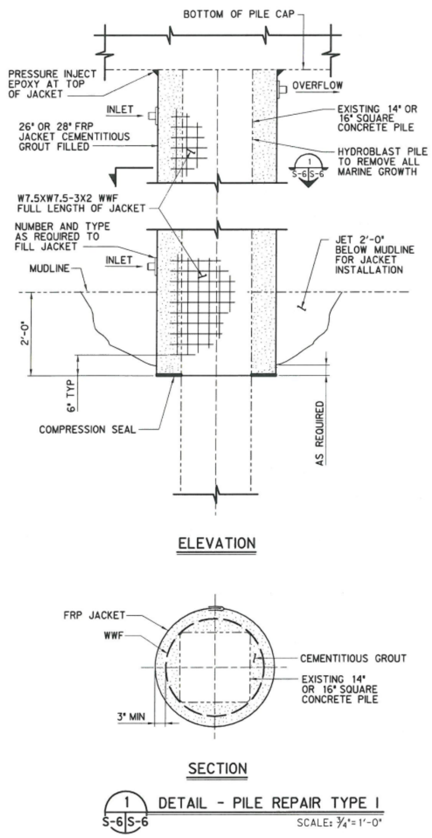
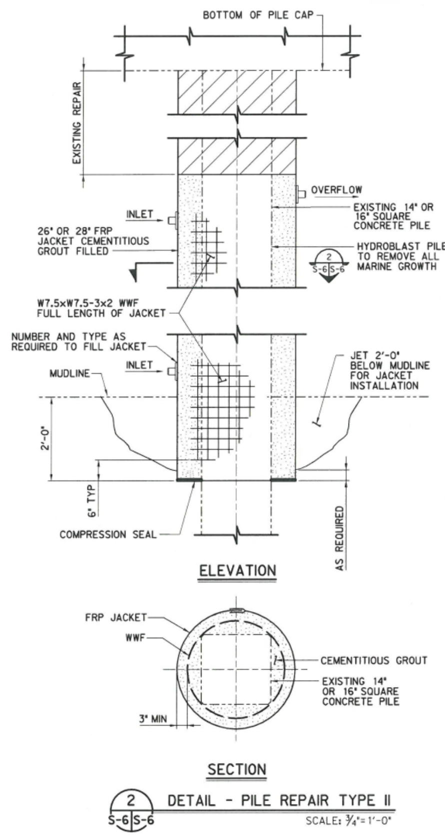
Timber Subdeck Replacement
Targeted Reconstruction

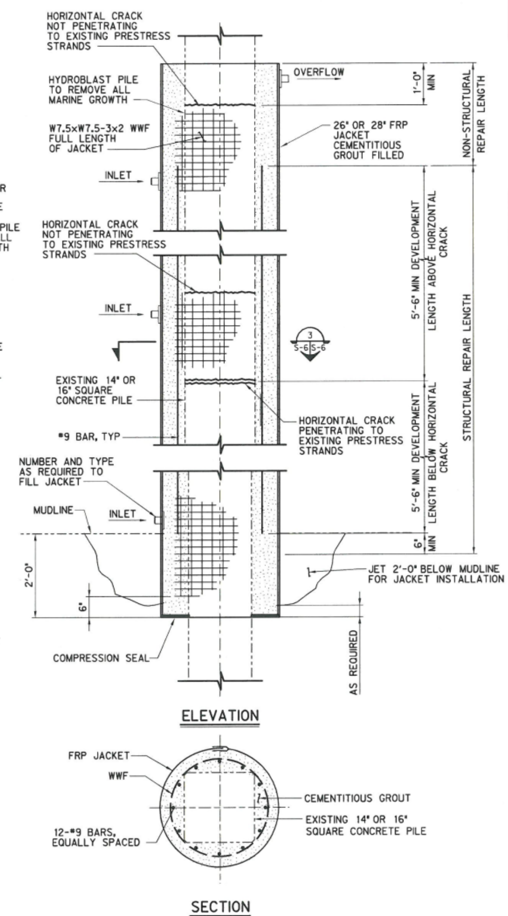


Concrete Pile – Jacketed Repairs

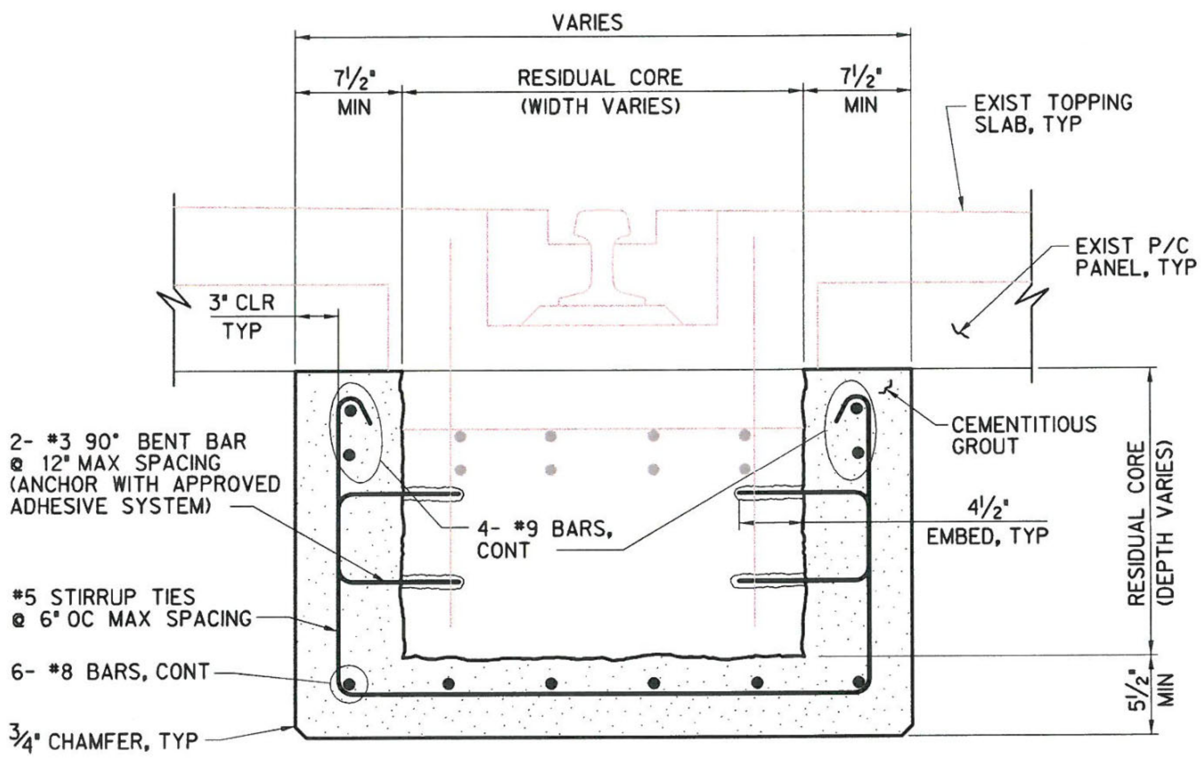




Threshold Criteria: 1/8" Crack Width



Crane Beam – Jacketed Repair of Concrete Corrosion



Threshold Criteria: Unsound concrete w/ visual indicators

4 S-3, S-4 | S-5 SECTION - TYPE II REPAIR

SCALE: 1½"= 1'-0"

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Environmental Deterioration Processes for Concrete Structures

Physical

- Freeze/Thaw
- Scaling
- ✓ Supra Design Events
- Settlement
- Temperature

Chemical

- ✓ Corrosion
- ✓ Carbonation
- Sulfate Attack
- ✓ ASR
- ✓ DEF

Deterioration is diagnosed/quantified by visual inspection & subsequent petrography

Petrography– Crane Beam

ASR, high chlorides and corrosion of reinforcement

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Loss of Section– Crane Beam

Depth of unsound concrete – 6+ inches

Petrography

	CSMT 1	DMT 5/6	DMT 11-13				FMT 4	NLP 4/5		SLP 10-12	
Yr of Constr	1933	2006	1970				1943	1937		1973	
Age (yrs)	80	7	43				70	76		40	
Type	Pier	Wharf	Wharf				Pier	Pier		Wharf	
Wharf Length (lf)		1105	1200							2055	
Pier Area (sf)	241000						78450	464100			
10 yr Tonnages (10^6 tons)	N/A	4.07	17.23				2.40	1.67		4.50	
Status	Load Restricted		Load Restricted				Load Restricted	Load Restricted		Load Restricted	
10 yr Investment ($M)		$24.00	$6.40				$3.40			$1.50	
Min Live Load (psf)	0	600	800				100	600		250	
Min Life Expectancy (yrs)	0	43	0				0	0		0	
MLE Report								MN 2011		MN 2008	
Petrogr Date	N/A	Nov-13	June-12	February-13	April-12	February-13	Nov-13	July-08	February-13	October-07	September-12
Lab		Tourney	CTL	Tourney	CTL	Tourney	Tourney	CTL	Tourney	CTL	CTL
Element		piles and caps	caps and beams	piles and crane beams	piles	piles and crane beams	piles	piles	piles and crane beams	piles	caps
ASR		results pending	minor	moderate/advanced	minor	minor	results pending	minor	moderate/advanced	minor	minor
DEF			none	confirmed	none	confirmed		confirmed	moderate	confirmed	confirmed
Chloride Profile (ppm/depth)				2682/4 to 3350/4		84/4 to 121/4				0.5 MM	2240/0.5 to 210/5
Corrosion of reinforcement			yes	severe on strands and ties		n/a			severe on strands and ties	confirmed	
Depth of carbonation (in)			6-35 mm		.02 to .12			0.12 to 0.16	0.63		0.04 to 0.3
Remedial Method		Reconstruction	Repair, targeted reconstruction				Repair	Repair		Repair, targeted reconstruction	

Alkali-Silica Reactivity (ASR)

Caused by a reaction between alkalis (high pH) in concrete pore solution and reactive silica in aggregate

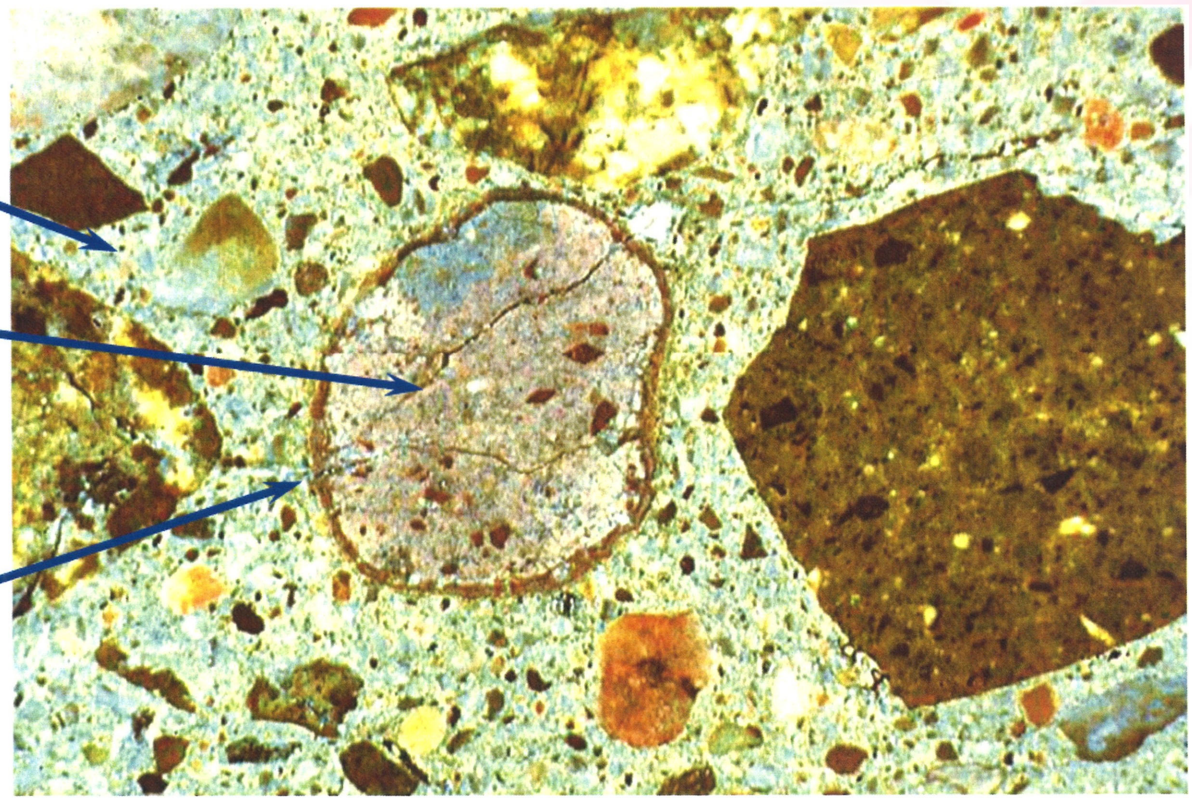
Manifests as map cracking with exudate within 5 to 15 years

Alkali-Silica Reactivity (ASR)

Cement paste

Reactive aggregate

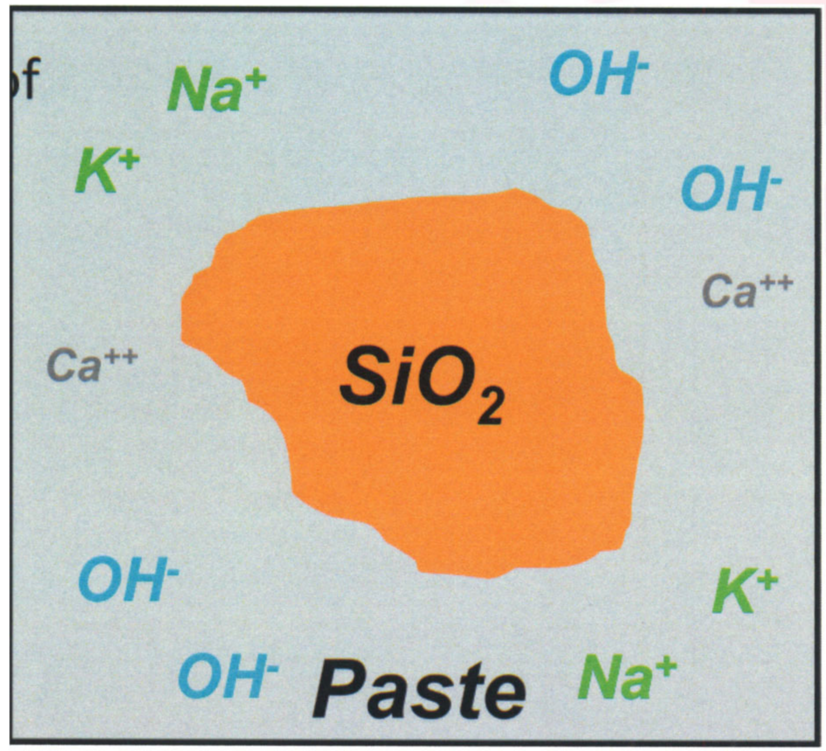
Reaction product



Courtesy PCI

Alkali-Silica Reactivity (ASR)

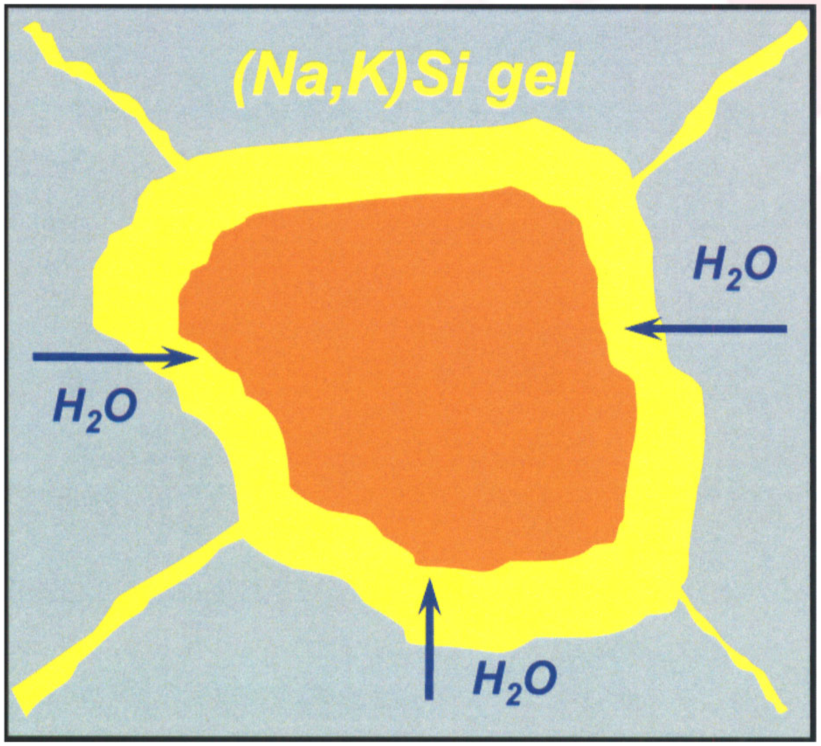
Pore solution includes significant quantities of sodium, potassium, hydroxl and calcium



Courtesy PCI

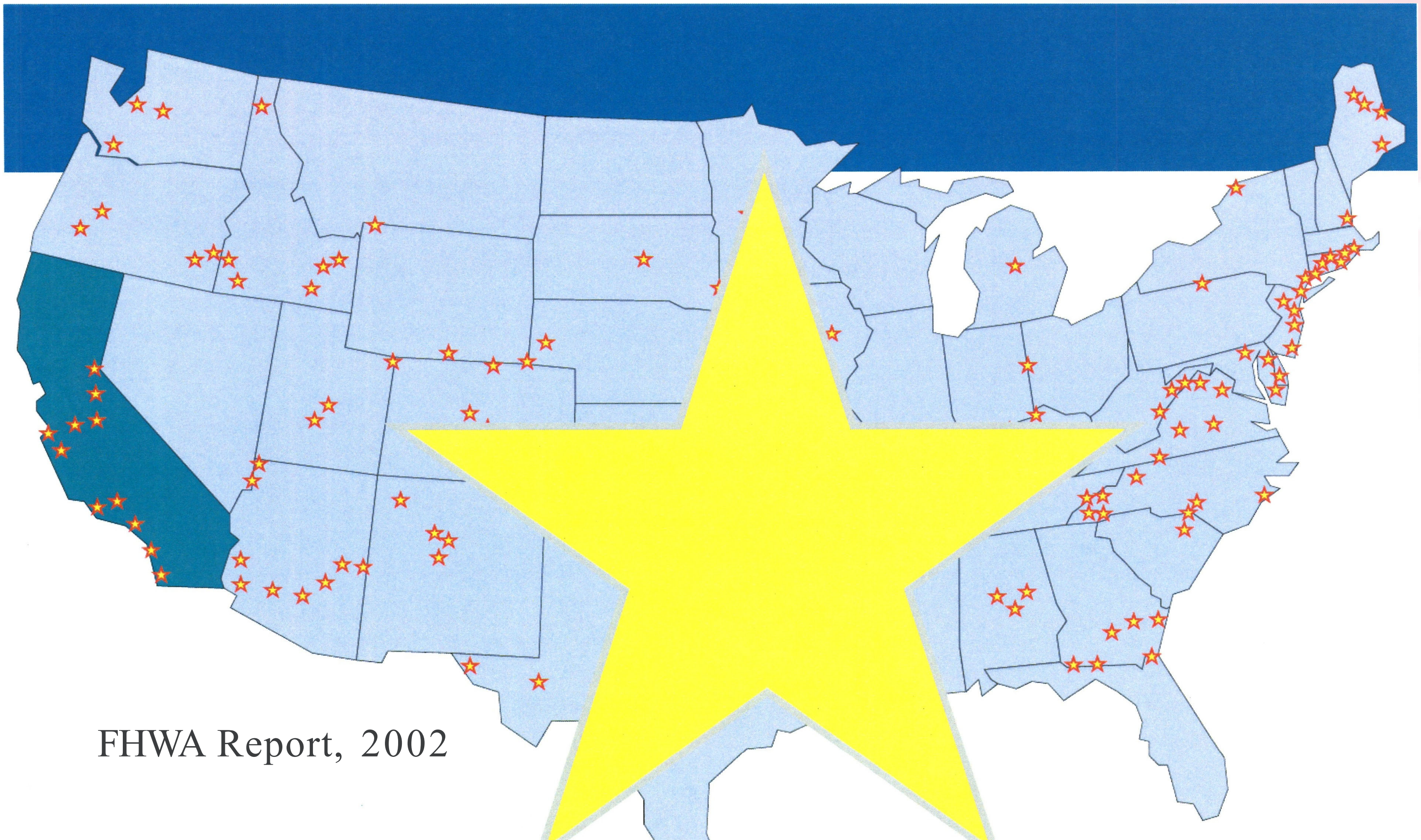
Alkali-Silica Reactivity (ASR)

- If the silica is reactive, it reacts with these ions forming an alkali-silica gel.
- The gel absorbs water from the surrounding cement paste and expands causing stresses that lead to cracking.



Courtesy PCI

Alkali-Silica Reactivity (ASR)



FHWA Report, 2002

Alkali-Silica Reactivity (ASR)

Mitigation measures include combinations of:

- ✓ Non-reactive aggregates
- ✓ Low-alkali cements
- ✓ Addition of SCMs including fly ash, silica fume and slag)

Delayed Ettringite Formation (DEF)

A form of sulfate attack where hardened concrete is damaged by expansion caused by the late onset ettringite formation. Typical when concrete reaches high temperatures during curing.

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Potential Deterioration Mode	Material Selection and Protective Measures Selection	Maintenance Modes	Life Cycle Costs	
			Initial	Long Term
Freeze and Thaw	Min. 6% Air Entrainment Sound Aggregates Strength > 3.5 ksi	None	Low	Low
	Proper Drainage and cover	None	Low	Low
	Membrane/Overlay	Continual Overlay Replacement every 20 years	Med	Med
ASR	Non-Reactive Aggregates	None	Med	Low
	Low Alkali Portland Cement	None	Med	Low
	Blended Aggregates Low Alkali Portland Cement SCMs (Fly Ash, Slag, etc.)	None	Med	Low
	Blended Aggregates Low Alkali Portland Cement Lithium Nitrate	None	Med	Low
	Proper Drainage	None	Low	Low
	Membrane/Overlay	Continual Overlay Replacement every 20 years	Med	Med
ACR	Non-Reactive Aggregates	None	Med	Low
	Blended Aggregates	None	Med	Low
	Proper Drainage	None	Low	Low
Sulfate Attack	Cement with low C3A content, early curing temperature <160°F	None	Low	Low
	Pozzolans, low w/cm, proper drainage	None	Low	Low
Delayed Ettringite Formation	Cement with low C3A content, early curing temperature <160°F	None	Low	Low
	Pozzolans, low w/cm, proper drainage	None	Low	Low

SHRB2 Renewal Project R19A, Design Guide for Service Life

Concrete Durability Strategies

MPA Mix Design for In-Water Concrete

PROPERTY	[6]Waterside Structures	Concrete Slab on Grade	[7]Utility Structures	[8]Miscellaneous Structures	Prestressed Concrete Piles	Precast Concrete Deck Panels	[11]Precast Concrete Utility Structures
28-Day Compressive Strength, ASTM C 39 (psi)	5,000	5,000	5,000	5,000	7,000	6,000	5,000
28-Day Flexural Strength, ASTM C 78 (psi)	--	700	--	--	--	--	--
Nominal Max Size Aggregate[5]	1"	2"	1-1/2"	1-1/2"	1"	1"	1"
Unmitigated Aggregate Reactivity	Innocu ous				Innocu ous	Innocu ous	
Cement Type	II, IS(MS)	II, IS(MS)	II, III or IS(MS)	II, III or IS(MS)	II, IS(MS)	II, IS(MS)	II, III or IS(MS)
ASTM C1202 Rapid Chloride Ion Testing	0.08%				0.06%	0.06%	
MacroFibers			Type III only	Type III only			Type III only
Slag Replacement, %	25%	25%	25%-50%	25%-50%	25%	25%	25%-50%
Water-Cement Ratio (by weight)	0.40	0.45	0.45	0.50	0.40	0.40	0.40
Design Slump (inch)	[2] 4	[3] 2-3	[2] 4	[2] 2-5	[4] 4	[2] 4	[2] 4
Air Entrainment, % (ASTM C 231)	6	5.5	6	6	6	6	6
Calcium Nitrite Corrosion Inhibitor	YES	NO	NO	NO	YES	YES	NO
[9] Water Reducing Admixture Required	YES	YES	YES	NO	YES	YES	YES
[10] Anti-Washout Admixture	YES	NO	NO	NO	NO	NO	NO

Specifications for Marine Concrete

All Cement

For category S1 exposure, an ASTM C 595, Type IS(MS) blended cement except as modified herein:

1. The blended cement shall consist of a mixture of ASTM C 150 Type II cement and ground iron blast-furnace slag. Alternatively, the blended cement may be batched at the ready mix plant if batching certifications required for NRMCA are submitted and approved. Type I, Type III, and Type V cements shall not be accepted, except as indicated in the mix design table. Type III cements may be approved for use in prestressed applications within the stipulated curing temperature limitations.
2. Ground Iron Blast-Furnace Slag: ASTM C 989, Grade 120. Testing shall be performed no more than six months prior to submittal date. Grade 100 slag may be approved under at the Engineer's discretion.
3. The ground iron blast-furnace slag shall comprise 25% - 50% by weight of total cementitious material, as specified for each application in the mix design table.
5. The tricalcium aluminate content of the blended cement shall be less than 8% by weight.

For mass concrete and steam cured precast items; the following shall be met in addition to the requirements above:

1. The maximum percent of sulfur reported as sulfate (SO3) in the blended cement shall be less than 3.0%.
2. The alkali content of the blended cement shall be less than 0.7%
3. The molar ratio of sulfate to tricalcium aluminate in the blended cement shall be less than 0.3.

Aggregates

3. Aggregates shall not contain any substance that may be deleteriously reactive with the alkalies in the cement in an amount sufficient to cause excessive expansion of the concrete.
4. For all aggregate sources, submit ASTM C1260 (or 12 month C1293, as stipulated below) test results dated within the last 6 months. Aggregates shall show expansions less than 0.10% at 16 days when tested in accordance with ASTM C 1260. Aggregate suppliers certified by and listed in the SHA's Aggregate Bulletin are preapproved and require only submittal of SHA OMT test results, current ASTM C1260 mortar bar (or C1293 prism) test results, and certification of the stipulated gradation for each mix design. Aggregates demonstrating expansions in excess of this limit shall not be accepted, regardless of inclusion in the SHA Aggregate Bulletin, unless 12 month C1293 expansions yield an innocuous result. These C1293 prisms shall not include pozzolans or slag in the mix and results shall be dated within the last 6 months. At the Engineer's discretion, consideration may be given for aggregates demonstrating non-innocuous C1260 results if successfully mitigated for aggregate reactivity in accordance with C1260 or C1567 in non-structural or non-marine applications only and as stipulated herein.

Admixtures - Corrosion Inhibiting:

a. Concentration of corrosion inhibitor shall be sufficient to produce a content not less than 5.1 pounds per cubic yard in the hardened concrete.

Service Life Issue	Solutions	Advantage	Disadvantage
Chemical reactions (ASR)	Non reactive siliceous aggregates	Reduce ASR	Hard to obtain in many areas
	Use of SCM	Reduce permeability, reduce ASR, limit alkalis from outside	Quality fly ash or slag missing in many areas
	Low w/cm	Reduce infiltration of solutions, limits alkalis from outside	Can produce high strength concrete that is brittle
	Chemical admixtures	Improved properties	Cost, incompatibility, side effects
	Lithium based admixtures	Inhibit ASR	Cost
	Limestone sweetening (blending with limestone)	Limit expansion	Reduced skid resistance
Chemical reactions (ACR)	Non reactive carbonate aggregates	Reduce ACR	Hard to obtain in some areas
	Reduce infiltration of solutions, limits alkalis from outside	Can produce high strength concrete that is brittle	Cracking
	Blend aggregate	Limit expansion	Hard to obtain in some areas
	Limit aggregate size to smallest practical	Limit expansion	Rich mixes with high paste content
Sulfate attack	Low C3A contents	Reduce sulfate attack	N/A
	Use of SCM	Reduce permeability, reduce sulfate attack, limit sulfates from outside	Quality fly ash or slag missing in many areas
	Low w/cm	Reduce infiltration of solutions, limits sulfates from outside	Can produce high strength concrete that is brittle

SHRB2 Renewal Project R19A, Design Guide for Service Life

Durability Technologies

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Critical Construction Phase Activities for Concrete Structures

Fabrication

- Mixing
- Consolidation
- Finishing
- ✓ Curing

Inspection

- ✓ Pile Driving

Steam Curing Temperature Limitations and Monitoring Provisions

Immediately after each pile has been cast and finished, it shall be placed in a curing chamber, curing box, or under a tight enclosure which will protect the pile from wind and drafts. Such chambers and enclosures shall be sized to allow full circulation of steam around exposed surfaces of the pile.

Instrumentation: Install exterior recording thermometers and interior temperature probes with enclosures and power source along with wiring. All thermometers and probes shall record continuously and automatically. Each pile shall be instrumented with either one exterior thermometer or one interior probe. Exterior thermometers and interiors probes shall be installed in an alternating sequence. Parallel casting beds shall have the instrumentation placed in a staggered and alternating pattern along the piles. The thermometer and the probe shall be installed close to the middle of the pile, not closer than 5 feet and not farther than 10 feet from the orifice where the steam is introduced. The exterior thermometer shall be located at the side where the steam is introduced. The interior probe shall be located more than 8-inches and less than 10-inches from the surface of the piles. Under no circumstances are the interior probes permitted to touch the jet tube. Do not commence concrete placement until temperature recording devices have been checked to the satisfaction of the Engineer. A uniform curing temperature shall be maintained throughout the entire length of the piles. Submit prints of the automatic readout daily.

Commencing not earlier than three (3) hours and not later than five (5) hours after completion of concrete placement, the piles shall be subjected to the continuous action of steam. Care shall be exercised to see that heat is introduced gradually to avoid thermal shock to the concrete. During the heating, the temperature rise shall not exceed 25 to 35 degrees Fahrenheit per hour. The interior temperature of the piles shall be held at a target temperature of 140 degrees F with an upward tolerance of 10 degrees F. A single pile reaching an interior temperature of more than 150 degrees F or less may be accepted at the option of the Engineer. A run of several piles with an interior exceeding 150 degrees F will be rejected.

Cooling shall follow the steaming cycle. Care shall be exercised to protect the piles from rapid drops in temperature, mechanical injury and other conditions likely to cause damage or loss of strength. During the cooling, the temperature drop shall not exceed 35 degrees F per hour until a temperature of 20 degrees F above ambient air temperature is reached. The cool down procedures shall be as follows:

Steam shall be turned off following the steam cycle.

The sides of the tarps shall be folded to the top of the form.

Transfer breaks shall be performed to confirm that the required 5,250 psi has been reached.

The tarps shall be completely removed, the top doors will be opened, and the strands will be released.

After steam curing, moist curing shall be applied using until a total steam and moist curing time of seven (7) days is achieved.

Driving Stresses for Prestressed Concrete Piles

- A new pile driving system, modifications to existing system, or new pile installation procedures shall be proposed by the Contractor if the pile installation stresses exceed the following maximum values:
  - Compression Stresses: 0.85(f'c) - fpe
  - Tension Stresses: 3 times the square root of f'c + fpe

- Reductions in allowable driving stresses appropriate for prestressed concrete piles in marine environments?

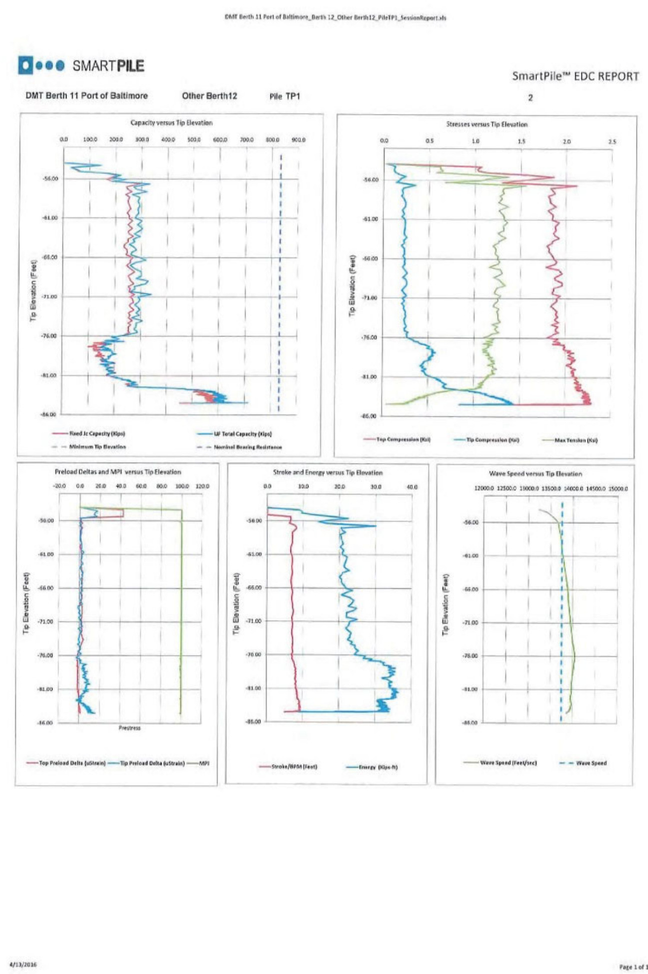
Embedded Data Collection of Driving Stresses of Prestressed Concrete Piles

What is EDC?

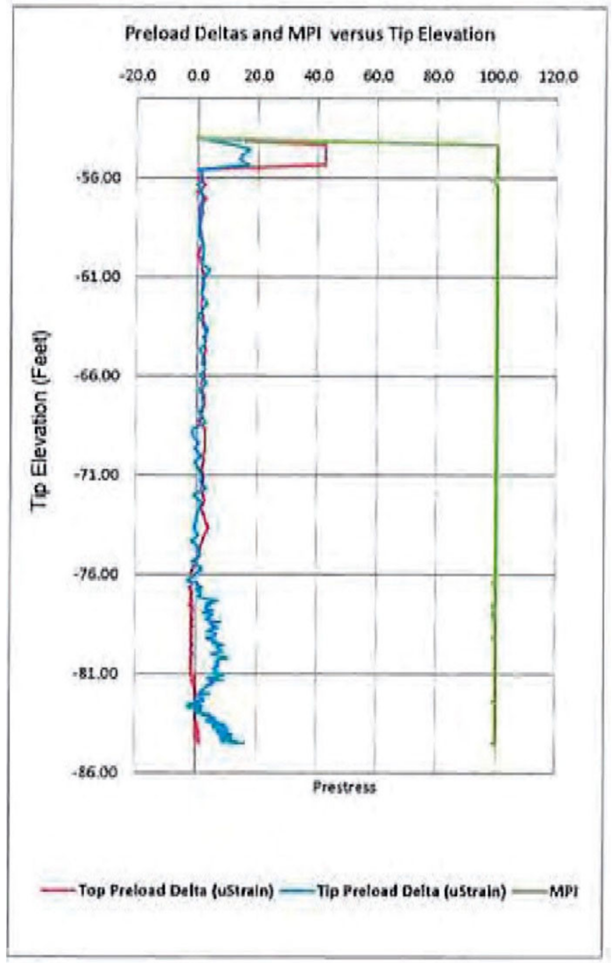
- Electronics/sensors embedded in the pile core at both pile ends
- Wireless data transmission from the pile
- Local workstation to collect sensor data as driving progresses
- Analytical and reporting software
- Improves quality by preventing damaging and unnecessary overdriving of piles

Courtesy SmartStructures

Embedded Data Collection
DMT11 Concrete Piles



Embedded Data Collection
DMT11 Concrete Piles



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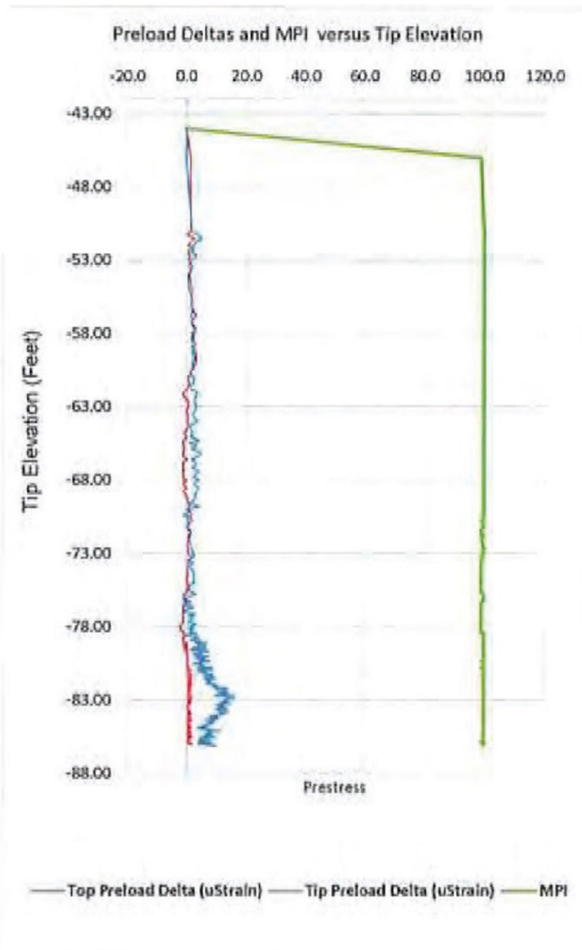
Embedded Data Collection
DMT11 Concrete Piles



Beta Method vs. Embedded Data Collection

Re-evaluation of the method to determine pile damage
using the Beta Method

Verbeek, G.E.H.
VMS, USA
Goble, G.
Goble Pile Test, USA

The theoretical review of the method showed clearly that the Beta Method cannot be a reliable indicator of pile toe damage… …the Beta method should not be used to protect against pile toe damage."

Verbeek, G.E.H. / Goble, G.

Beta Method

D. W. KOZERA, INC.
Case Method & iCAP® Results

Page 1
PDIPLOT2 2016.1.999.0 - Printed 11-April-2016

DUNDALK MT BERTH 11-12 - TP-4-1
OP: VELAUTHAM JEYAVIJITHAN, P.E.

24 INCH PCC ICE I-46
Date: 10-April-2016

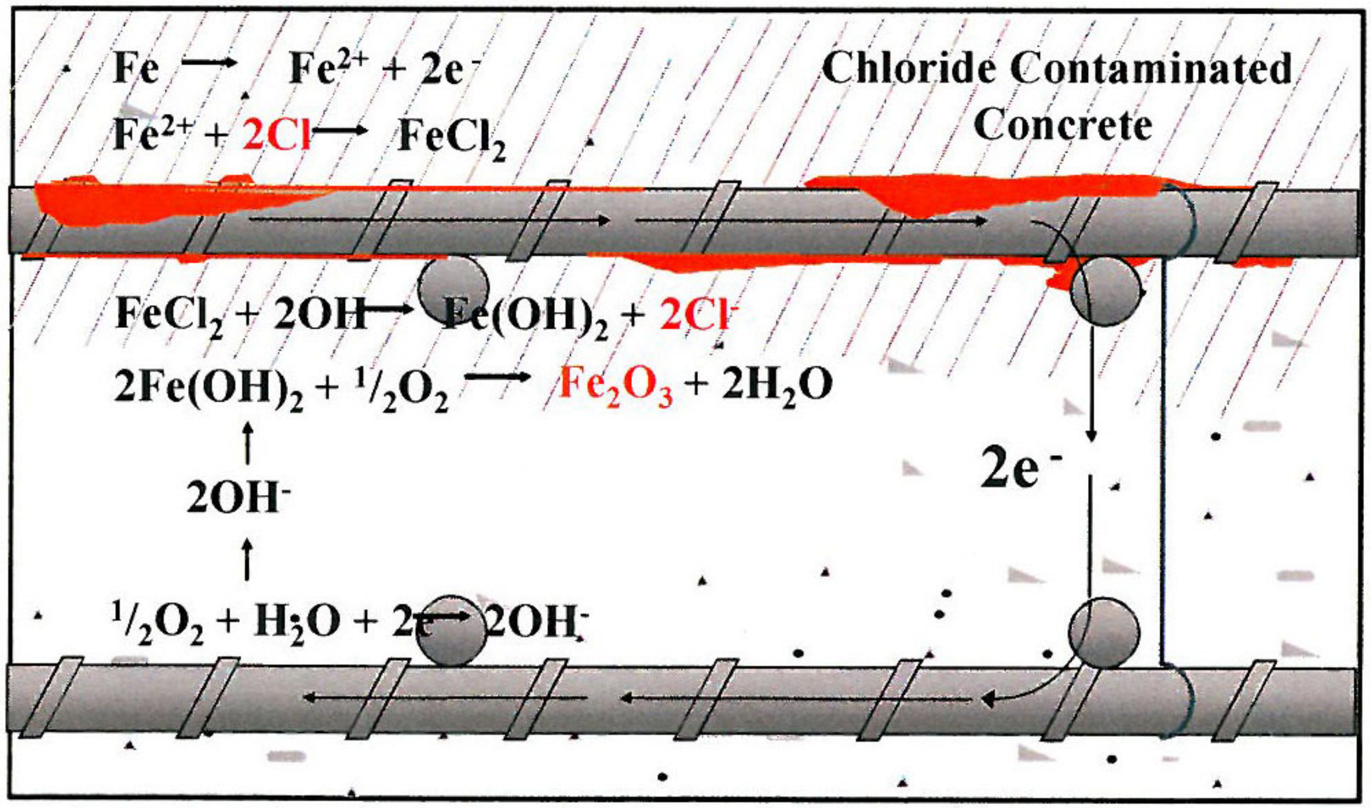
AR: 576.00 in²
LE: 96.00 ft
WS: 13,750.0 f/s

SP: 0.150 k/ft³
EM: 6,121 ksi
JC: 0.60 []

CSX: Max Measured Compr. Stress
TSX: Tension Stress Maximum
FMX: Maximum Force
RMX: Max Case Method Capacity
EMX: Max Transferred Energy

STK: O.E. Diesel Hammer Stroke
BTA: BETA Integrity Factor
LTD: Length to Damage
ETR: Energy Transfer Ratio

BL#	Depth	BLC	CSX	TSX	FMX	RMX	EMX	STK	BTA	LTD	ETR
	ft	bl/ft	ksi	ksi	kips	kips	k-ft	ft	(%)	ft	(%)
15	61.00	3	1.63	1.01	937	0	26.5	7.0	80.0	90.5	22.1
16	61.33	3	1.50	0.89	864	0	23.6	6.6	81.0	90.5	19.7
18	62.00	3	1.66	1.06	957	0	27.2	7.1	80.0	90.5	22.7
19	62.33	3	1.53	0.91	884	0	26.4	6.7	81.0	90.5	22.0
21	63.00	3	1.62	1.02	931	0	26.8	6.8	80.0	90.5	22.4
23	63.67	3	1.61	1.00	929	0	26.9	6.8	80.0	90.5	22.4
27	65.00	3	1.66	1.05	956	0	27.9	6.9	80.0	90.5	23.3
28	65.31	3	1.66	1.06	954	0	26.7	7.0	82.0	89.1	22.3
29	65.63	3	1.62	1.02	934	0	27.0	6.8	82.0	89.1	22.5
32	66.56	3	1.66	1.05	959	0	27.6	7.0	80.0	89.1	23.0
33	66.88	3	1.65	1.04	949	0	26.2	6.8	80.0	90.5	21.8
34	67.19	3	1.60	1.00	923	0	26.9	6.7	81.0	90.5	22.4
35	67.50	3	1.63	1.03	940	0	27.0	6.8	81.0	90.5	22.6
36	67.81	3	1.69	1.08	975	0	27.6	7.0	81.0	90.5	23.0
37	68.13	3	1.66	1.05	958	0	29.2	7.0	82.0	90.5	24.4
38	68.44	3	1.67	1.06	960	0	27.9	7.0	81.0	89.1	23.3
39	68.75	3	1.69	1.07	976	0	28.4	7.0	81.0	90.5	23.7
40	69.06	3	1.72	1.10	992	0	29.8	7.3	82.0	90.5	24.9
41	69.38	3	1.65	1.02	950	0	28.3	7.0	81.0	90.5	23.6
43	70.00	3	1.68	1.06	970	0	27.8	6.9	80.0	89.1	23.2
44	70.23	4	1.60	0.97	921	0	26.9	6.8	80.0	90.5	22.4
45	70.45	4	1.72	1.07	990	0	28.0	7.1	81.0	90.5	23.4
46	70.68	4	1.70	1.05	978	0	26.1	7.0	80.0	90.5	21.8
47	70.91	4	1.68	1.02	970	0	28.5	7.0	84.0	90.5	23.8
48	71.14	4	1.70	1.04	981	0	26.6	7.1	80.0	90.5	22.2
49	71.36	4	1.67	1.00	960	0	26.6	6.9	81.0	90.5	22.2
51	71.82	4	1.83	1.13	1,053	0	31.7	7.6	83.0	90.5	26.5
53	72.27	4	1.71	1.04	983	0	29.7	7.2	84.0	90.5	24.8
55	72.73	4	1.74	1.09	1,003	0	29.6	7.4	83.0	89.1	24.8
57	73.18	4	1.74	1.07	1,001	0	29.1	7.1	82.0	90.5	24.3
59	73.64	4	1.71	1.06	987	0	28.9	7.2	84.0	90.5	24.2
61	74.09	4	1.71	1.06	984	0	30.2	7.2	82.0	89.1	25.2
63	74.55	4	1.74	1.07	1,001	11	29.4	7.3	83.0	90.5	24.5
65	75.00	4	1.75	1.08	1,008	5	29.4	7.3	84.0	90.5	24.6
67	75.42	5	1.69	1.03	975	17	27.8	7.1	80.0	89.1	23.2
69	75.83	5	1.77	1.09	1,020	27	30.4	7.5	83.0	90.5	25.4
71	76.25	5	1.68	1.03	970	27	26.7	7.1	80.0	90.5	22.3
73	76.67	5	1.71	1.06	987	20	28.8	7.2	82.0	89.1	24.0
75	77.08	5	1.71	1.06	988	8	27.9	7.2	81.0	90.5	23.3
77	77.50	5	1.74	1.06	1,001	19	29.6	7.2	84.0	90.5	24.8
79	77.92	5	1.71	1.04	986	15	28.1	7.0	82.0	90.5	23.4
81	78.33	5	1.88	1.16	1,080	20	30.0	7.5	82.0	90.5	25.1
85	79.17	5	1.78	1.09	1,024	2	29.3	7.3	84.0	90.5	24.5
87	79.58	5	1.91	1.21	1,100	19	31.0	7.7	82.0	90.5	25.9
89	80.00	5	1.71	1.05	985	2	28.6	7.2	83.0	90.5	23.9



Corrosion Macrocell

SHRB2 Renewal Project R19A, Design Guide for Service Life

MARYLAND DEPARTMENT OF TRANSPORTATION

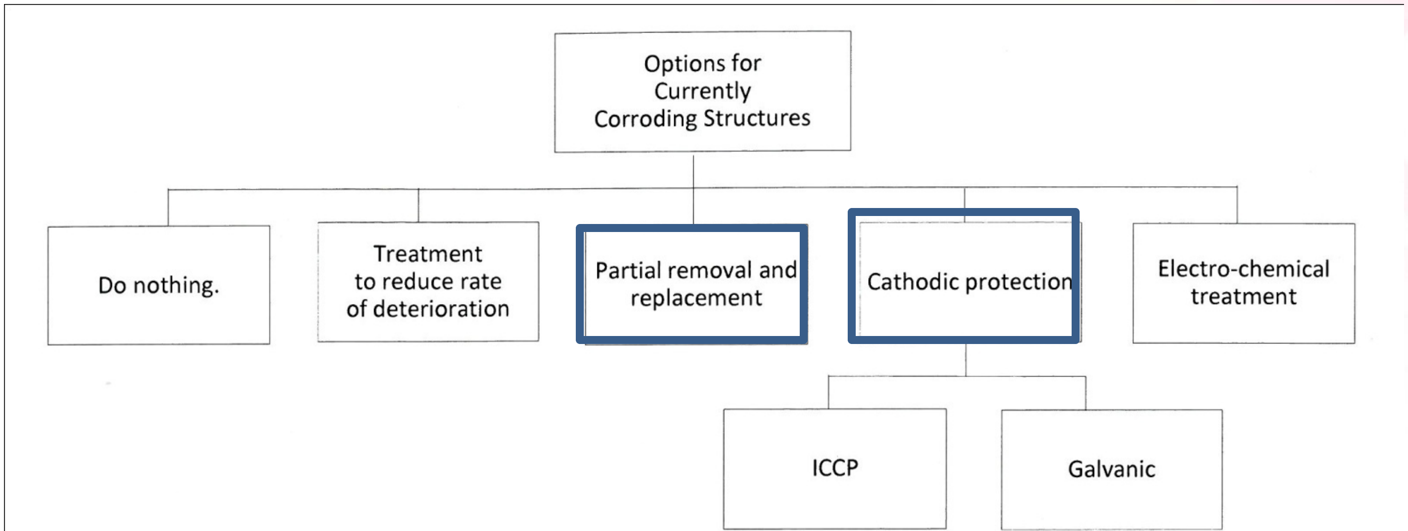


Figure 5.13. Options for corroding structures.

Strategies for Corroding Structures

SHRB2 Renewal Project R19A, Design Guide for Service Life

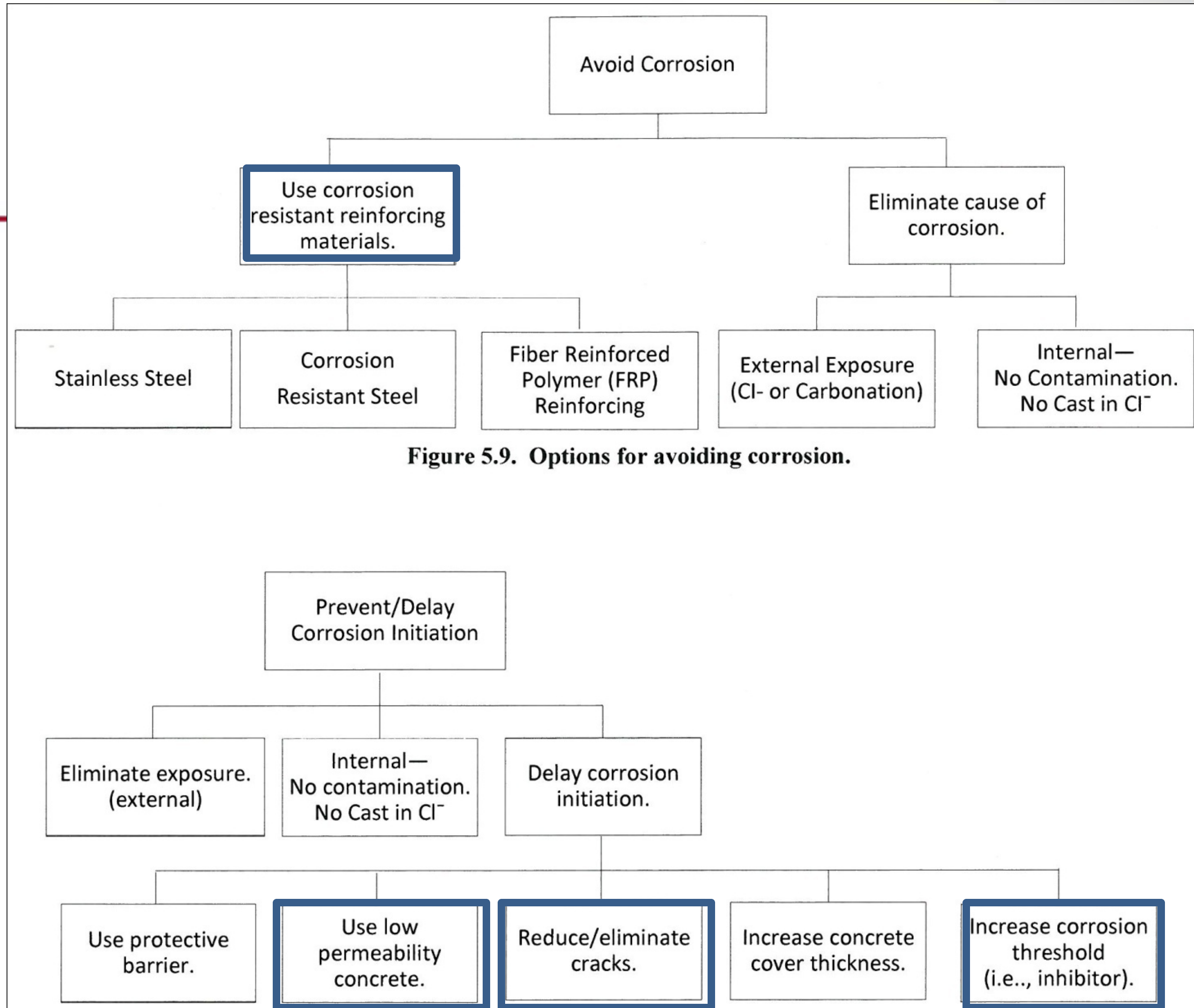


Figure 5.9. Options for avoiding corrosion.

Figure 5.10. Options for preventing or delaying corrosion initiation.

Corrosion Delay and Avoidance Strategies

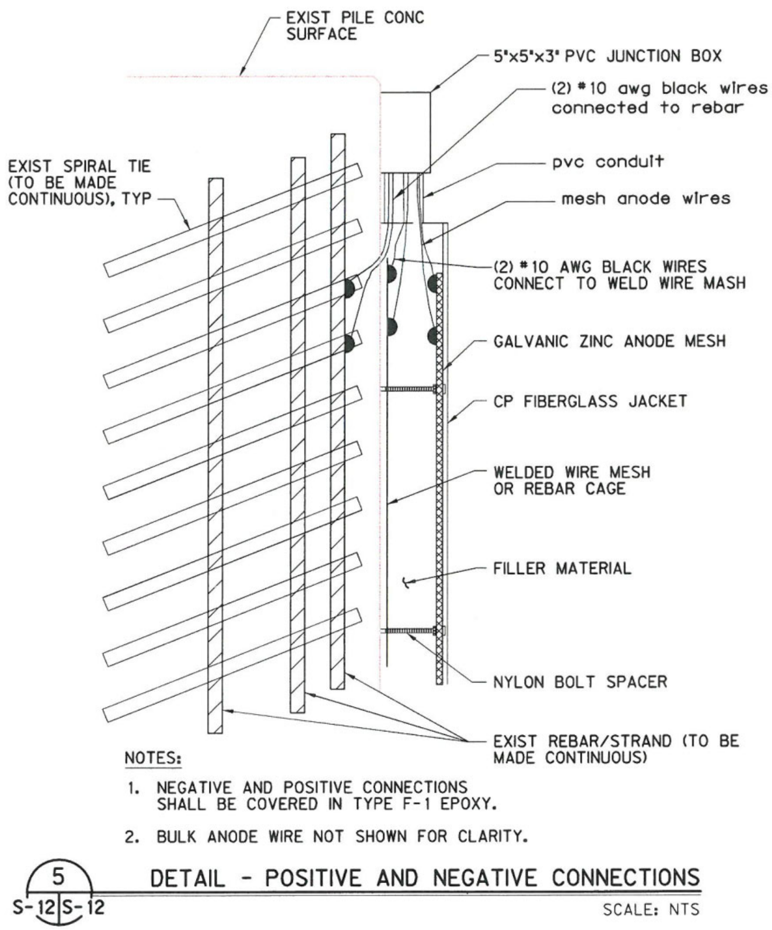
SHRB2 Renewal Project R19A, Design Guide for Service Life

Service Life Issue	Solutions	Advantage	Disadvantage
Corrosion of reinforcement	Low permeability	Reduce infiltration of aggressive solutions	Can produce high strength concrete that is brittle
	membranes and coatings	Reduce infiltration of aggressive solutions	Difficult to apply in the field, wear of traffic
	Sealers for pore lining and blocking	Reduce infiltration of aggressive solutions	Difficult to apply in the field, concrete may be difficult to penetrate
	Use of low w/cm	High strength, low permeability	Excessive cracking, shrinkage
	Low shrinkage	Minimize cracking	Low water content may adversely affect workability
	Low modulus of elasticity	High deformation, minimize deck cracking	Reduce stiffness
	Use of SCM	Reduce permeability	Quality fly ash or slag missing in many areas
	Large max aggregate size	Less surface area, loess water, cement, and paste	Less bond
	Well graded aggregates	Less paste	Problem when good shape is missing
	Chemical admixtures	Reduced permeability	Cost, incompatibility, side effects
	Cover	More resistance to penetration of solutions	Wider cracks, extra weight and cost
	Overlays	Create a low permeability protective layer over the conventional concrete.	Difficult to place, expensive, and is prone to cracking, proper curing is critical.
	Corrosion Inhibitors	Stable protective layer on the steel	Cost

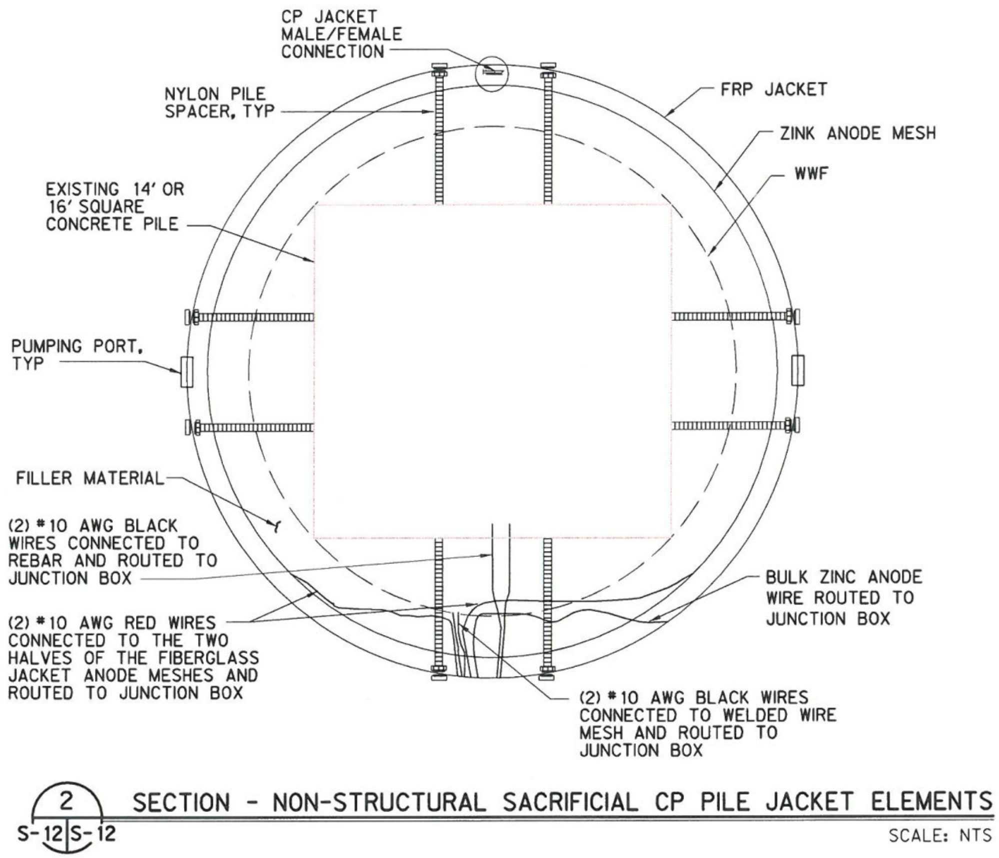
Corrosion Technologies

SHRB2 Renewal Project R19A, Design Guide for Service Life

Jacketed Concrete Pile
Zinc Mesh CP Wiring Schematic



Jacketed Concrete Pile
Zinc Mesh CP Wiring Schematic



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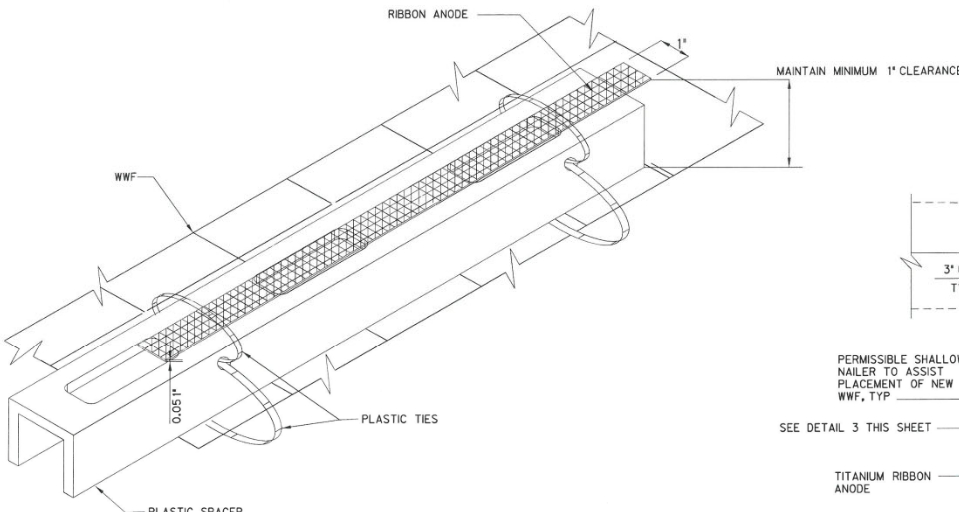
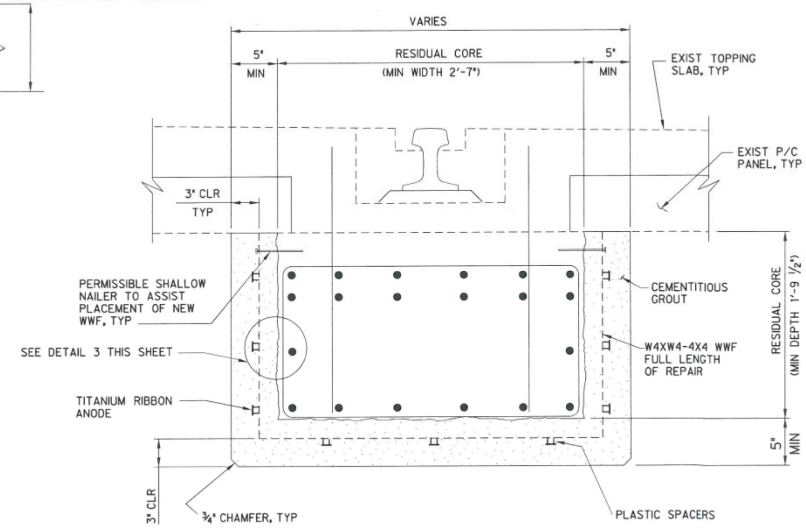
Crane Beam – Jacketed Repair of Concrete Corrosion
Impressed Current CP System

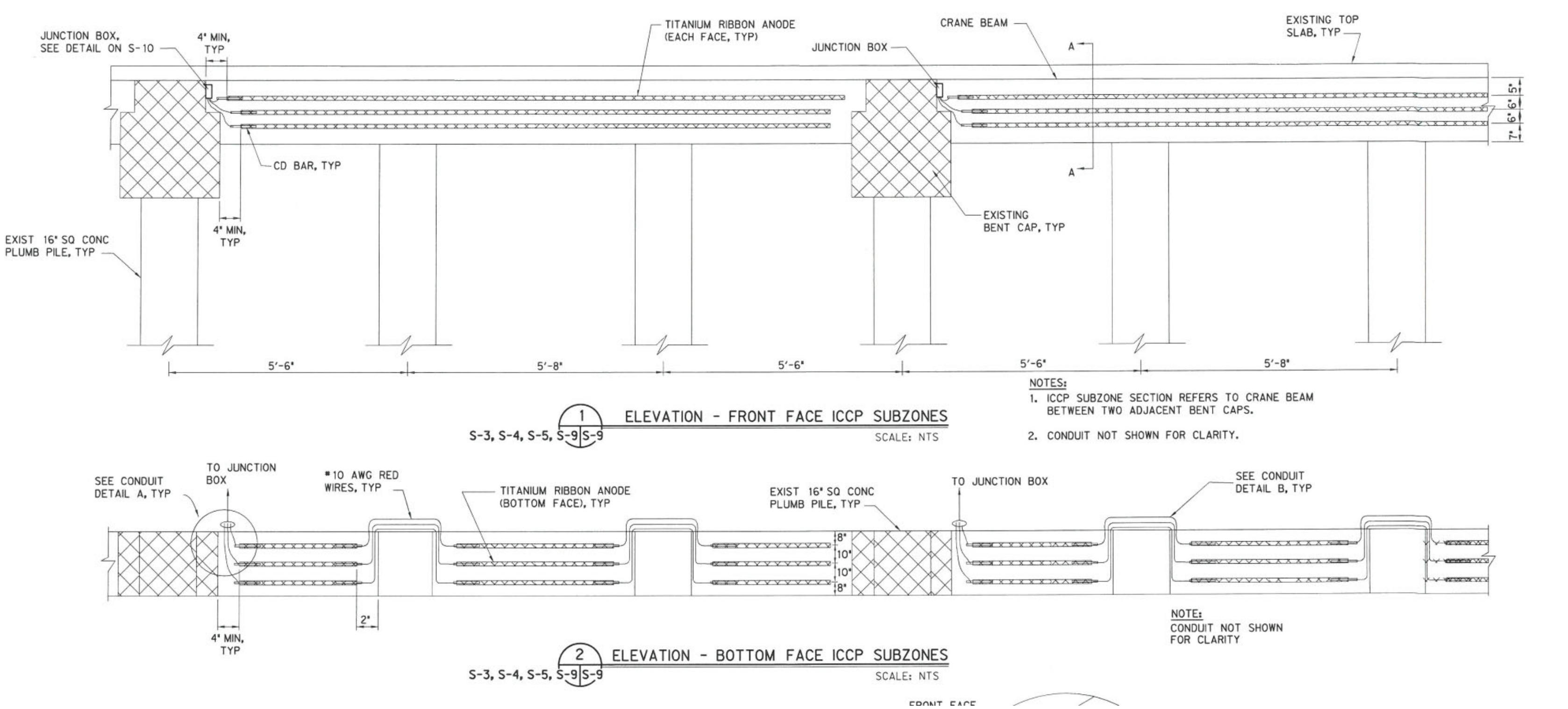


1 S-11 | S-11 DETAIL - TITANIUM RIBBON ANODE INSTALLATION OVER WWF
SCALE: NTS



2 S-11 | S-11 SECTION - CRANE BEAM TYPE I REPAIR
SCALE: NTS

Crane Beam – Jacketed Repair of Concrete Corrosion Impressed Current CP System



Research
Corrosion Resistant Reinforcing Steel

- FHWA In House, SK Lee and Paul Virmani: chloride threshold and corrosion time for 12 varieties

- UKansas, Matt O'Reilly: Rapid microcell and cracked beam tests to establish corrosion rates for BB ECR and SS varieties

- FHWA/Florida DOT, Mario Paredes and William H. Hartt: chloride threshold and corrosion time for BB and SS varieties in support of Florida DOT's policy to implement alloys that will not corrode even if concrete is cracked, poorly consolidated and/or with zero concrete cover.

Hot Dip Galvanized Reinforcement

- GALVANIZED REINFORCING STEEL
- A. Under Bid Alternate B, all reinforcing steel within the superstructure shall be galvanized.
- B. All galvanized reinforcing steel shall be deformed billet-steel and shall conform to **ASTM A 706**, Grade 60.
- C. Galvanized reinforcing bars shall be galvanized in accordance with ASTM A 767, Class 1.
- 1. Prior to galvanizing, steel bars shall have all grease, dirt, mortar, scale, injurious rust, or any other foreign substance removed.
- 2. **Prior to galvanizing, all bars shall be bent and fabricated**.
- 3. The average coating thickness, of a minimum of 3 tests, shall be **3.5 ounces per square foot or 6 mils**.
- 4. All bars shall be inspected after galvanizing. If cracking/and or loss of the coating is observed, repair coating as described in ASTM A 767.
- D. All galvanized mild steel spirals located within the superstructure shall conform to ASTM A 82.
- E. All galvanized welded wire fabric shall conform to ASTM A 1060.
- F. Welding of galvanized bars is not permitted without the approval of the Engineer.
- 1. When permitted, welding of galvanized reinforcing shall conform to AWS D1.4 and AWS WZC. Welds shall only be made on the steel free of zinc adjacent to the weld. The zinc coating shall be removed at least one inch from either side of the intended weld zone, and on all sides of the bar by grinding or alternate approved method. After weld is completed, the zinc coating in the area of the weld shall be repaired using procedures conforming to ASTM A 780.

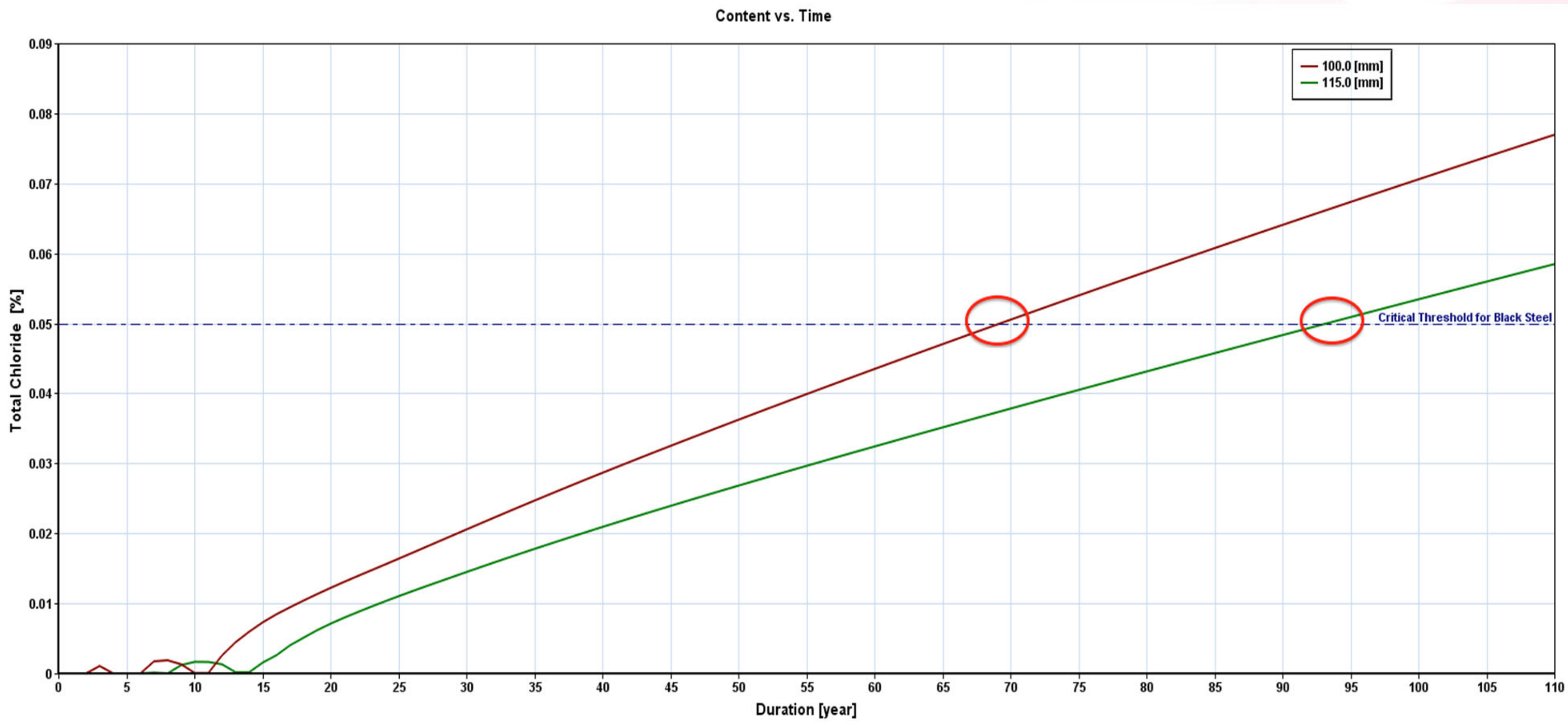
Under Bid Alternate B**, all steel wire ties, supports, standees, and all other reinforcing accessories** comprised of steel, and in direct contact with reinforcing, shall be galvanized. Reinforcing accessories in direct contact with reinforcing shall not introduce dissimilar metals or coatings within the concrete.

Hot Dip Galvanized Reinforcement

- **DMT4 Reconstruction Base Bid: $19.8M**
- **Base Bid BB: 739T**
- **HDG Alternate: 942T for additional $872K (4.4%)**
- **Unit price BB: $2283/ton**
- **Unit price HDG: $2717/ton**

STADIUM ANALYSES

Coupled ion transport analyses that simulate Corrosion Initiation Time Histories



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Courtesy SIMCO

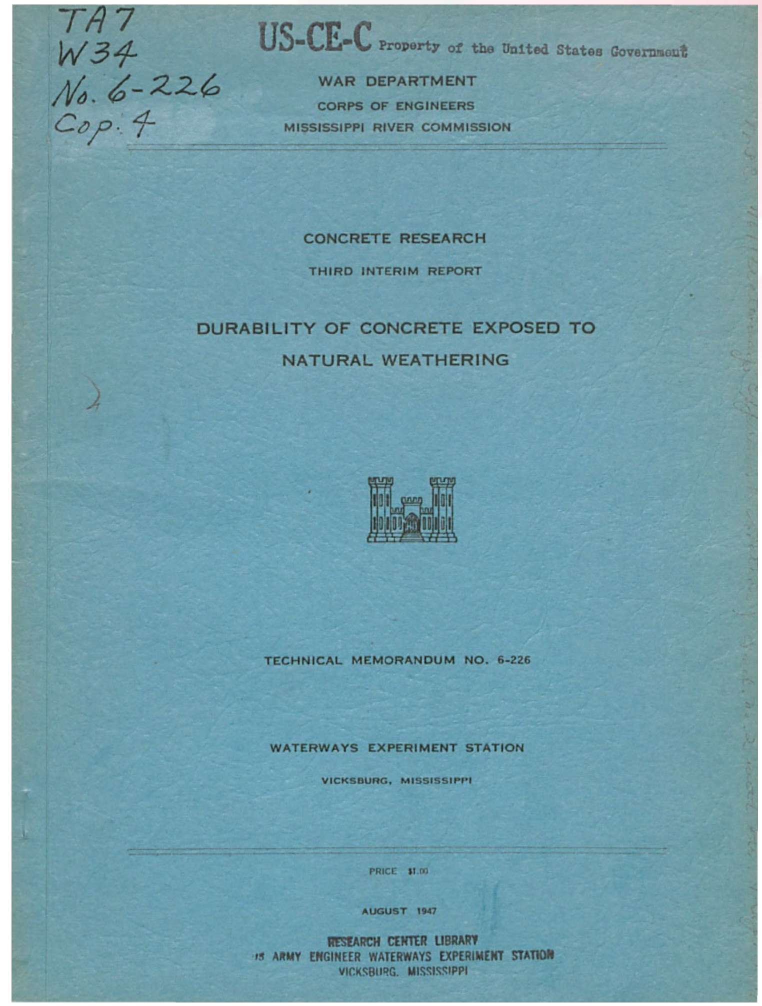
STADIUM Results for MPA Mix Designs

Element	Salinity (‰)	STADIUM® Analysis Graph ID	Reinforcement	Corrosion Inhibitor (gal/CY)	Cover (inches)	Time to Initiation + 10 years propagation (years)	Service Life (years)
Pile – Severe Exposure	30	A	Black	0	3.0	7 +10	17
	30	A	Black	0	3.25	9+10	19
	30	A	Black	0	3.5	10 + 10	20
	30	A	Black	3.5	3.0	65 + 10	75
Pile – Severe Exposure	18	B	Black	0	3.0	11 + 10	21
	18	B	Black	0	3.25	13+10	23
	18	B	Black	0	3.5	15+10	25
	18	B	Black	2.5	3.0	72+10	>75
Deck – Severe Exposure	30	C	Black	0	3.0	7+10	17
	30	C	Black	0	3.25	9+10	19
	30	C	Black	0	3.5	11+10	20
	30	C	Black	3.0	3.25	66+10	>75
	30	C2	Black	3.5	3.0	>75	>75
Deck – Severe Exposure	18	D	Black	0	3.0	12+10	22
	18	D	Black	0	3.5	14+10	24
	18	D	Black	0	4.0	17+10	27
	18	D	Black	2.0	3.5	70+10	>75
	18	D2	Black	2.5	3.0	>75	>75
Deck - Moderate Exposure	20	E	Black	0	3.0	21+10	31
	20	E	Black	0	3.25	24+10	34
	20	E	Black	0	3.5	29+10	39
	20	E	Black	2.0	3.0	29+10	>75
Deck - Moderate Exposure	12	F	Black	0	3.0	37+10	47
	12	F	Black	0	3.25	45+10	55
	12	F	Black	0	3.5	55+10	65
	12	F	Black	2.0	3.0	>75	>75

Confirmation of STADIUM Results for MPA Mix Designs

USACE Treat Island Weathering Program

- U.S. Army Engineer Research and Development Center (ERDC) conducts long-term durability research at the Treat Island Natural Weather Station, Eastport, Maine
- Coring and analysis of exposed concrete specimens placed in the mid-1990s
- In continuous use since 1936 to study concrete durability
- Tide levels that vary by as much as 22 feet with temperatures during the coldest part of the winter range from minus 10 degrees Fahrenheit to 37 degrees Fahrenheit
- Subjected to between 100 and 160 freeze-thaw cycles, cyclic inundation of saltwater and air-drying, chloride intrusion, wetting and drying, and abrasion-erosion
- MPA specimens placed in 2016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MISSISSIPPI RIVER COMMISSION

CONCRETE RESEARCH
THIRD INTERIM REPORT

DURABILITY OF CONCRETE EXPOSED TO
NATURAL WEATHERING

TECHNICAL MEMORANDUM NO. 6-226

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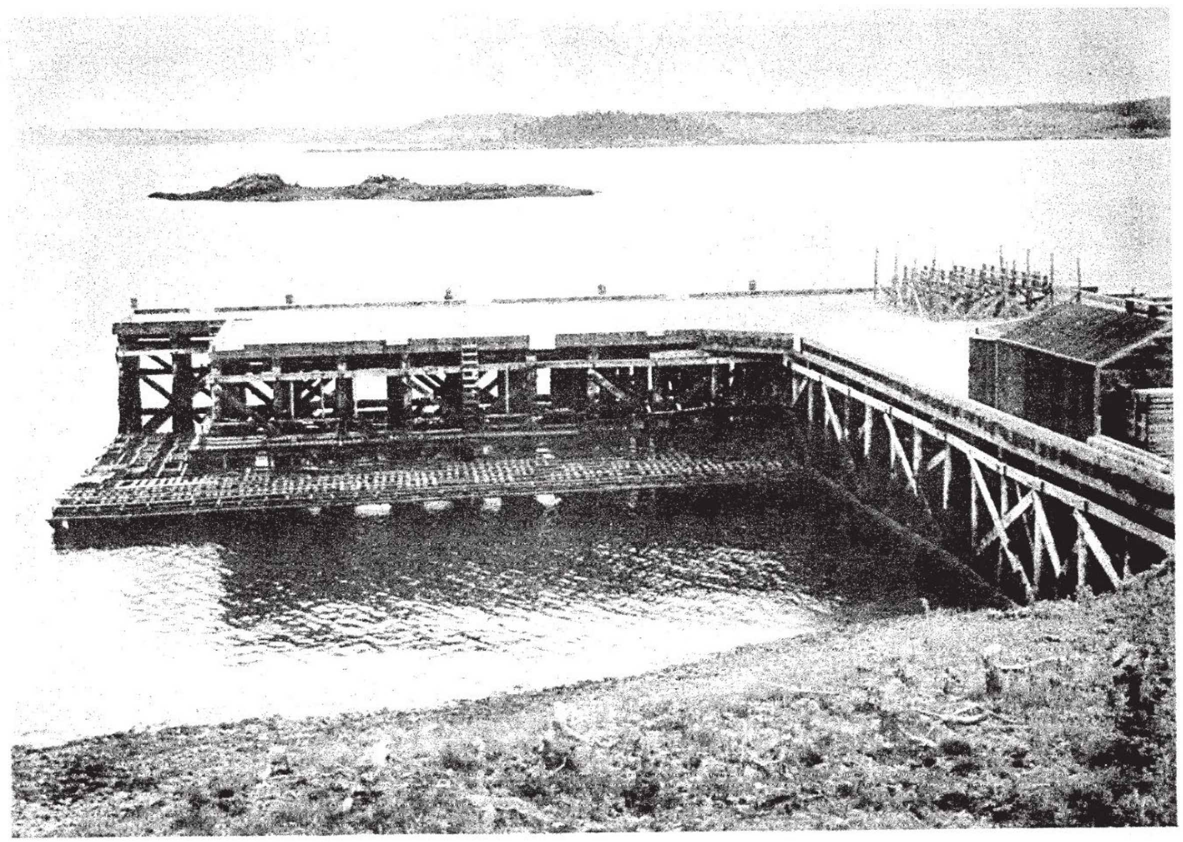
Confirmation of STADIUM Results for MPA Mix Designs

USACE Treat Island Weathering Program



Exposure rack and wharf, Treat Island, Maine, 1941