Performance-Based Concrete Mixtures for Durable, Long-Life Bridges

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Reducing the Carbon Footprint of Concrete Construction with Silica Fume
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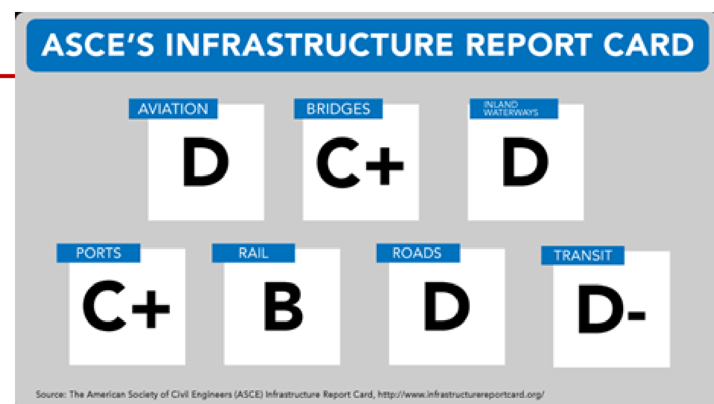
Bridges in the United States

The U.S. has 614,387 bridges, almost four in 10 of which are 50 years or older.

- *56,007 (**9.1%)** of the nation's bridges were **structurally deficient in 2016,*** (*requiring significant maintenance, rehabilitation or replacement*)**.**
- *83,557 **(13.6%)** were categorized as **functionally obsolete** (below current design standards, e.g. narrow lanes or low load capacity)*
- *The most recent estimate puts the nation's backlog of bridge rehabilitation needs at $123 billion.*



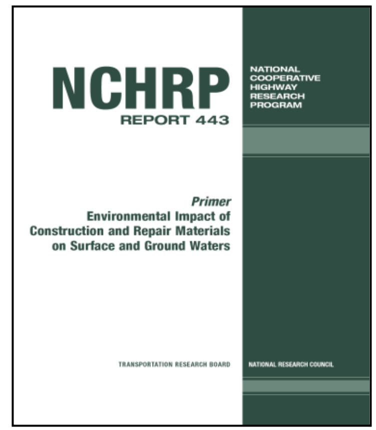
Functionally Deficient Bridges

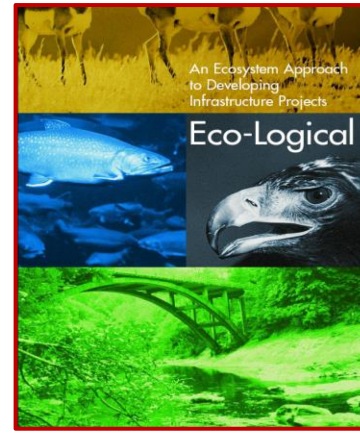
Infrastructure investments of a half-century ago are straining to support modern population levels and commercial activities they were not designed to accommodate and are sorely inadequate relative to the natural and man-made hazards they face.

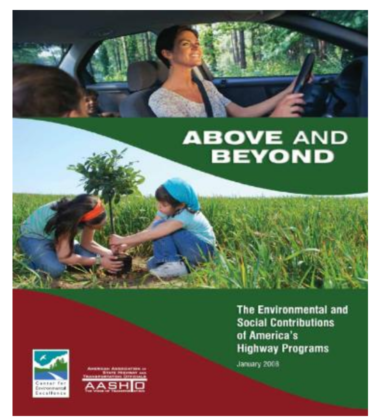
Infrastructure Goals of FHWA & AASHTO

Enable the delivery of safe, environmentally-friendly bridge infrastructure, and provide a high level of service.

- Long-Term Infrastructure Performance
- Durable Infrastructure Systems
- Accelerated Construction
- Environmentally Sensitive Infrastructure
- Performance-Based Specifications
- Comprehensive and Integrated Infrastructure Asset Management
- Core Infrastructure R&D Facilities, Capabilities, and Functions





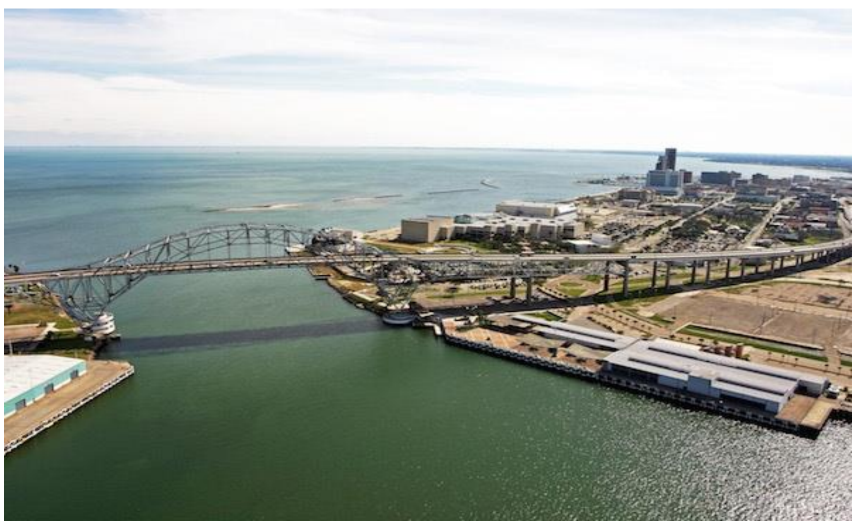


Transportation Impacts and Indicators on Sustainability

Economic	Social	Environmental
Traffic Congestion	Inequity of Impacts	Air Pollution
Mobility Barriers	Mobility Disadvantaged	Climate Change
Crash Damages	Human Health Impacts	Habitat Loss
Transportation Facility Costs	Community Cohesion	Water Pollution
Consumer Transportation Costs	Community Livability	Hydrological Impacts
Depletion of Non-Renewable Resources	Aesthetics	Noise Pollution

Economic	Social	Environmental
Accessibility - Commuting	Safety	Climate Change Emissions
Accessibility - Land Use Mix	Health and Fitness	Other Air Pollution
Accessibility - Smart Growth	Community Liveability	Noise Pollution
Transport Diversity	Equity - Fairness	Water Pollution
Affordability	Equity - Non-drivers	Land Use Impacts
Facility Costs	Equity - Disabilities	Habitat Protection
Freight Efficiency	Non-motorized Transport Planning	Resource Efficiency
Planning	Citizen Involvement	

The Longest Concrete-segmented, Cable-stayed Bridge in the US



Largest Issues:

- structural deficiencies
- navigational restrictions of the current bridge,
- improve safety conditions of motorists, and
- create community connectivity and increased level of service to the community.

Neighborhood Connectivity

- The selected route isolated two neighborhoods.
  - residents of Hillcrest and Washington-Coles adversely affected received fair compensation to relocate;
  - receive home and neighborhood improvements as mitigation

Replacement with Cable-Stayed Bridge

- Main span of 505 meters (1655 feet)
- Main tower height 164 meters (538 feet)
- Clearance 62 meters (205 feet) above water
- Precast concrete segments for the main span and approaches
- Precast piles and girders for the structure maximizing the volume of bridge elements
- Fabricated using local materials and labor

Cable-Stayed Bridge

Design Requirements

- 75 and 170-year service life in panels and drilled shafts
- Thermal Requirements
  - Maximum peak curing temperature of all mass elements shall not exceed 71 °C (160 °F) during curing, nor exceed graduated differential temperature limits, the first that was of more than 2.0 °C (45 °F) within the first 48 hours.
- Specification Limitations
  - 50% maximum replacement with SCMs
- Strength Requirements
  - 28 day specified strength must be met at no later than 56 days
- Sustainability Requirements
  - INVEST Sustainable Rating System

Mixture Requirements

- Air, Slump, and Compressive strength ASTM C31 / ASTM C39
- Hardened Air Void Analysis ASTM C457
- Freeze/Thaw Resistance ASTM C666
- Surface Scaling ASTM C672
- 28-Dry Shrinkage ASTM C157
- Chloride Permeability ACI 1202
- Modulus of Elasticity at 3, 7, 28, 56, 90, 1 year, and 2 year.
- ASR at 14 and 28-Days ASTM C1260 / C1567
- Creep
- Chloride Ion Diffusion ASTM C1556

Stay-Cabled Bridge

- The precast panel mixtures utilized a ternary binder mixture with 35% slag cement and 15% fly ash and 0.32 (W/B) ratio.
- The drilled shaft mixtures have utilized a 45% replacement of portland cement with fly ash and a 0.43 W/B.

	Mixture ID	Cement Type I/II kg/m3 [lb/yd3]	Grade 100 Slag kg/m3 [lb/yd3]	Fly Ash kg/m3 [lb/yd3]	Silica Fume kg/m3 [lb/yd3]	Mix Water kg/m3 [lb/yd3]
Precast Panels	BCE100	205 [350]	185 [315]	0	20 [35]	132 [224]
	BCE101	205 [350]	115 [189]	75 [126]	20 [35]	132 [224]
	BCE102	205 [350]	145 [350]	65 [105]	0	132 [224]
	BCE103	235 [350]	225 [350]	0	24 [40]	145 [246]
Drilled Shafts	DS1	210 [350]	0	175 [293]	0	165 [280]
	DS2	226 [385]	0	186 [315]	0	132 [238]

Concrete Mixture Designs

	Mixture ID	Cement Type I/II kg/m3 [lb/yd3]	Grade 100 Slag kg/m3 [lb/yd3]	Fly Ash kg/m3 [lb/yd3]	Silica Fume kg/m3 [lb/yd3]	Mix Water kg/m3 [lb/yd3]
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	BCE102	205 [350]	145 [350]	65 [105]	0	132 [224]
	BCE103	235 [350]	225 [350]	0	24 [40]	145 [246]
Drilled Shafts	DS1	210 [350]	0	175 [293]	0	165 [280]
	DS2	226 [385]	0	186 [315]	0	132 [238]

Testing Results

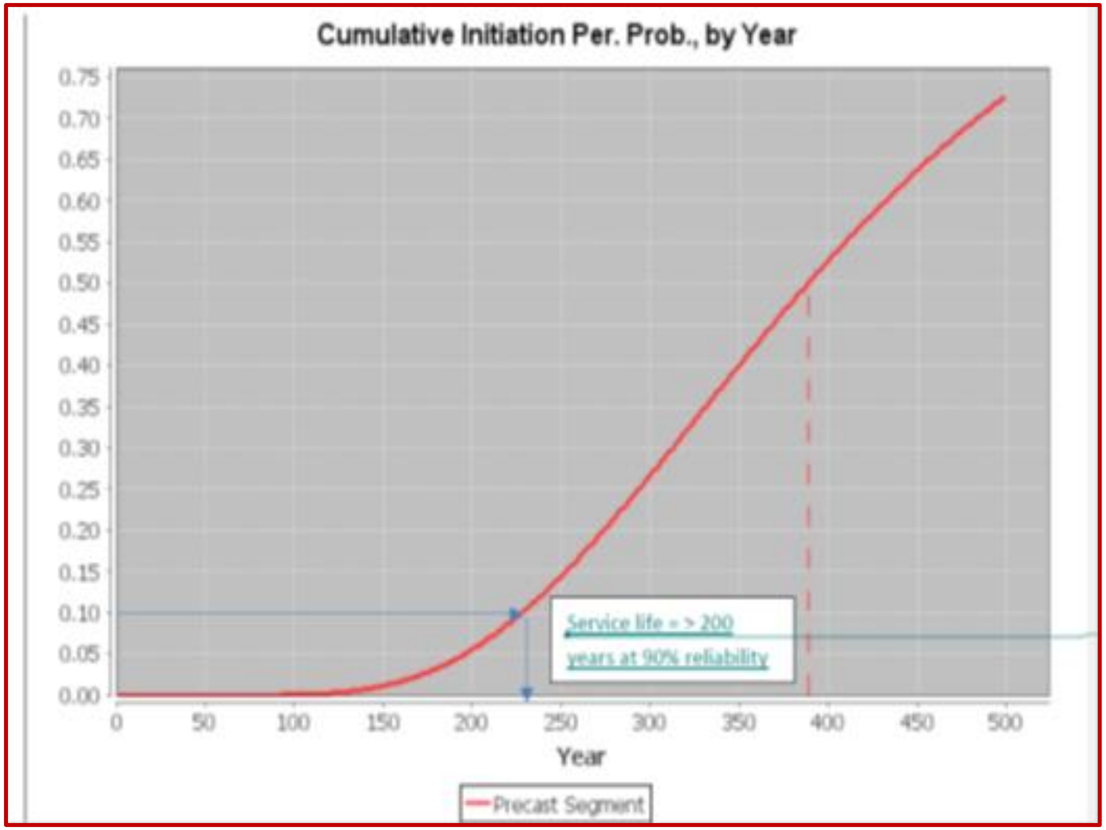
2 sets of specimens cast for each concrete mixture.

- Standard laboratory conditions
- Accelerated curing conditions
  - 49 °C (120 °F) air and the length change and transport property specimens in a 38 °C (100 °F) water bath

Mixture ID	BCE100	BCE101	BCE102	BCE103	DS1	DS2
Compressive Strength, ASTM C 1012, MPa (psi)						
12 Hr	4.4 (635)	7.1 (1025)	3.1 (450)	8.6 (1250)	2.4 (535)	3.0 (440)
1 Day	16.8 (2440)	15.9 (2300)	16.9 (2455)	20.8 (3025)	12.3 (1790)	10.6 (1540)
28 Days	83.0 (12030)	83.0 (12040)	82.5 (11960)	87.1 (12630)	51.8 (7510)	46.8 (6780)
56 Days	84.8 (12290)	81.2 (11780)	87.6 (12700)	90.8 (13170)	58.8 (8520)	57.4 (8320)
Accelerated Cure Compressive Strength, ASTM C 1012, MPa (psi)						
12 Hr	26.7 (3870)	23.0 (3335)	21.4 (3110)	33.0 (4780)	13.4 (1875)	11.0 (1600)
1 Day	45.1 (6540)	43.0 (6240)	40.9 (5925)	48.4 (7020)	20.3 (2945)	17.9 (2590)
Standard Length Change of Hardened-Hydraulic Mortar and Concrete, ASTM C 157, %						
28 Days	-0.014	-0.011	-0.02	-0.014	-0.019	-0.023
Resistance To Chloride Penetration, ASTM C 1202, Coulombs						
28 Days	221	223	578	249	1520	881
56 Days	140	123	468	137	616	490
Accelerated Cure Resistance To Chloride Penetration, ASTM C 1202, Coulombs						
28 Days	141	101	271	111	307	N/A
56 Days	108	75	289	103	127	N/A
Boiled Absorption, ASTM C 642, % mass						
28 Days	1.7	1.6	1.9	1.5	3.2	4.0
Porosity, ASTM C 642, % Volume						
28 Days	13.1	12.9	12.5	12.8	12.8	12.8
Bulk Diffusion Coefficient*, ASTM C 1556, x 10^{-13} m^2/s (1 x 10^{-13} m^2/s = 0.000124 x in^2/y)						
28 Days	7.60	8.35	9.60	5.30	2.15	1.70
Accelerated Cure Bulk Diffusion Coefficient*, ASTM C 1556, x 10^{-13} m^2/s (1 x 10^{-13} m^2/s = 0.000124 x in^2/y)						
28 Days	5.85	6.90	5.55	5.20	7.40	N/A
Chloride Migration Coefficient from Non-Steady-State Migration NT BUILD 492, x10^{-13} D m^2/s (1 x 10^{-13} m^2/s = 0.000124 x in^2/y)						
28 Days	5.45	13.00	22.70	3.60	77.00	42.80
Accelerated Cure Chloride Migration Coefficient from Non-Steady-State Migration NT BUILD 492, x10^{-13} D m^2/s (1 x 10^{-13} m^2/s = 0.000124 x in^2/y)						
28 Days	4.85	3.50	7.50	2.50	1.49	N/A
56 Days	3.50	3.80	7.20	1.50	6.90	N/A
Bulk Electrical Conductivity of Hardened Concrete, ASTM 1760, Ω^{-1}						
28 Days	921.0	368.0	226.0	363.0	69.0	148.0
56 Days	N/A	578.0	429.0	632.0	162.0	398.0
Accelerated Cure Bulk Electrical Conductivity of Hardened Concrete, ASTM 1760, Ω^{-1}						
28 Days	1725.0	1830.0	579.0	1500.0	563.0	N/A
56 Days	1760.0	2240.0	850.0	1515.0	1100.0	N/A

Service Life

A corrosion-inhibiting admixture was required at dosages between 5.0-10.0 L/m3 (1-2 gal/yd^3) to meet the service life requirements in the specification.



Project Development

- There are 60 criteria within INVEST organized by module.

- The Project Development (PD) module includes twenty-nine criteria that are generally organized from planning to design to construction.

Project Development
Achievement Levels

	Achievement level	Fraction of Total Points Possible	Points Required				
			Paving	Basic Rural	Extended Rural	Basic Urban	Extended Urban
	Platinum	60%	34	57	69	63	76
	Gold	50%	29	48	58	53	63
	Silver	40%	23	38	46	42	50
	Bronze	30%	17	29	35	32	38

- The Project Development module includes criteria that span the entire project development process from early planning, alternatives analysis, environmental documentation, preliminary and final design, and construction.

- Criteria includes economic analysis, LCCA, habitat restoration, bicycle and pedestrian access, reduce and reuse materials, long life pavement design, etc.

Stillwater Lift Bridge

Currently, severe traffic congestion in downtown Stillwater causes pedestrian and traffic safety problems, which are amplified by Lift Bridge operations. The bridge, which opened in 1931, was listed on the National Register of Historic Places in 1989.

St. Croix Crossing

- Extradosed Bridge Design
  - Cross between cable-stayed and precast box girder bridge
  - Lower main pillar than cable-stayed
- 1523 m (5,075 ft) bridge
- 20 m (67 ft) tower height
- 13 pier structures
  - 5 in the waterway
- Environmental Challenges
  - Waterway, Bluffs, and Endangered Species

Additional Challenges

- **Construction in Bluffs**
  - Hand construction in some areas
  - Turbidity curtains, concrete barriers and silt fences were erected to control soils and construction traffic within the project to protect adjacent wetlands

- **Preservation of endangered species**

- **Water quality**
  - Testing daily of water to insure lack of contamination and neutral pH

Dotted Blazing Star

Higgins Eye Pearly Mussel

St. Croix Crossing

Design Requirements

- 100-year service life
- Thermal Requirements
  - Maximum peak curing temperature of all mass elements shall not exceed 71 °C (160 °F) during curing, nor exceed graduated differential temperature limits, the first that was of more than 2.0 °C (45 °F) within the first 48 hours.
- Strength Requirements
  - 28 day specified strength must be met at no later than 56 days
- Concrete Placement
  - Due to extended haul times to the point of placement, all mixtures must remain plastic for 180 minutes.
  - All mixtures must be tested for standard delivery to 90 minutes and for extended delivery times up to 180 minutes

Mixture Requirements

- Air, Slump, and Compressive strength ASTM C31 / ASTM C39
- Hardened Air Void Analysis ASTM C457
- Freeze/Thaw Resistance ASTM C666
- Surface Scaling ASTM C672
- 28-Dry Shrinkage ASTM C157
- Chloride Permeability ACI 1202
- Modulus of Elasticity at 3, 7, 28, 56, 90, 1 year, and 2 year.
- ASR at 14 and 28-Days ASTM C1260 / C1567
- Creep
- Chloride Ion Diffusion ASTM C1556

St. Croix Crossing

- Precast segments utilized air entrained concretes of 24, 41, 55 and 62 MPa (3500, 6000, 8000, and 9000 psi) depending on segment location.
- Piers utilized air-entrained 55 MPa (8000 psi) concrete with stripping strengths achieved between 24-48 hours after placement.

- Admixtures included an air entrainer, non-chloride accelerator, mid-range water-reducer, and viscosity modifier.
- The non-chloride accelerator and mid-range water reducer were used in precast segments and cast-in-place (CIP) box-girder mixtures to insure adequate demolding strength and to achieve slump requirements.
- An air entrainer was utilized in all exposed structural elements to insure durability against freezing and thawing.

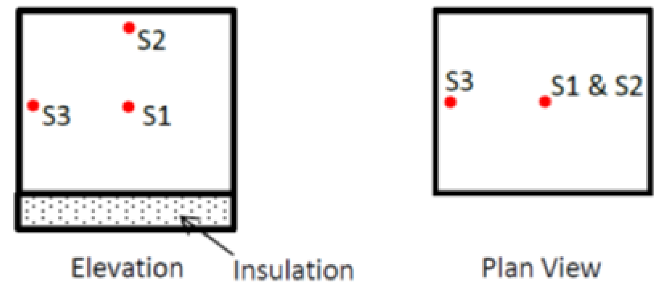
St. Croix Crossing

	Mixture ID	Cement Type I/II kg/m³ [lb/yd³]	Grade 100 Slag kg/m³ [lb/yd³]	Fly Ash kg/m³ [lb/yd³]	Silica Fume kg/m³ [lb/yd³]	Sand 190 mm [0.75 in] kg/m³ [lb/yd³]	Gravel 190 mm [0.75 in] kg/m³ [lb/yd³]	Granite 190 mm [0.75 in] kg/m³ [lb/yd³]	Mix Water kg/m³ [lb/yd³]	W/B
PIERS MASS CONCRETE	SCB46-1 SHAFTS PIERS 1-7	45 [80]	200 [360]	50 [90]	0	820 [1475]	1000 [1800]	0	138 [239]	0.45
	SCB46-3 SHAFTS PIER 13	50 [90]	200 [360]	50 [90]	0	822 [1475]	1002 [1800]	0	128 [232]	0.43
	SCB46-7 PIER 1-7, 13	47 [84]	208 [375]	56 [101]	0	764 [1375]	933 [1680]	0	131 [235]	0.42
	SCB46-9, PIERS 5-6, 8-12	50 [90]	223 [402]	60 [108]	0	753 [1355]	917 [1650]	0	133 [240]	0.40
	SCB46-10 EXTRADOSED PIER	50 [90]	223 [402]	60 [108]	0	758 [1365]	0	925 [1665]	133 [240]	0.40
CROSS BEAM MASS CONCRETE	SCB83-12 SCB83-12A SCB83-12B CROSS BEAMS 8-12	67 [120]	178 [320]	106 [190]	17 [30]	749 [1348]	0	911 [1640]	128 [231]	0.35
	SCB83-18 CROSS BEAMS 8-12	94 [170]	194 [350]	67 [120]	11 [20]	743 [1338]	0	743 [1338]	128 [231]	0.35
FOOTINGS ABUTMENTS/ RETAINING WALLS	SCB46-2	180 [324]	0	120 [216]	0	814 [1465]	994 [1790]	0	138 [248]	0.46
ABUTMENTS/ STEM & BACK WALLS	SCB46-8	129 [232]	64 [116]	129 [232]	0	754 [1358]	922 [1660]	0	136 [244]	0.42
PILE FILL	SCB56-4	207 [372]	0	138 [248]	0	811 [1460]	964 [1735]	0	145 [260]	0.42
CIP UNITS 1-2 & SKIRT	SCB63-11 SCB63-11B SCB63-12E SCB63-11F	141 [254]	82 [147]	163 [294]	0	722 [1300]	0	880 [1584]	139 [250]	0.34
CLOSURE POUR & EXTERNAL STRUTS & CIP UNIT 3	SCB83-13	184 [332]	92 [166]	184 [332]	0	699 [1258]	0	856 [1540]	138 [249]	0.30
PRECAST SEGMENTS 41 & 55 MPA [6000 & 8000 Psi]	SCB83-14 SCB83-15 SCB83-16 SCB83-16C SCB83-16D	311 [560]	89 [160]	44 [80]	0	710 [1278]	0	868 [1562]	142 [256]	0.32

Strength and Thermal Testing

- Stressing and stripping strength of mass concrete was performed with Flir Match Cure Boxes.

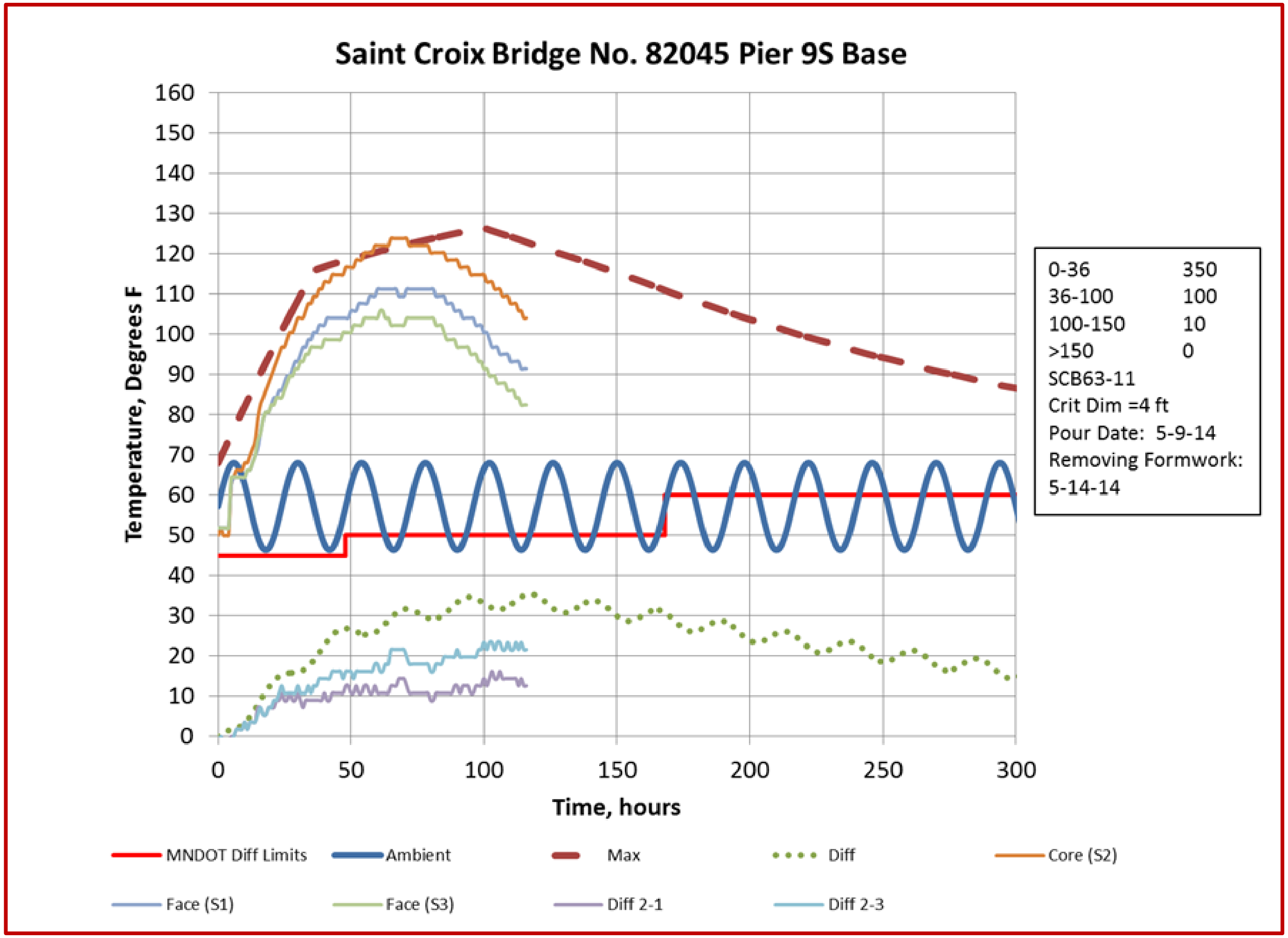
- All segment concrete was 8,000 psi or 9,000 psi with a 4,000 psi requirement in 18-hours for stripping strength.



The heat of hydration of each mass concrete mixture was modeled for internal temperature and the temperature differential

1.2 m x 1.2 m x 1.2 m (4 ft x 4 ft x 4 ft) unreinforced concrete block was constructed and instrumented with sensors to determine the semi-adiabatic internal temperature rise

Representative Thermal Modeling Result



Placement of Concrete

Closing the Loop

Stillwater's Lift Bridge is now closed to motorists, but the two-lane bridge will be resurfaced and integrated into a 5-mile pedestrian and bicycle path.

The bridge will also be restored to look as it did when it opened in 1931.

General Discussion on SCMs and DEF

- The enhanced particle packing and chemical reactivity associated with most SCMs greatly reduces permeability through increased tortuosity of the cement paste.
- These effects are attributed to the
  - pozzolanic reaction,
  - improved quality of the interface between the cement paste and the aggregate; and,
  - reduced internal bleeding.

- Heat reduction is seen in concrete mixtures with replacement rates of 15-25% for fly ash and 65 to 80% for slag cement.
- Successful mitigation against delayed ettringite formation (DEF) at concrete temperature up to 77 °C (170 °F) has also been accomplished in concrete mixtures with at least 25% Class F fly ash, at least 35% Class C fly ash, or at least 35% slag cement.

Durability = Sustainability

Enhancing long-term durability

- **Significantly reduces the impact of operational embodied energy** (non-renewable energy consumed to maintain, repair, restore, refurbish or replace materials, components or systems) during the structure's life span.
- Operational energy is heavily influenced by the **durability and maintenance of construction materials**, systems and components installed in the structure, and the **life span of the structure**.

Conclusions

Additional improvements in sustainable project delivery are achievable -

- integration of material and design selection based upon life cycle analysis measurements;
- implementation of life cycle costing analysis versus lowest cost economics;
- use of innovative materials, performance specification and technologies;
- and collaborative platforms during project design and construction.