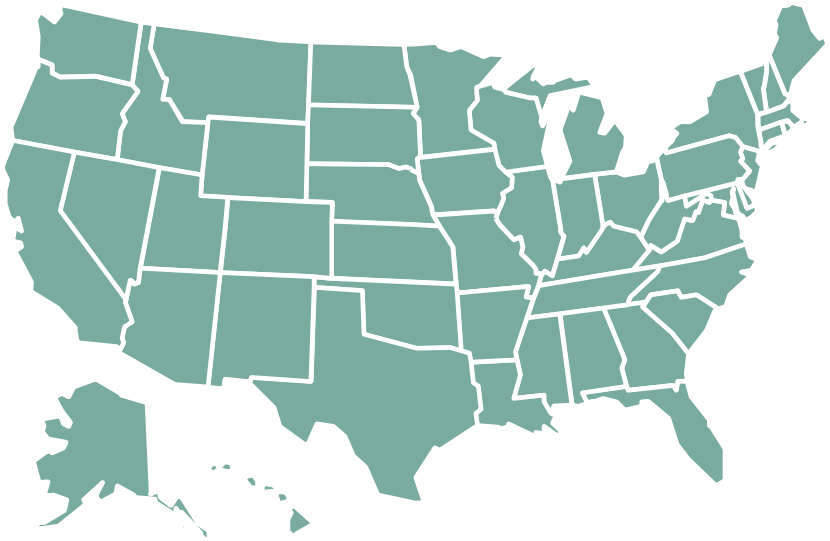
NCHRP Research Report 819: Self-Consolidating Concrete for Cast-in-Place Bridge Components

NCHRP Project 18-16

NCHRP is a State-Driven Program

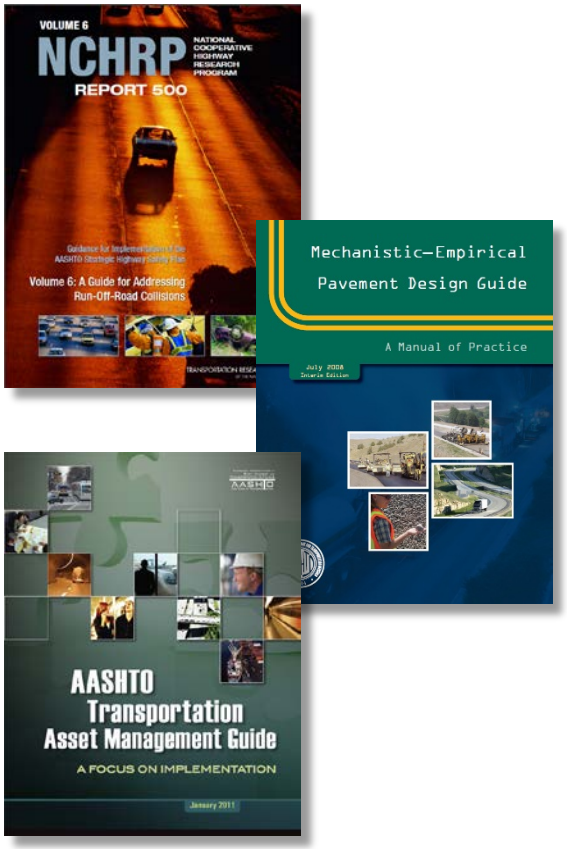
- Sponsored by individual state DOTs who
  - Suggest research of national interest
  - Serve on oversight panels that guide the research.



- Administered by TRB in cooperation with the Federal Highway Administration.

Practical, ready-to-use results

- Applied research aimed at state DOT practitioners
- Often become AASHTO standards, specifications, guides, syntheses
- Can be applied in planning, design, construction, operations, maintenance, safety, environment



Previous NCHRP Publication Related to Self-Consolidating Concrete

- NCHRP Report 628: Self-Consolidating Concrete for Precast, Prestressed Concrete Bridge Elements

You can learn more about this publication by visiting www.trb.org

Added Considerations for Cast-in-Place Self-Consolidating Concrete

- Off-site, Third-Part Batching and Transit
- Constructability
- Material Performance/Properties in non-Prestressed Applications

Today’s Speaker

- *Professor George Morcous*
  University of Nebraska-Lincoln

SELF-CONSOLIDATING CONCRETE FOR CAST-IN-PLACE BRIDGE COMPONENTS

NCHRP Project 18-16 (Report 819)

George Morcous, Ph.D., PE

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COLLEGE OF ENGINEERING

Omaha, NE

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Acknowledgments

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Table of Content

Definition

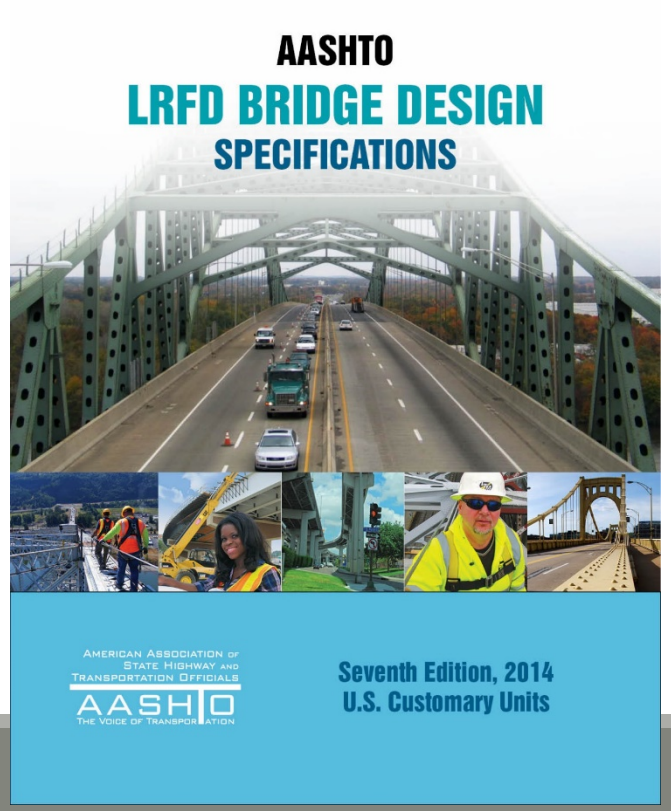
"SCC is a specially proportioned hydraulic cement concrete that enables fresh concrete to flow easily into the forms and around steel reinforcement without segregation and without any mechanical consolidation" (NCHRP 819)

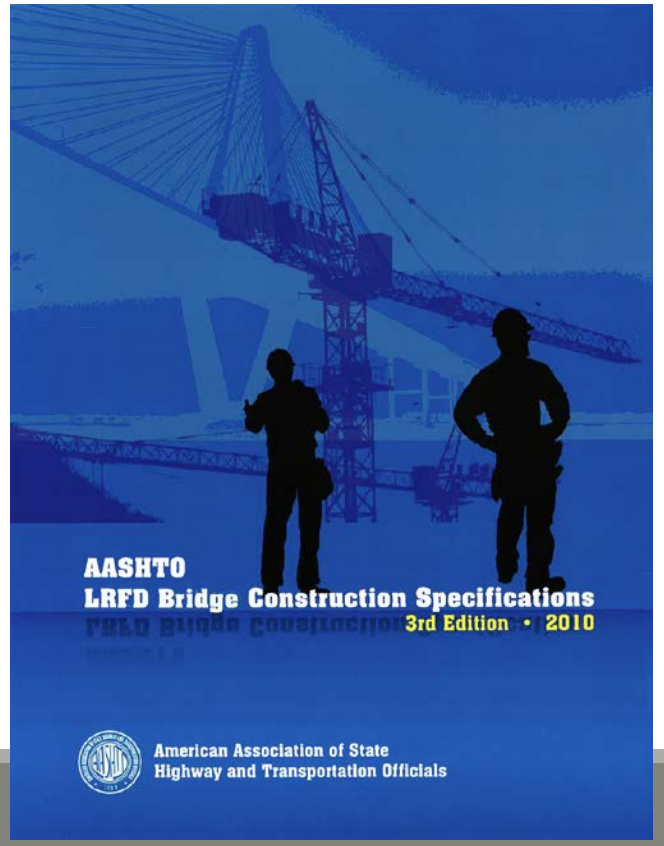
Key workability properties of SCC:

- Filling Ability
- Passing Ability
- Stability

Problem Statement

- SCC has limited use in cast-in-place (CIP) bridge construction due to:
  - Lack of design specifications
  - Lack of construction guidelines
  - Concerns about design and construction issues affecting structural integrity



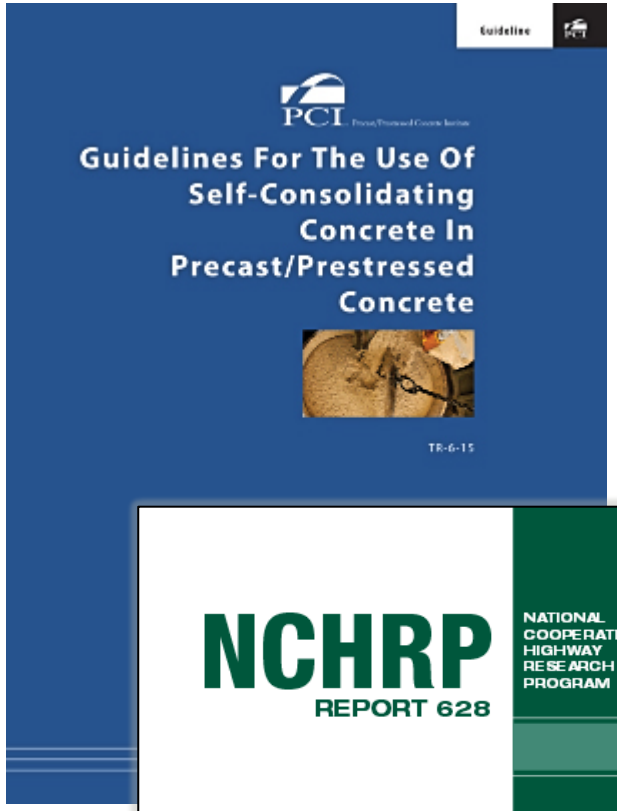


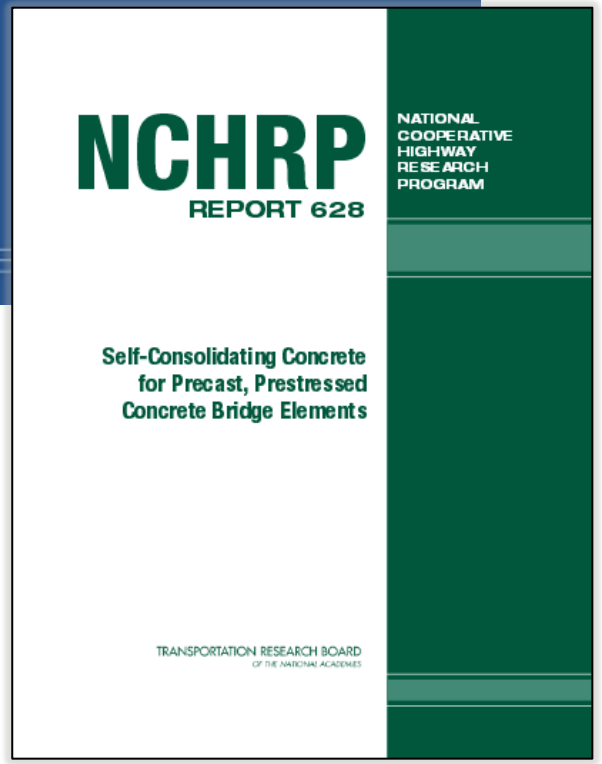
Problem Statement

- The use of SCC in precast/prestressed concrete bridge components has been growing in US since early 2000.

- Several studies focused on the use of SCC in the controlled condition of precast/prestressed concrete plants.

- Cast-in-place bridge components differ with respect to:
  - Compressive strength (4 – 8 ksi)
  - Constituent materials (aggregate type, NMSA, SCM/filler, w/cm, etc.)
  - Component geometric characteristics
  - Conditions of transporting, placing, and curing
  - Properties, such as bond, time of setting, workability retention, formwork pressure, etc.





Research Objectives and Scope

OBJECTIVES:

1. Develop guidelines for the use of SCC in CIP bridge components
2. Recommend changes to AASHTO LRFD Bridge Design and Construction Specifications

SCOPE:

- Project focused on bridge substructure and superstructure components
- Bridge deck, approach slab, and drilled shafts were not considered.

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1. Definition
2. Problem Statement
3. Research Objectives and Scope
4. Research Approach **(chapter 1)**
5. Research Results **(chapter 2)**
6. Conclusions **(chapter 3)**

Research Approach

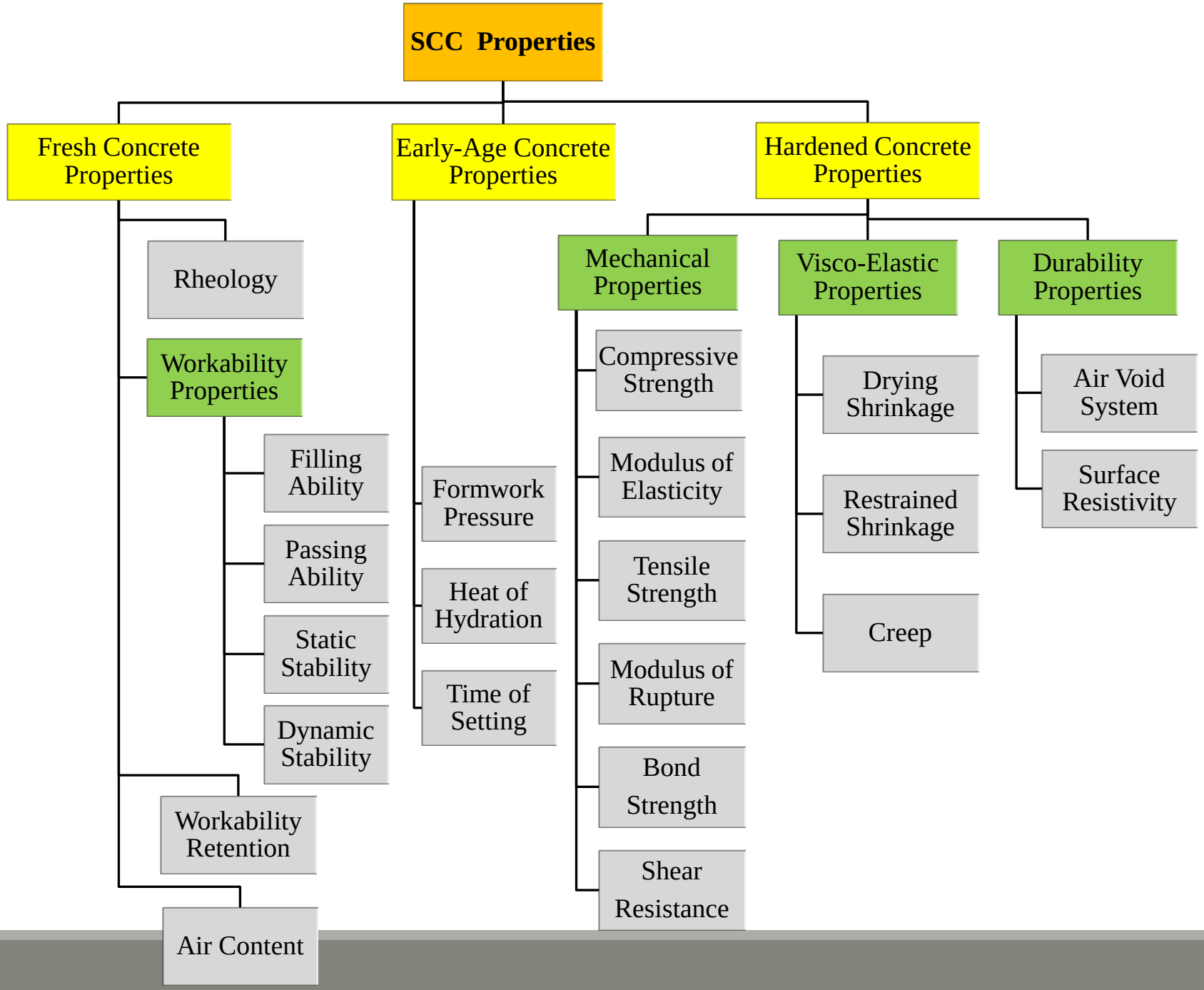
1- Literature Review

- NCHRP 628
- ACI 237R-07 ETS Document
- PCI TR-6-15 Guidelines for the Use of SCC in Precast/Prestressed Concrete
- European and Japanese Guidelines and Recommendations
- RILEM State of the Art Report (228-MPS-14)
- State DOT Sponsored Research Projects
- Published Research Articles

Outcome:

- SCC properties relevant to design and construction of CIP components

Research Approach



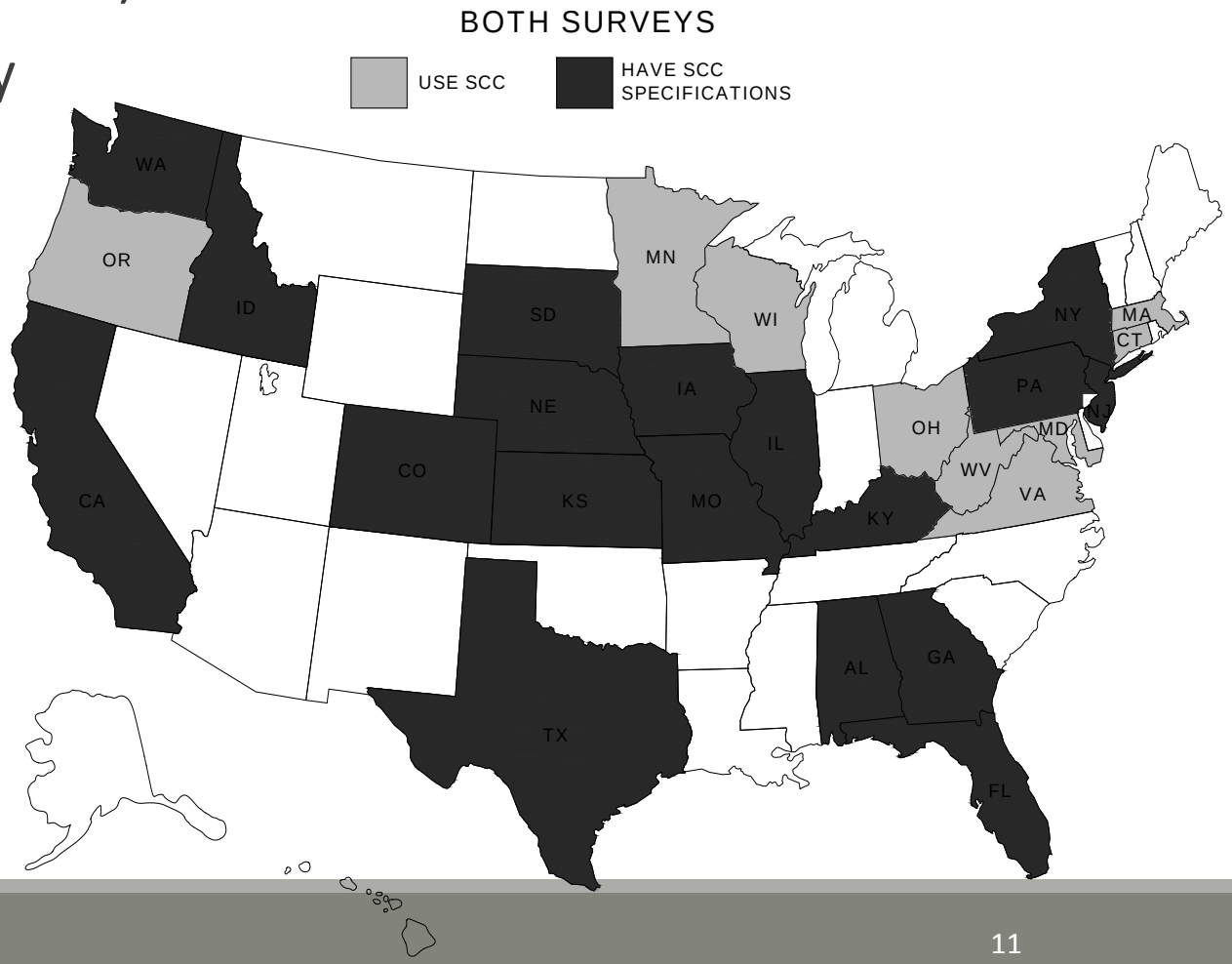
Research Approach

2- Surveys:

- NDDOT Project Survey (Mamaghani, et al., 2010)
- National Concrete Consortium (NCC) Survey

Outcomes:

- SCC Applications
- Constituent Materials
- Mix Proportioning
- Performance Requirements



Research Approach

Coarse Aggregate		SCC Mixtures								CVC Mixtures	Number of Mixtures
Type	NMSA (in.)	Cement Type I/II + 25% Class C Fly Ash		Cement Type I/II + 25% Class F Fly Ash		Cement Type I/II + 30% GGBFS		Cement Type I/II + 20% F Ash+15% LSP		Cement Type I/II + 25% Class F Fly Ash	
		Low Slump Flow	High Slump Flow	Low Slump Flow	High Slump Flow	Low Slump Flow	High Slump Flow	Low Slump Flow	High Slump Flow		
Crushed Limestone (AASHTO M43)	3/4 (No. 67)	X	X	X	X	X	X	X	X	X	9
	1/2 (No. 78)	X	X	X	X	X	X	X	X	X	9
	3/8 (No. 8)		X		X		X		X	X	5
Natural Gravel (AASHTO M43)	3/4 (No. 67)	X	X	X	X	X	X	X	X	X	9
	1/2 (No. 78)	X	X	X	X	X	X	X	X	X	9
	3/8 (No. 8)		X		X		X		X	X	5
Number of Mixtures		4	6	4	6	4	6	4	6	6	46

Research Approach

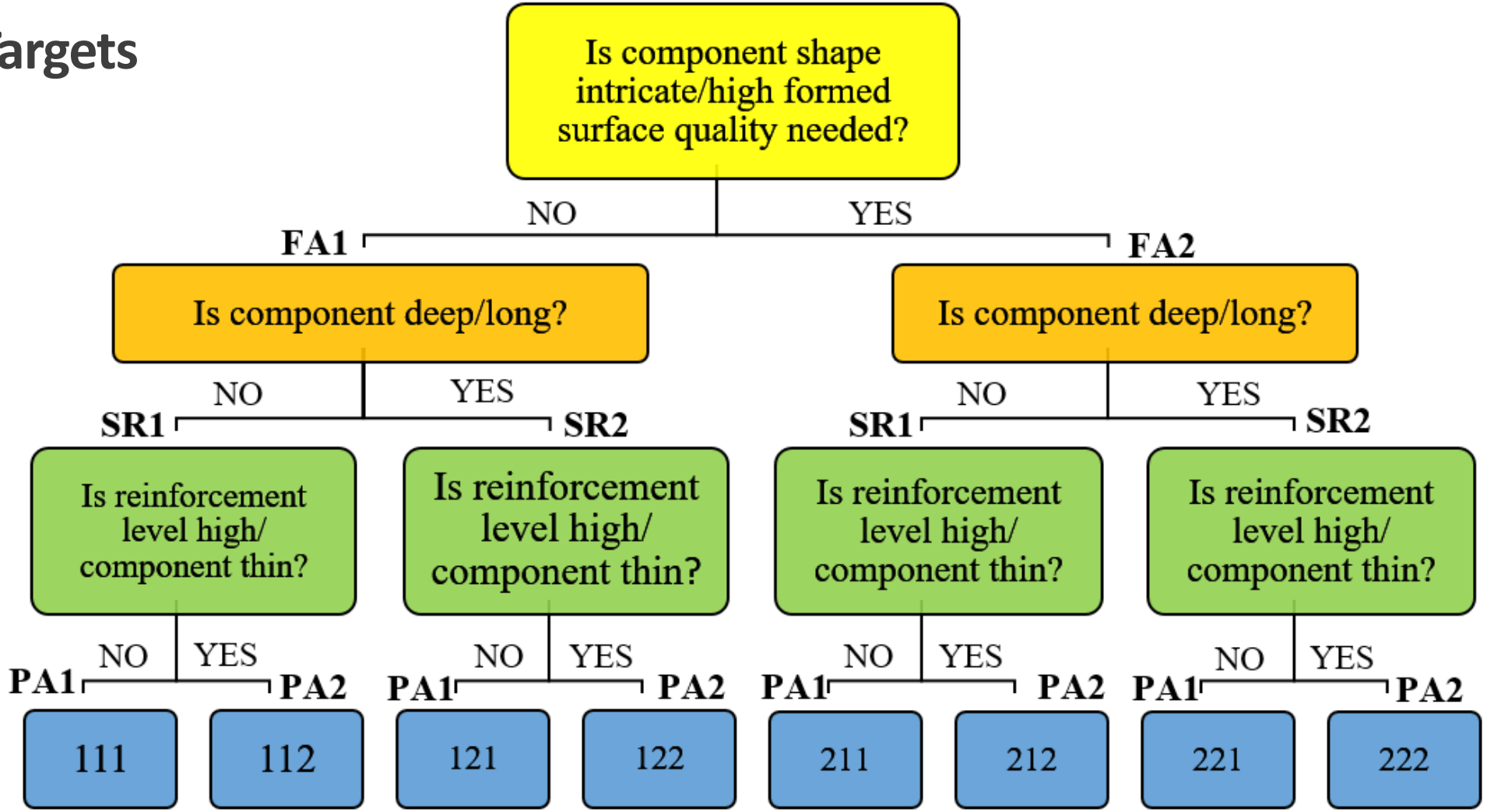
3- Workability Targets

Workability Property	Class	Value/Range
Filling Ability (FA)	FA1	22 in. ≤ Slump Flow < 26 in.
	FA2	26 in. ≤ Slump Flow ≤ 30 in.
Passing Ability (PA)	PA1	80% > Filling Capacity ≥ 70% 2 in. < J-Ring ΔD ≤ 4 in. 0.6 in. < J-Ring ΔH ≤ 0.8 in.
	PA2	Filling Capacity ≥ 80% J-Ring ΔD ≤ 2 in. J-Ring ΔH ≤ 0.6 in.
Segregation Resistance (SR)	SR1	10% < Column Segregation ≤ 15% 0.5 in. < Penetration ≤ 1 in. VSI = 1
	SR2	Column Segregation ≤ 10% Penetration ≤ 0.5 in. VSI = 0

Component Geometric Characteristic	Class	Value/Definition
Length	Low	≤ 33 ft
	High	> 33 ft
Depth	Low	≤ 16 ft
	High	> 16 ft
Thickness	Low	≤ 8 in.
	High	> 8 in.
Shape Intricacy	Low	Concrete flows in a single direction
	High	Concrete flow around corners and cutouts
Formed Surface Quality	Low	Unexposed to the travelling public
	High	Exposed to the travelling public
Level of Reinforcement	Low	Large spacing between bars (≥ 3 in.)
	High	Small spacing between bars (< 3 in.)

Research Approach

3- Workability Targets



Research Approach

23 Mixtures with Crushed Limestone

Mixture Type	SCC Mixtures																				CVC Mixtures		
SCMs/Fillers	25% Class C Fly Ash					25% Class F Fly Ash					30% GGBFS					20% Class F Fly Ash + 15% LSP					25% Class F Fly Ash		
Flowability	Low slump flow		High slump flow			Low slump flow		High slump flow			Low slump flow		High slump flow			Low slump flow		High slump flow			2 - 4 in. slump		
NMSA, in.	3/4	1/2	3/4	1/2	3/8	3/4	1/2	3/4	1/2	3/8	3/4	1/2	3/4	1/2	3/8	3/4	1/2	3/4	1/2	3/8	3/4	1/2	3/8
Mixture ID	111	121	211	221	222	111	121	211	221	222	111	121	211	221	222	111	121	211	221	222	No. 67	No. 78	No. 8
Cement Type I/II, lb/cy	531	535	568	572	587	531	535	568	572	587	521	525	539	543	558	456	460	488	491	504	494	553	572
SCM, lb/cy	177	178	189	191	196	177	178	189	191	196	223	225	231	233	239	140	141	150	151	155	165	184	191
Filler, lb/cy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	105	106	113	113	116	0	0	0
Coarse Agg., lb/cy	1,542	1,462	1,518	1,439	1,334	1,542	1,462	1,518	1,439	1,334	1,542	1,462	1,530	1,450	1,345	1,542	1,462	1,518	1,439	1,334	1,674	1,485	1,350
Natural Sand, lb/cy	1,262	1,297	1,242	1,276	1,334	1,262	1,297	1,242	1,276	1,334	1,262	1,297	1,252	1,286	1,345	1,262	1,297	1,242	1,276	1,334	1,193	1,271	1,356
Water, lb/cy	280	295	280	295	305	280	295	280	295	305	280	295	280	295	305	280	295	280	295	305	280	295	305
HRWRA, oz/cwt	12.0	14.0	12.0	16.0	13.0	6.0	4.0	8.0	8.0	13.0	12.0	10.0	18.0	16.0	15.0	11.0	9.0	12.0	12.0	15.0	0.0	0.0	0.0
VMA, oz/cwt	0.0	0.0	6.0	0.0	0.0	3.0	0.0	3.0	6.0	0.0	0.0	0.0	3.0	3.0	0.0	0.0	0.0	3.0	6.0	0.0	0.0	0.0	0.0
AEA, oz/cwt	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Total Weight, lb/cy	3,792	3,767	3,797	3,772	3,756	3,792	3,767	3,797	3,772	3,756	3,828	3,803	3,832	3,807	3,792	3,786	3,761	3,790	3,765	3,749	3,806	3,788	3,774
Total Aggregate, lb/cy	2,804	2,759	2,760	2,714	2,669	2,804	2,759	2,760	2,714	2,669	2,804	2,759	2,782	2,737	2,691	2,804	2,759	2,760	2,714	2,669	2,867	2,756	2,706
Total Powder, lb/cy	708	713	757	763	783	708	713	757	763	783	744	750	770	776	797	702	707	751	756	776	659	738	763
W/P Ratio	0.40	0.41	0.37	0.39	0.39	0.40	0.41	0.37	0.39	0.39	0.38	0.39	0.36	0.38	0.38	0.40	0.42	0.37	0.39	0.39	0.43	0.40	0.40
S/A Ratio	0.45	0.47	0.45	0.47	0.50	0.45	0.47	0.45	0.47	0.50	0.45	0.47	0.45	0.47	0.50	0.45	0.47	0.45	0.47	0.50	0.42	0.46	0.50
Paste Volume %	37.0%	38.0%	38.0%	39.0%	40.0%	37.0%	38.0%	38.0%	39.0%	40.0%	37.0%	38.0%	37.5%	38.5%	39.5%	37.0%	38.0%	38.0%	39.0%	40.0%	36.0%	38.5%	39.6%
Coarse Agg. Vol. %	34.4%	32.6%	33.9%	32.1%	29.8%	34.4%	32.6%	33.9%	32.1%	29.8%	34.4%	32.6%	34.1%	32.4%	30.0%	34.4%	32.6%	33.9%	32.1%	29.8%	37.4%	33.1%	30.1%

Research Approach

4- Testing of Lab-Mixed Concrete Specimens

	Property	Test Method	Standard/Source	Target Values/Ranges	Time(s) of Testing
Hardened Concrete Properties	**Compressive Strength**	Compressing 4x8 in.Cylinders	AASHTO T 22	min 4,000 - 6,000 psi	7, 14, 28, 56 days
	Modulus of Elasticity	Compressometer for 4x8 in. Cylinders	ASTM C469	AASHTO LRFD 5.4.2.4	28 days
	Tensile Strength	Splitting 4x8 in. Cylinders	AASHTO T 198	AASHTO LRFD 5.4.2.7	28 days
	Modulus of Rupture	Simple Beam with Third-Point Loading	AASHTO T 97	AASHTO LRFD 5.4.2.6	28 days
	Bond Strength	Pull-out of Vertical Bars	RILEM/CEB/FIB. 1970	Comparison to CVC	28 days
		Pull-out of Horizontal Bars	RILEM/CEB/FIB. 1970	Comparison to CVC	28 days
	Shear Resistance	Push-off Test	Mattock and Hawkins, 1972	AASHTO LRFD 5.8.4.1	28 days
		Beam Test	Lachemi, et al, 2005	AASHTO LRFD 5.8.3.3	28 days
	Shrinkage	Drying Shrinkage	AASHTO T 160	AASHTO LRFD 5.4.2.3.3	7, 14, 28, 56 days
		Restrained Shrinkage	ASTM C1581	Comparison to CVC	28 days
	Creep	Two 6x12 in. Cylinders	ASTM C512	AASHTO LRFD 5.4.2.3.2	28 - 365 days
	Air Void System	Linear-Traverse Method	ASTM C457	For Comparison Only	28 days
	Surface Resistivity	Four Point Wenner Array Probe	AASHTO TP 95	For Comparison Only	28 days

Research Approach

5- Testing of Ready-Mixed Concrete Full-Scale Specimens

Table of Content

1. Definition
2. Problem Statement
3. Research Objectives and Scope
4. Research Approach **(chapter 1)**
5. Research Results **(chapter 2)**
   - Small-scale specimens
   - Full-scale specimens
6. Conclusions **(chapter 3)**

Research Results

- **From Small-Scale Lab-Mixed Concrete Specimens:**
  - Fresh concrete properties
  - Early-age concrete properties
  - Hardened concrete properties

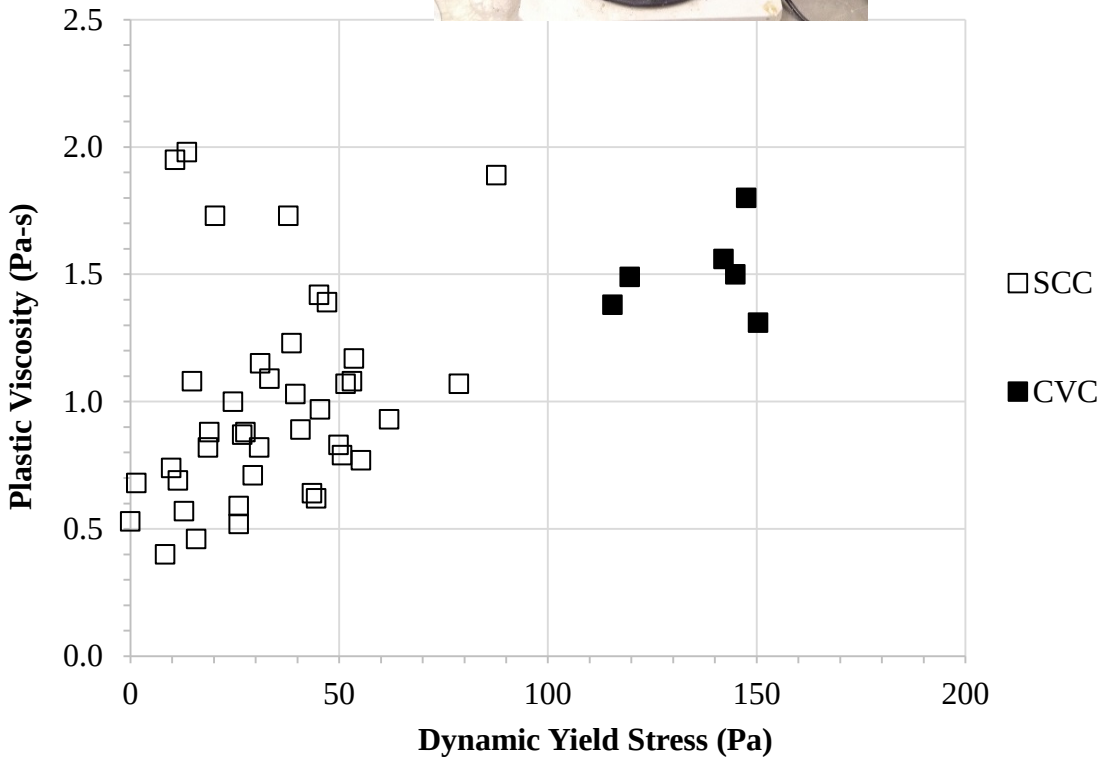
- **From Full-Scale Ready-Mixed Concrete Specimens:**
  - Constructability
  - Structural Performance

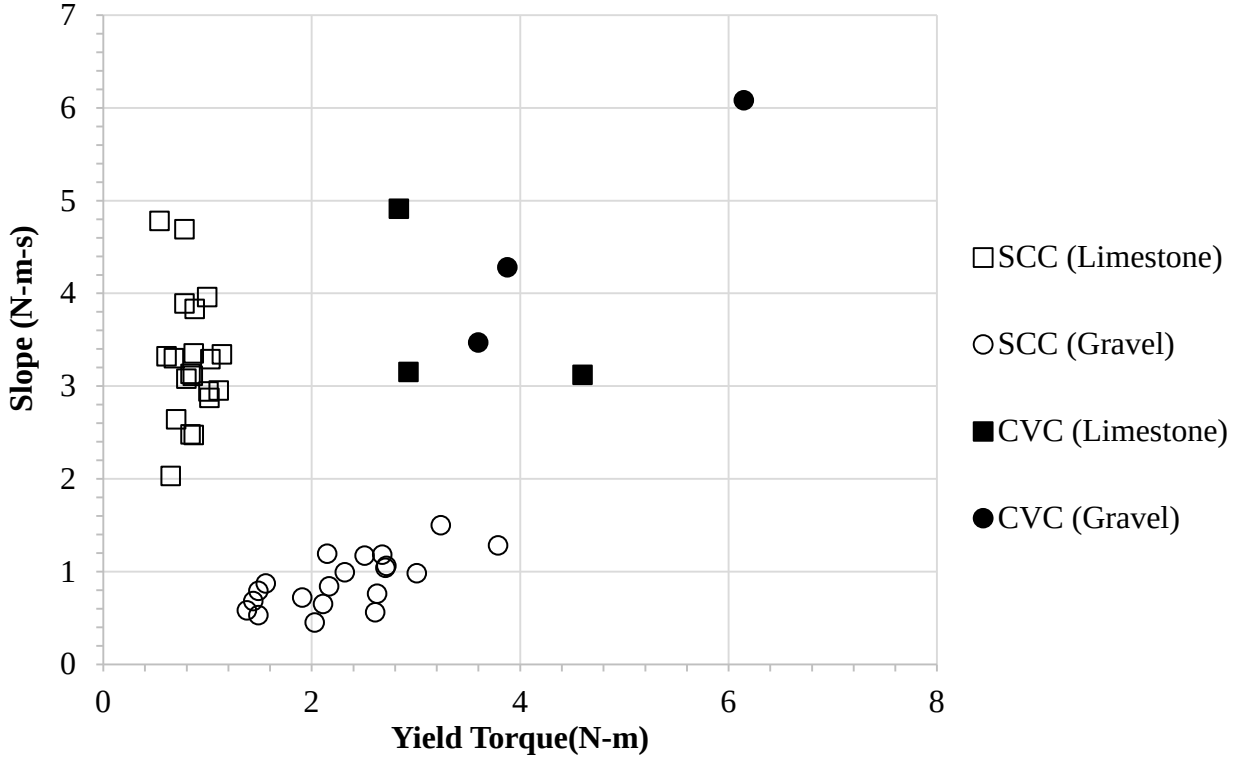
Rheology

Mortar Rheometer

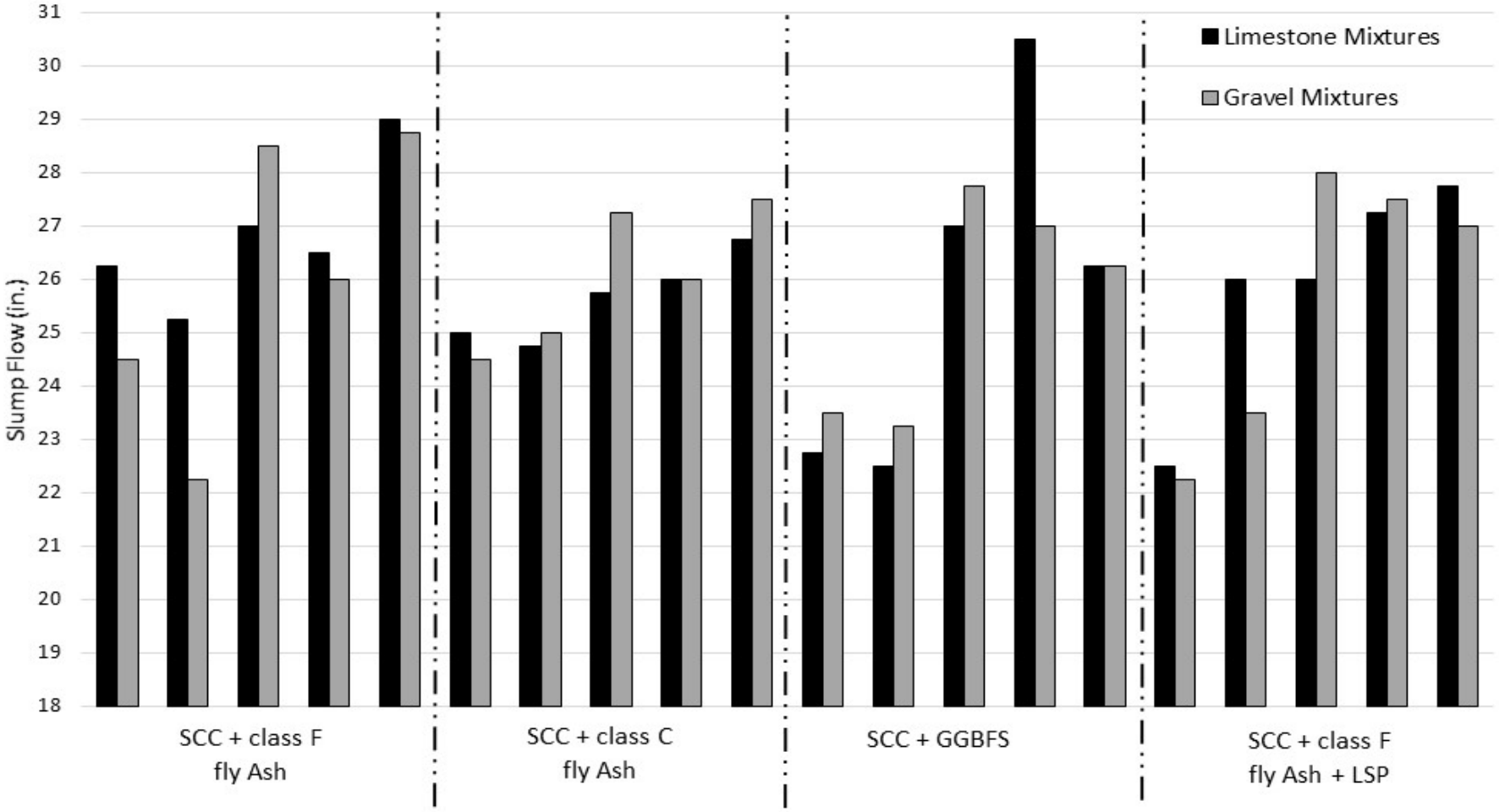
SCC has lower yield stress than CVC and wide range of viscosity

Concrete Rheometer

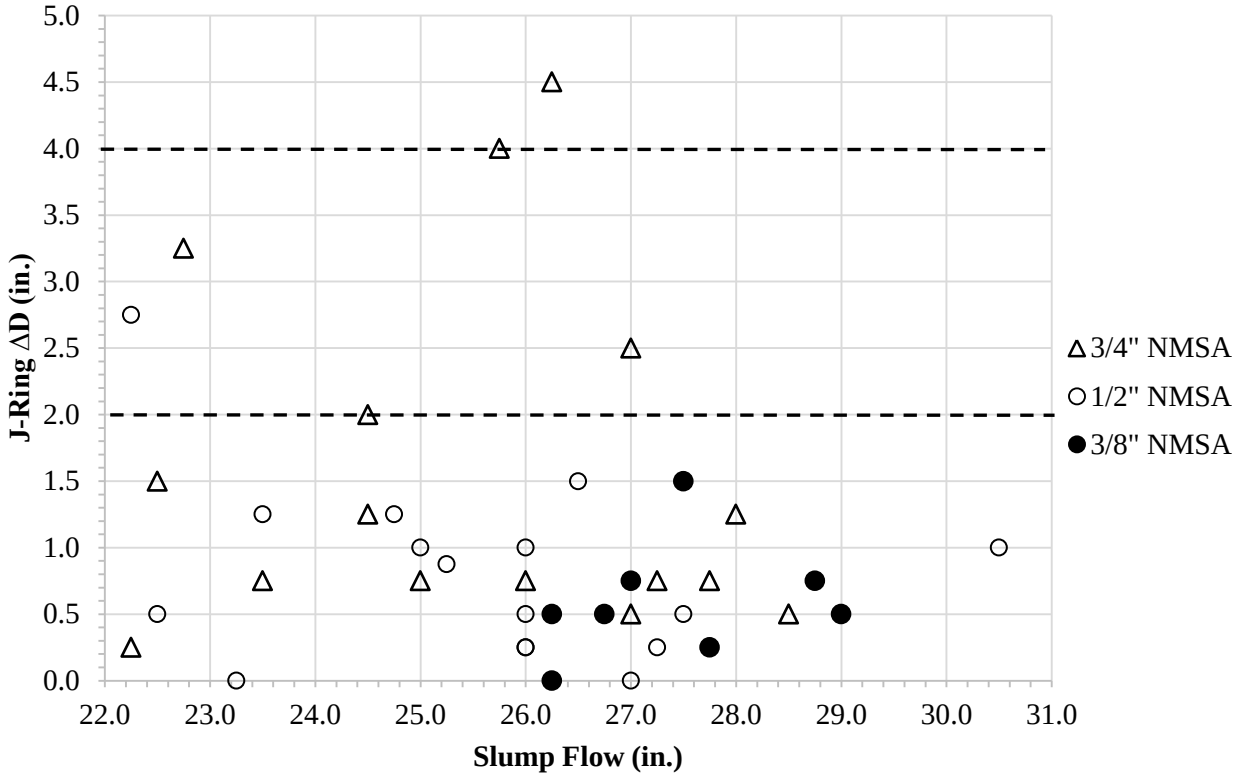


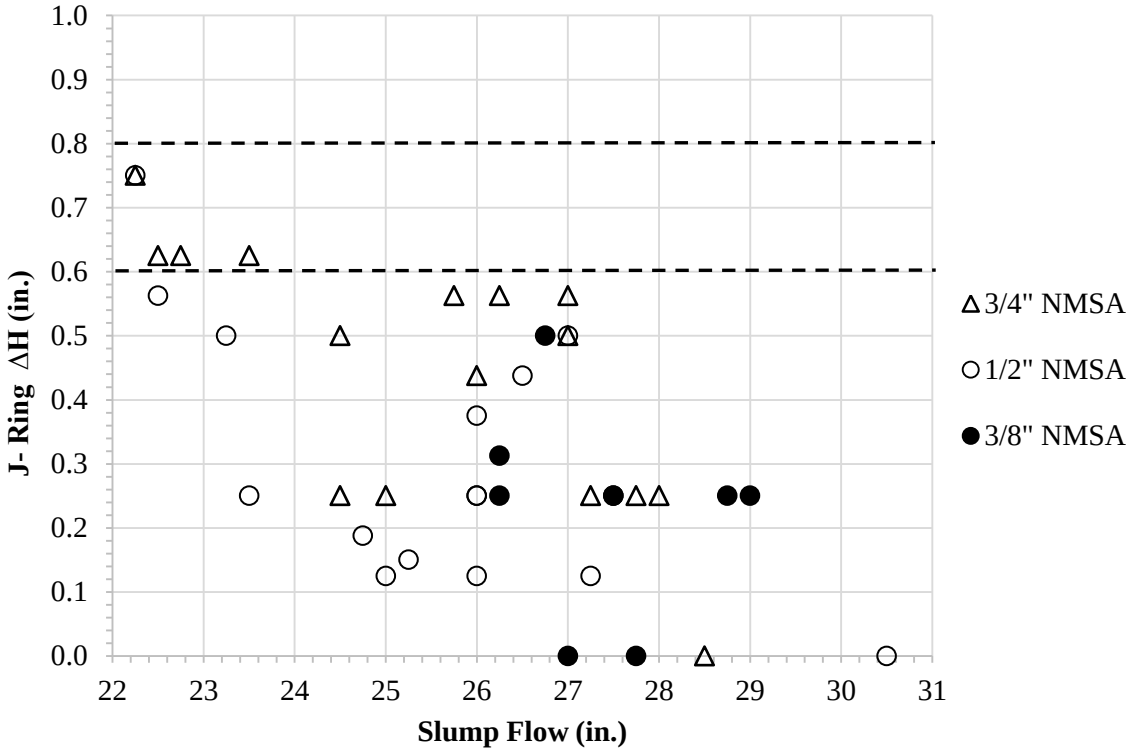


Filling Ability ***(AASHTO T347)***

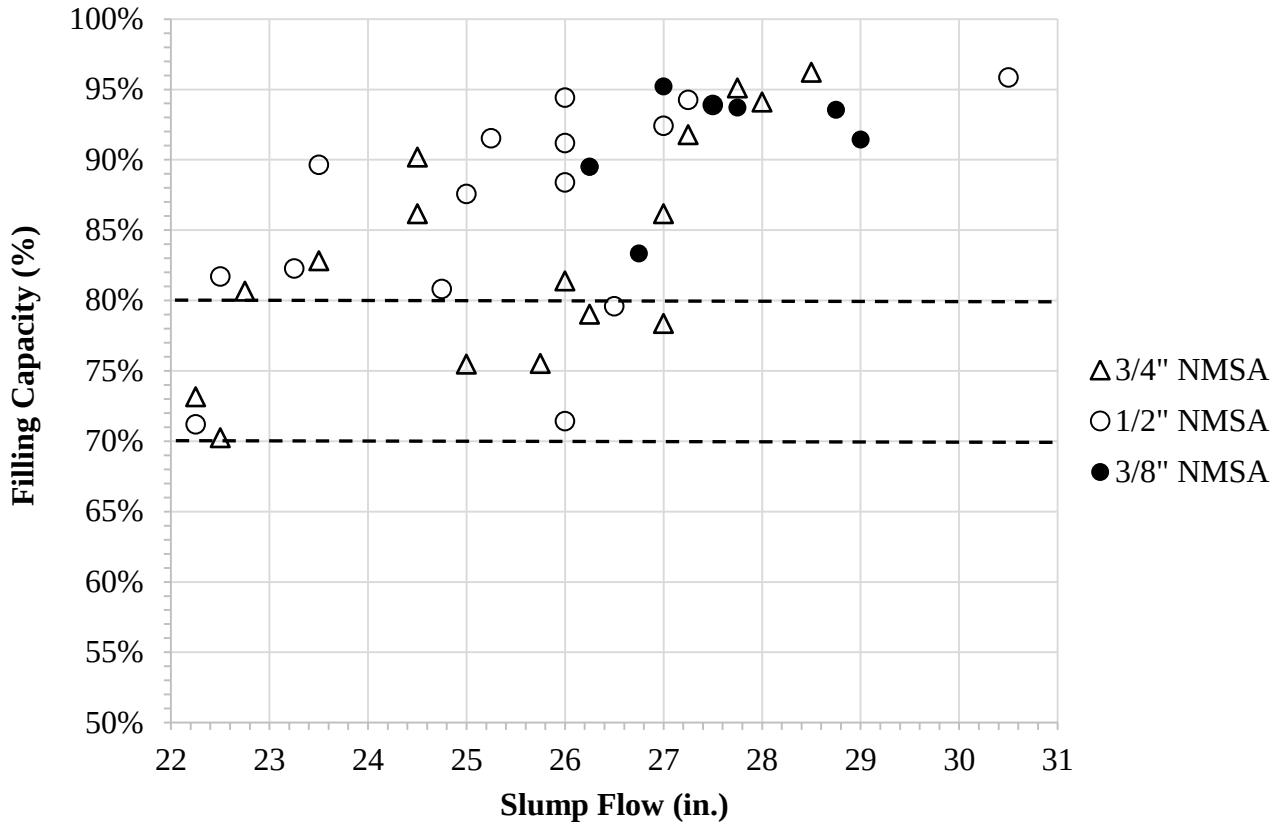


Passing Ability ***(AASHTO T345)***

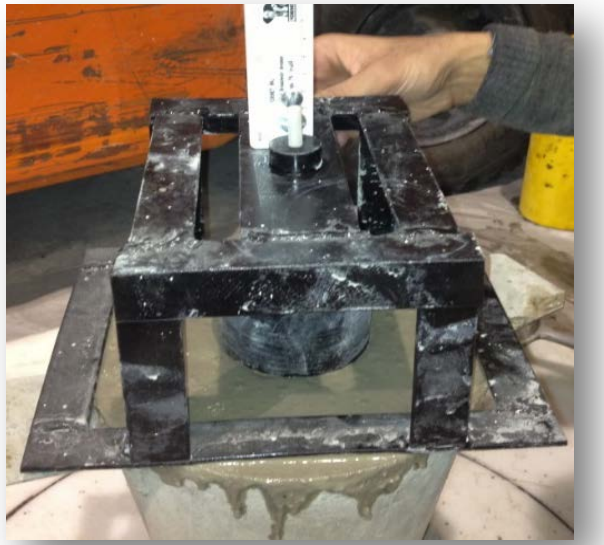




Filling Capacity *(AASHTO T349)*

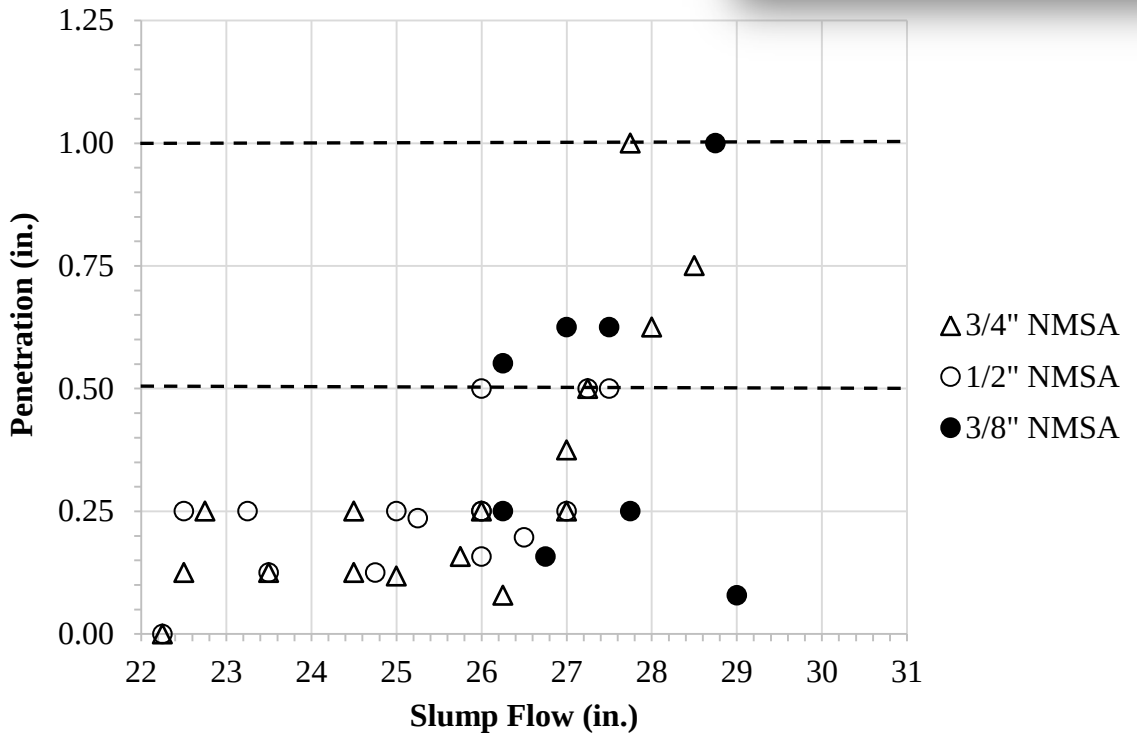


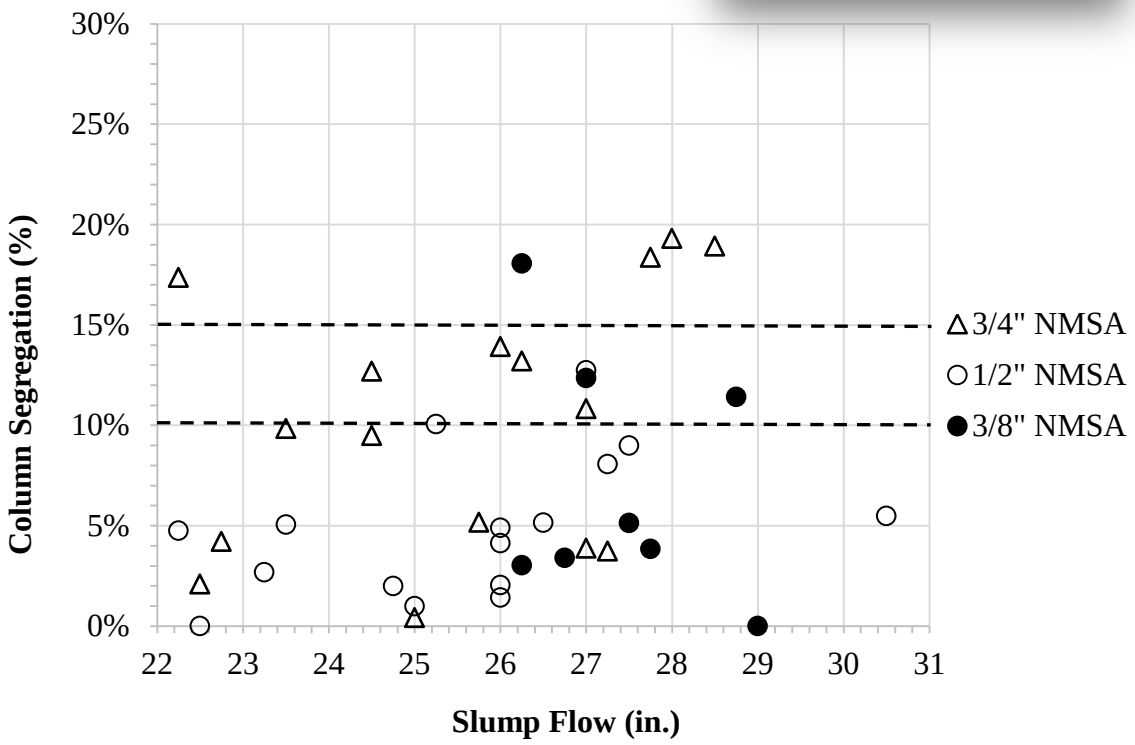
Static Stability



ASTM C1712

ASTM C1610

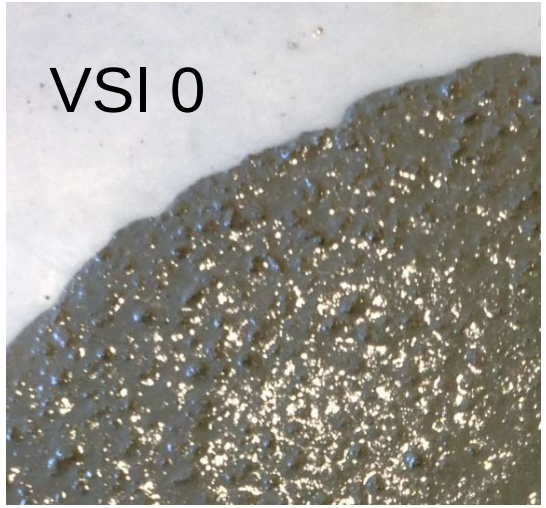


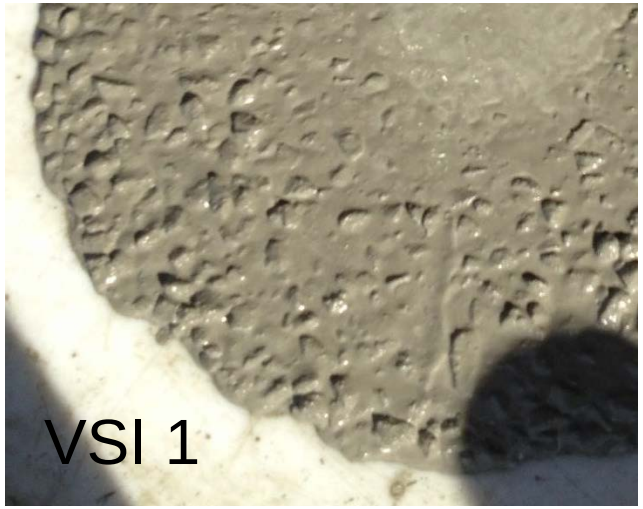


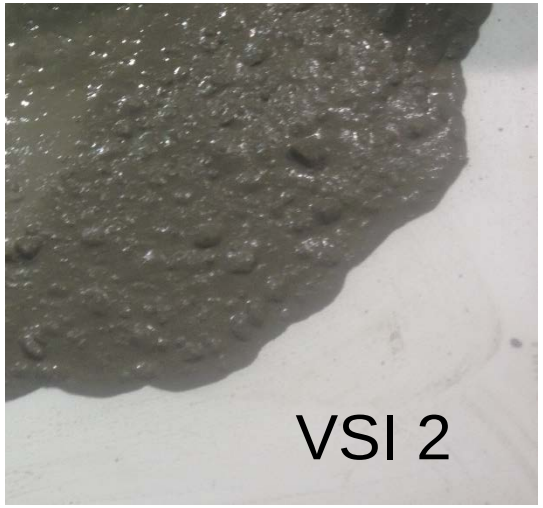
Static Stability

Visual Stability Index (VSI)

AASHTO T351







Hardened Visual Stability Index (HVSI)

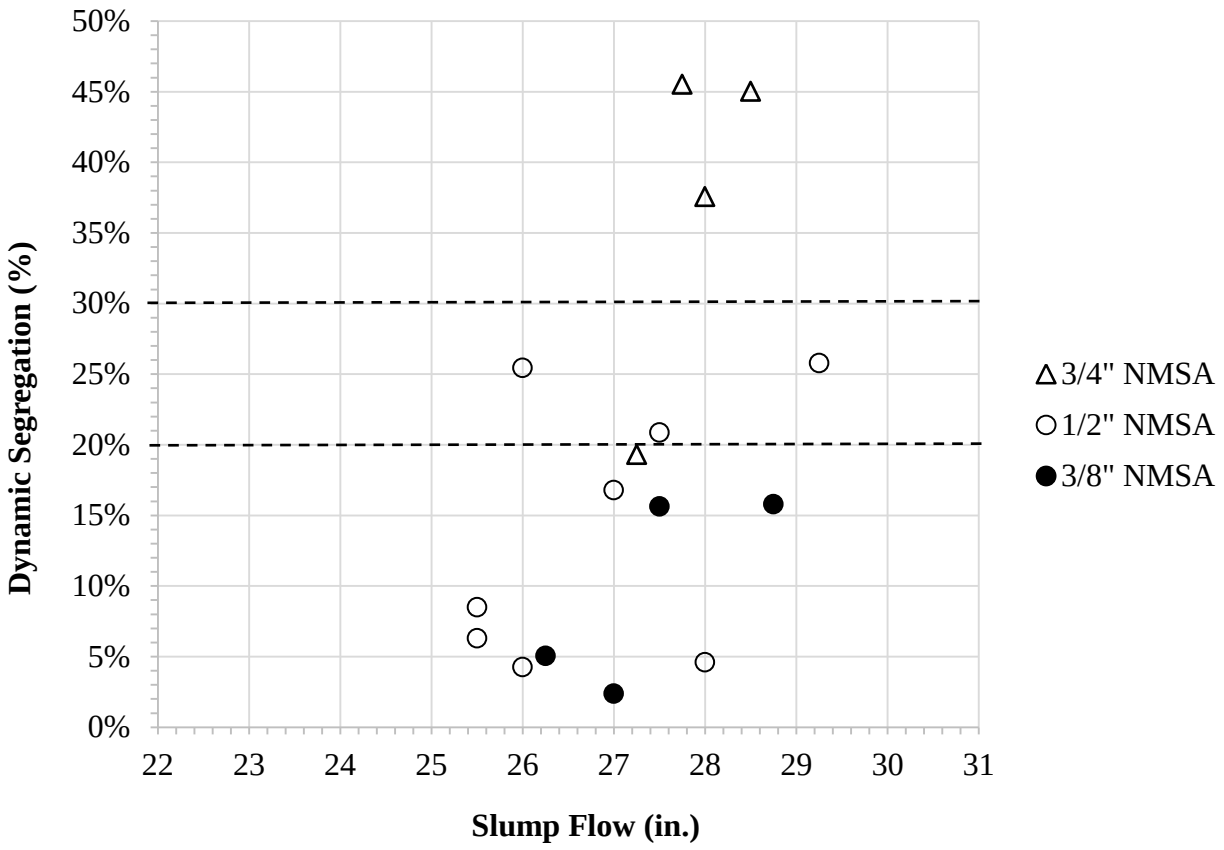
AASHTO PP 58

HVSI 0

HVSI 1

HVSI 2

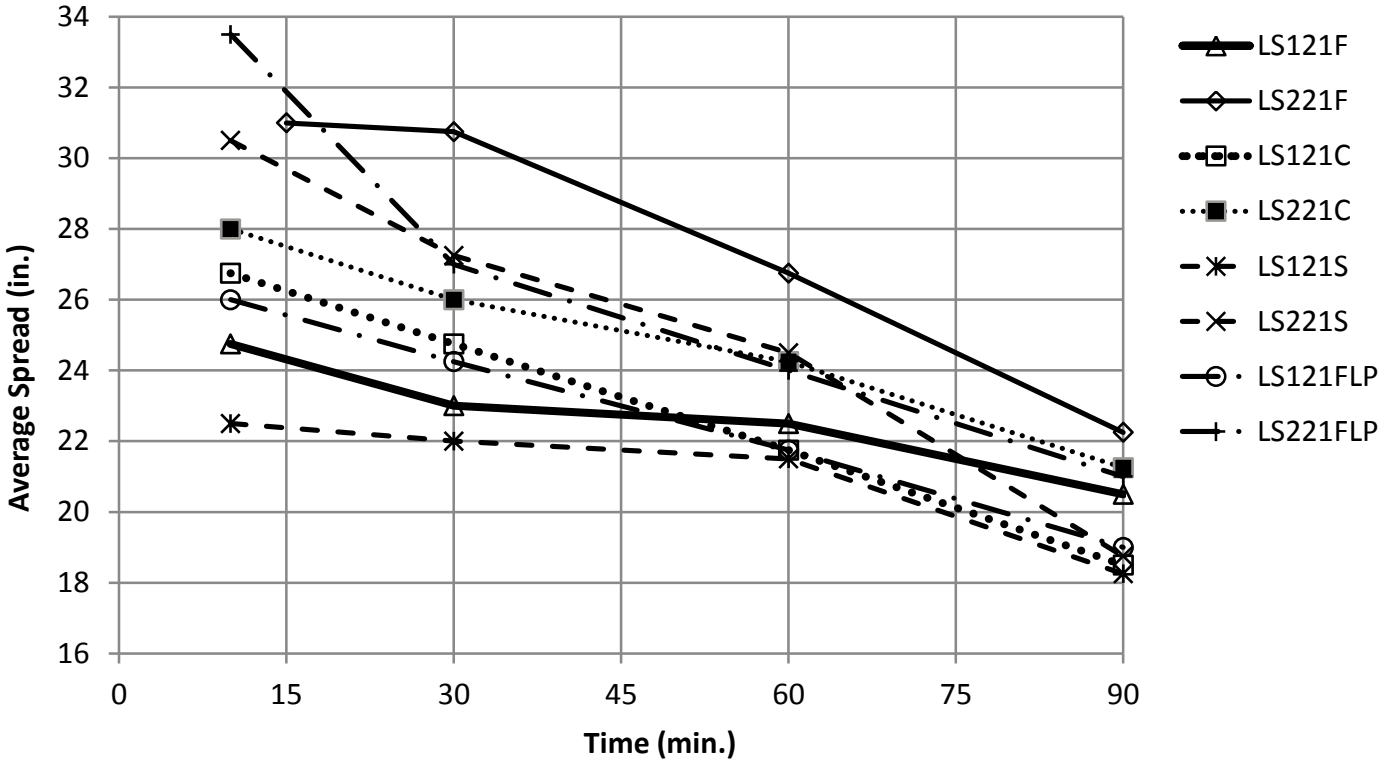
Dynamic Stability



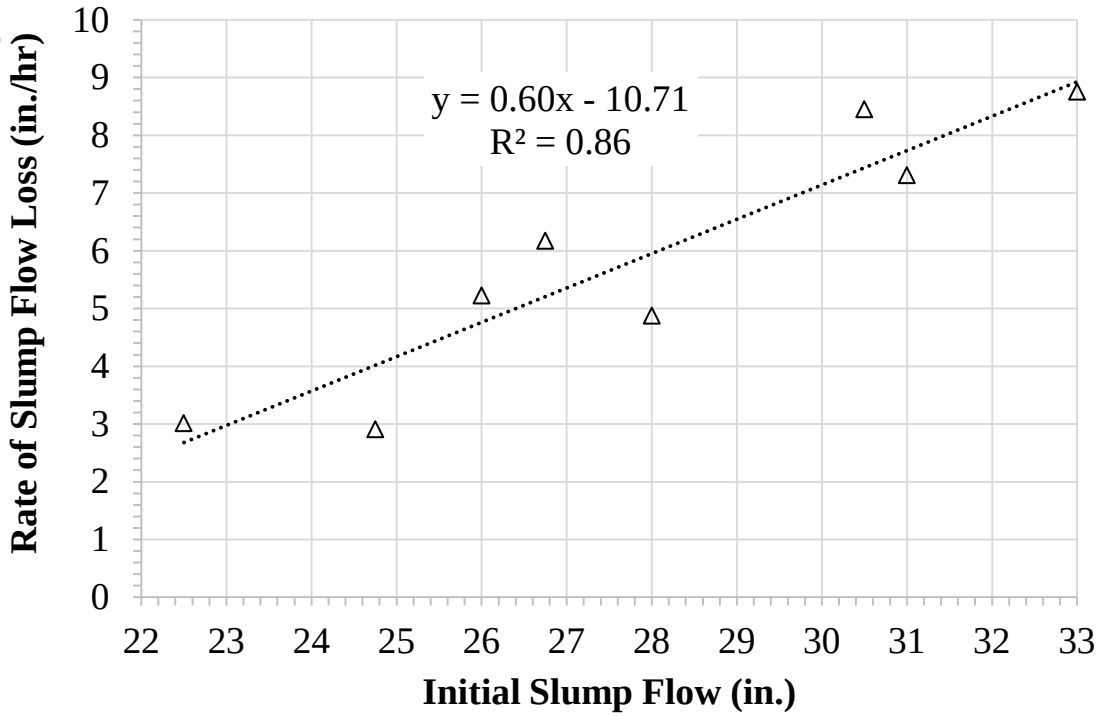
Lange, et al. (2008)

Modified

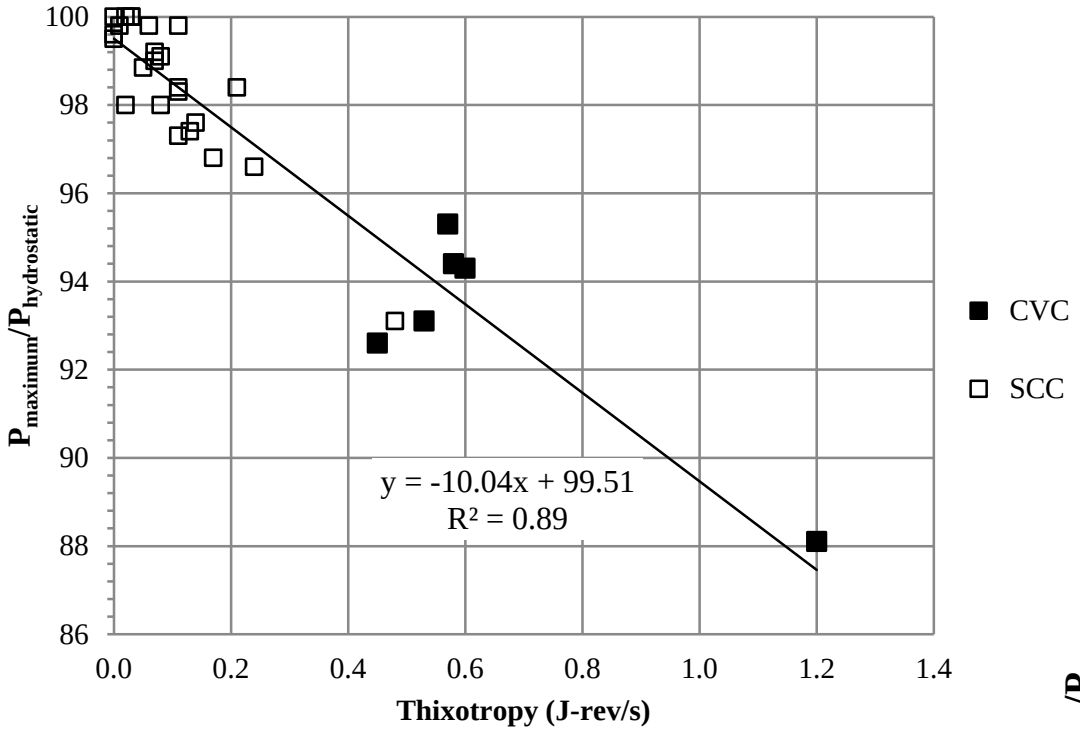
Workability Retention

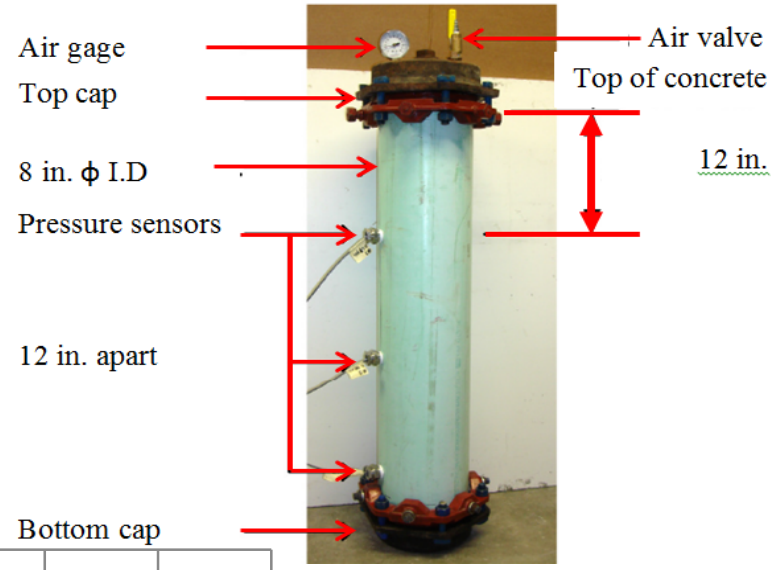


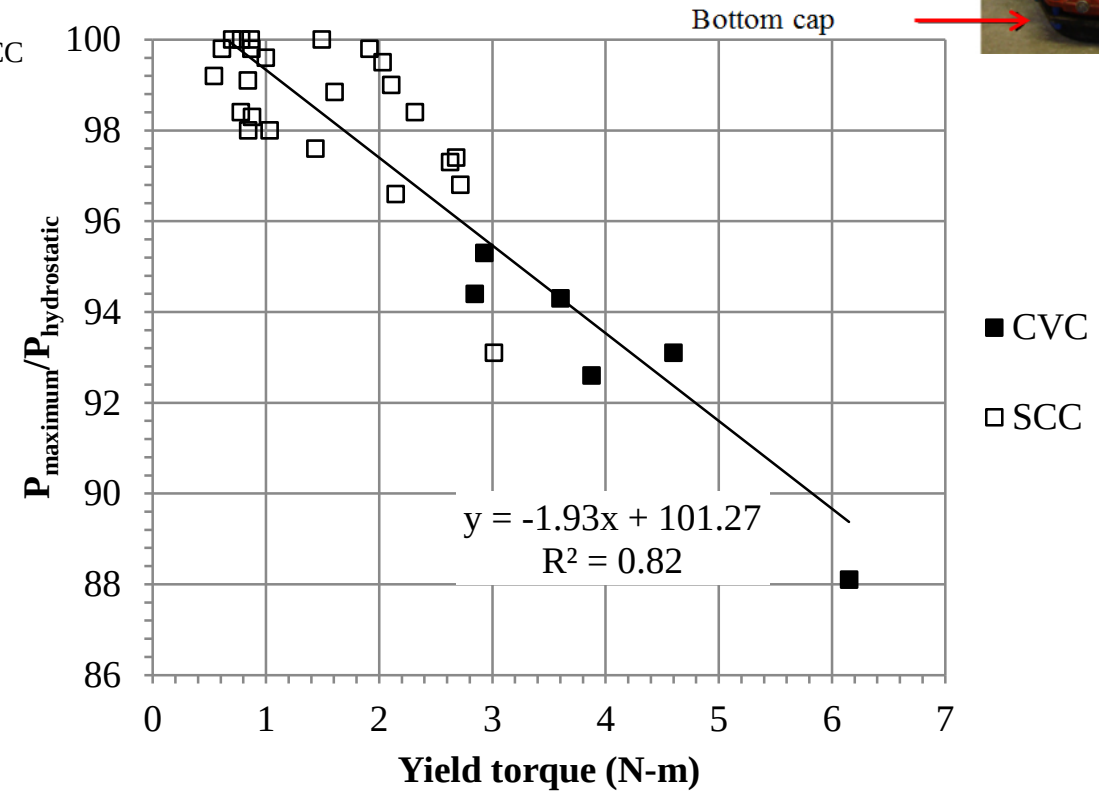
WRA should be used for extended workability



Formwork Pressure





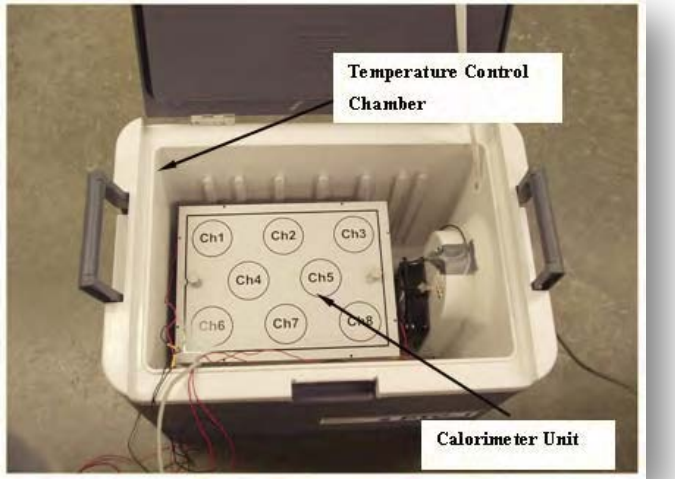


SCC has higher formwork pressure than CVC

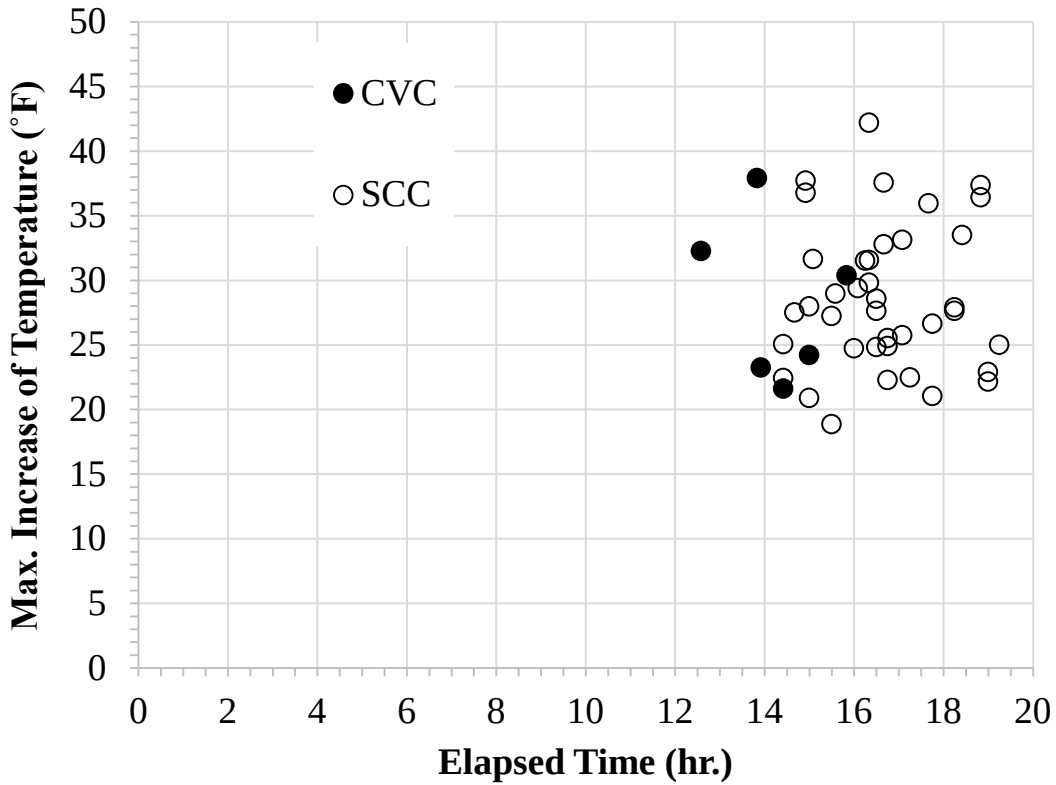
Heat of Hydration

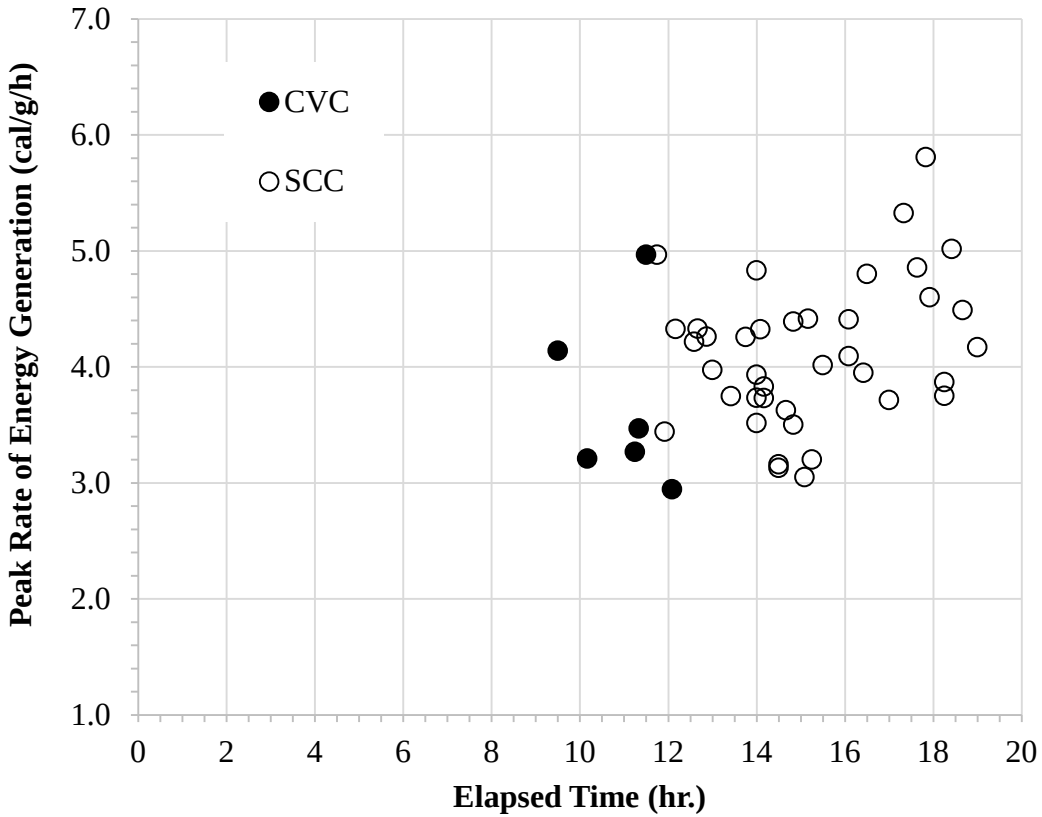
Semi-adiabatic calorimetry

Isothermal calorimetry
(ASTM C1702)



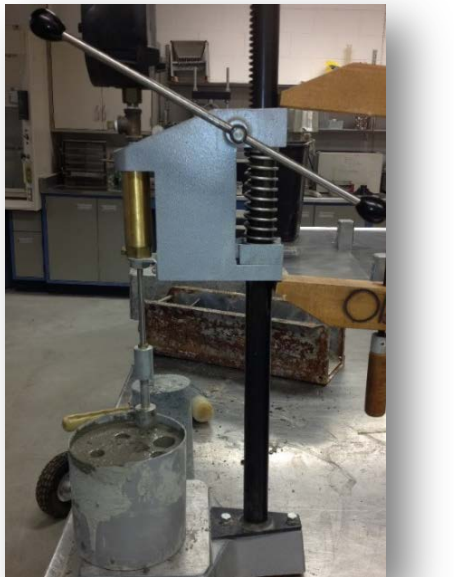
No difference in HOH
Delay in reaching peak value

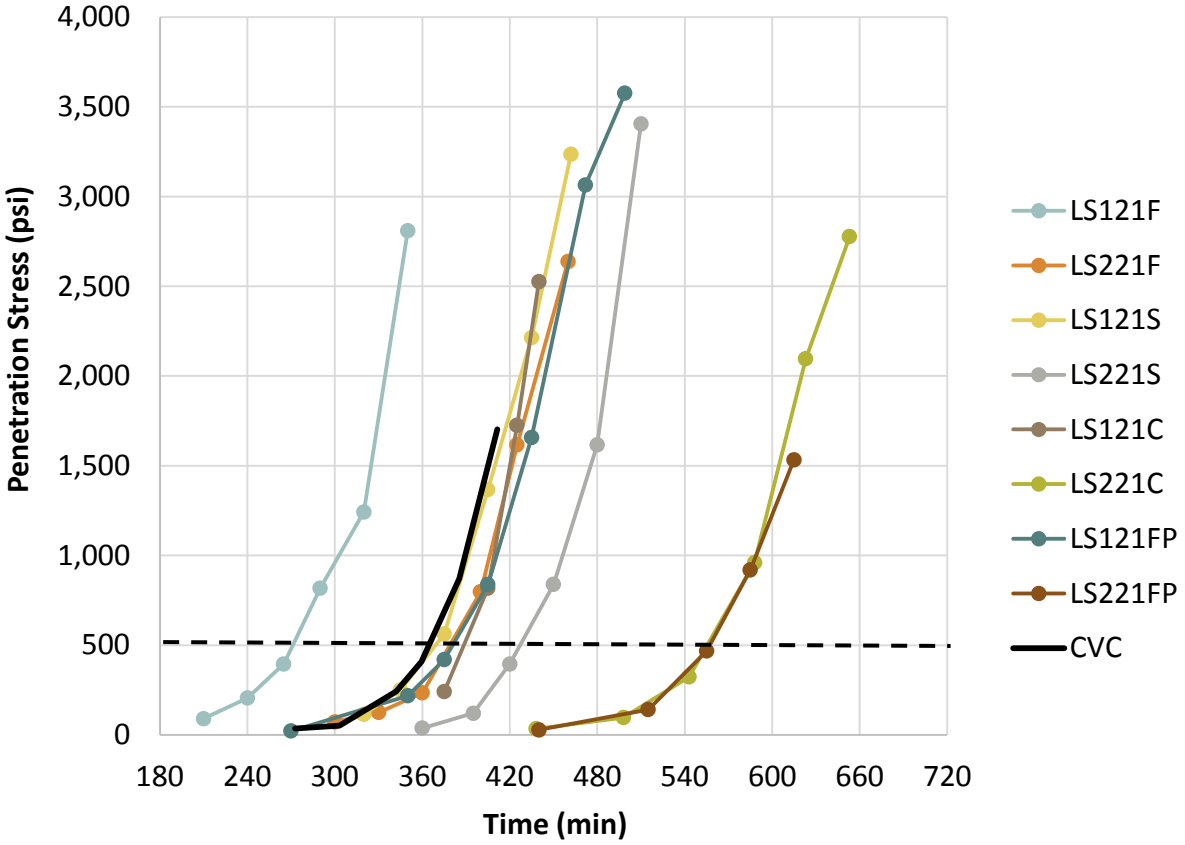


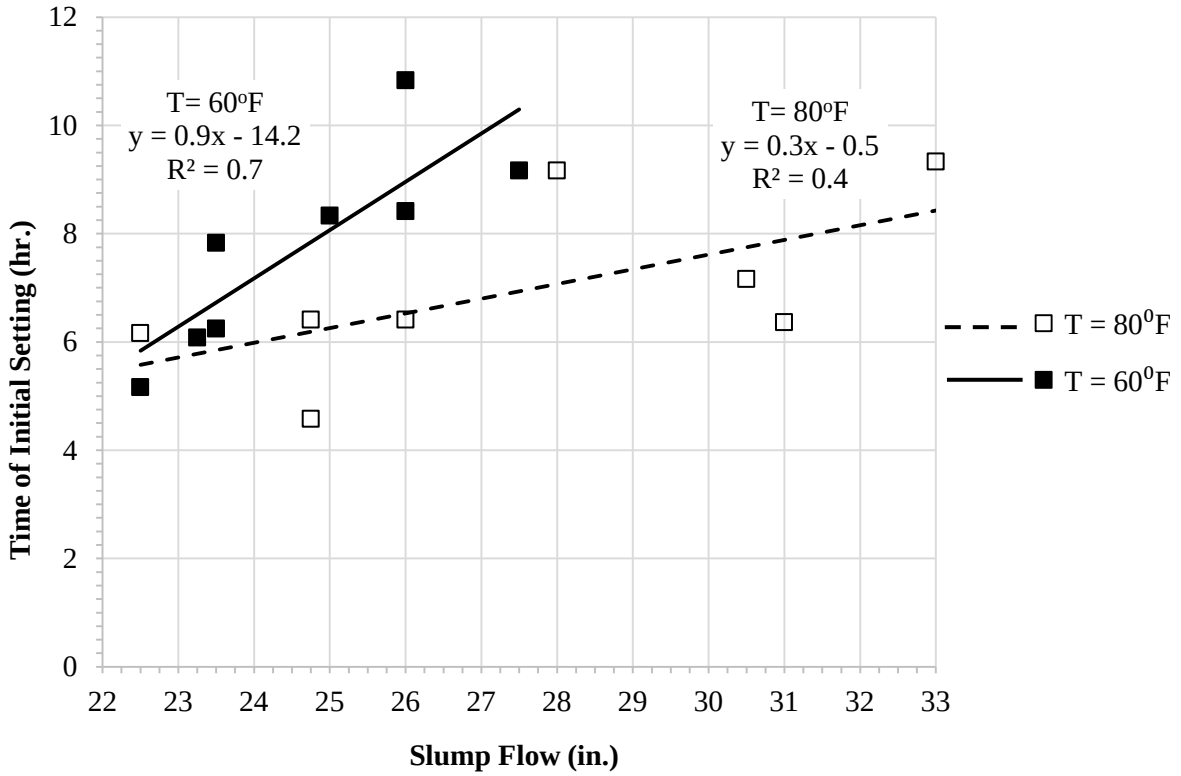


Time of Setting (AASHTO T197)

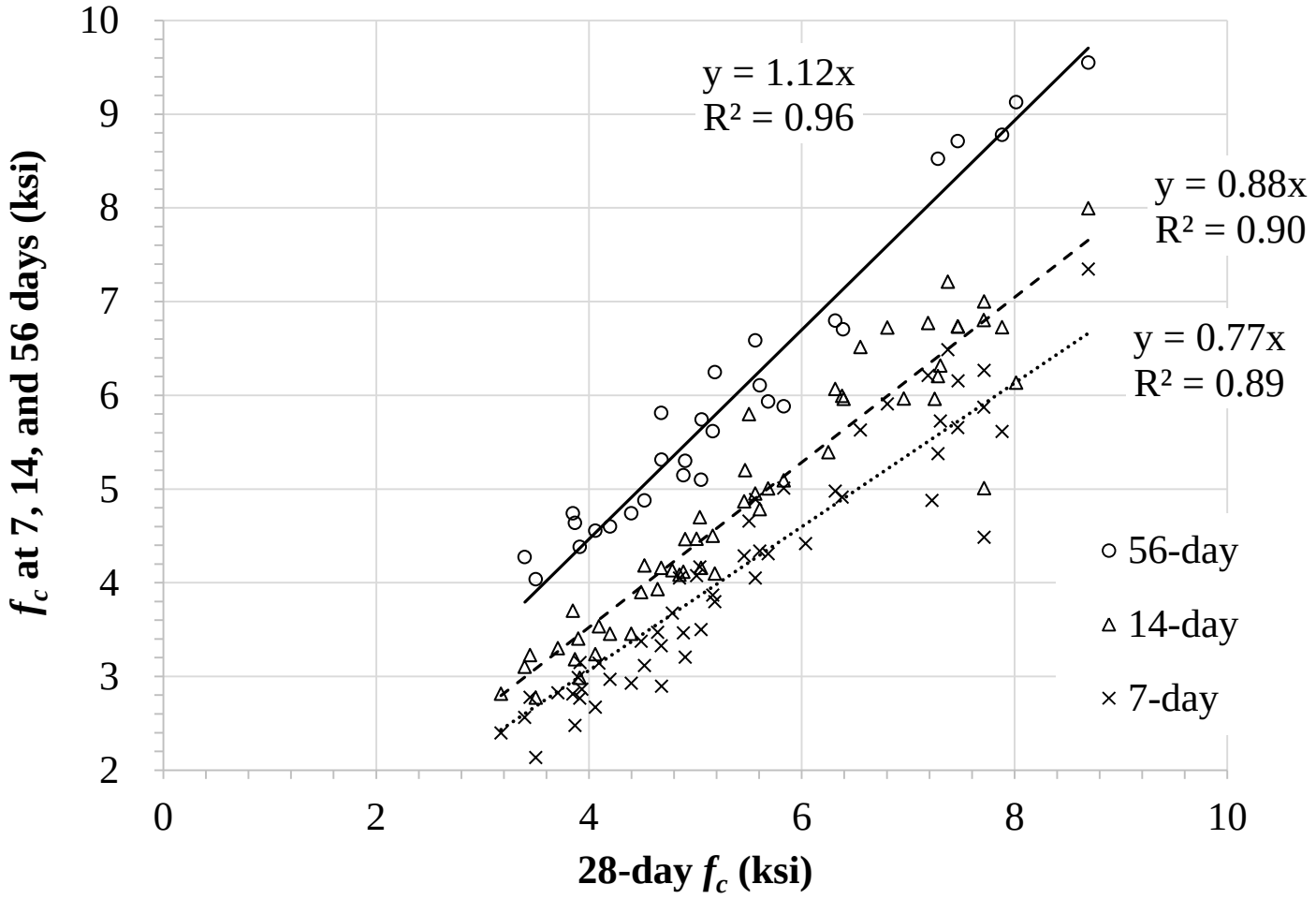
Depends on SCM, Slump Flow, and temperature







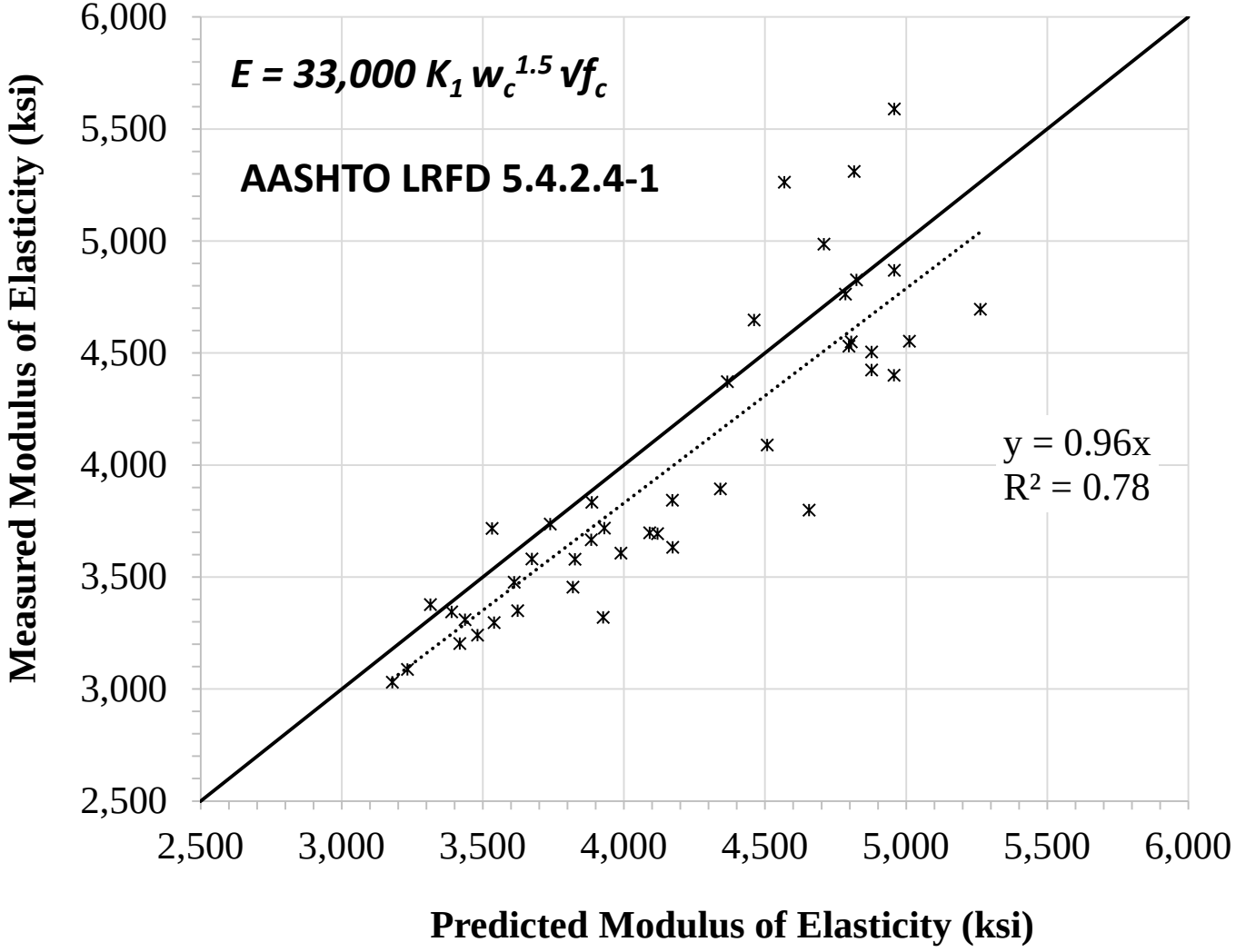
Compressive Strength (AASHTO T22)

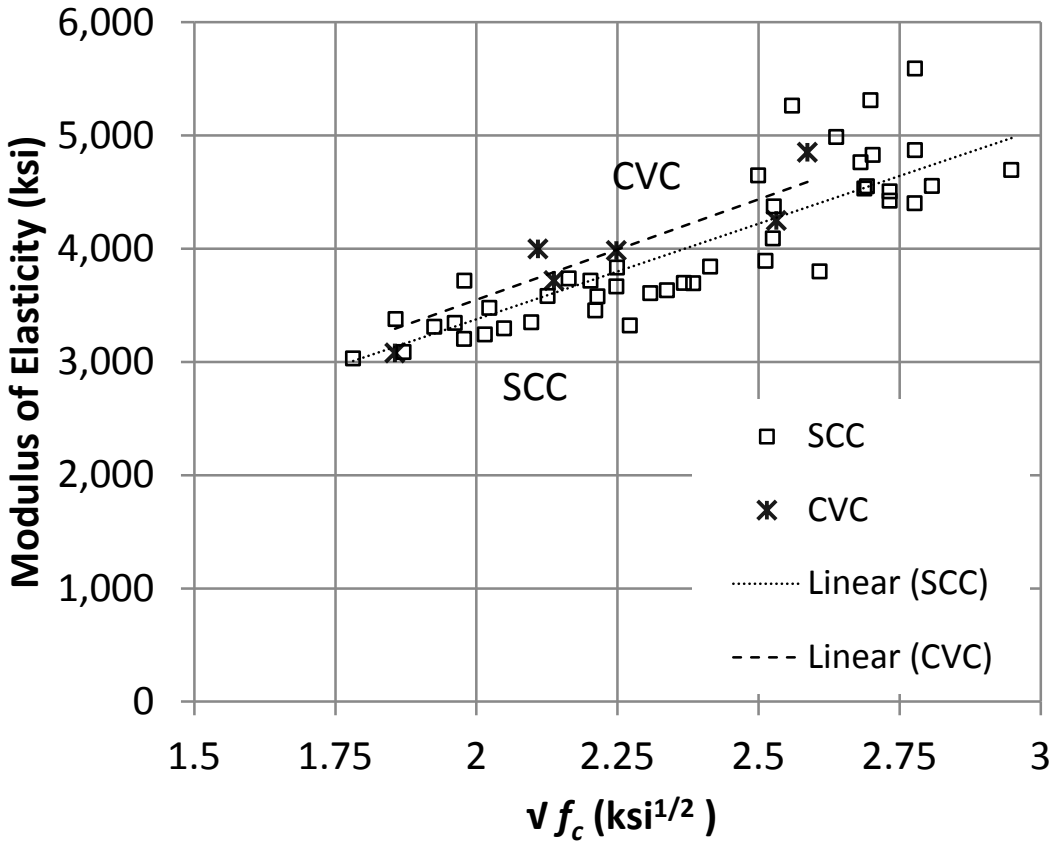


T (days)	Predicted Ratio According to ACI 209	Measured Ratio for SCC
7	0.70	0.77
14	0.88	0.88
56	1.09	1.12

No Modification

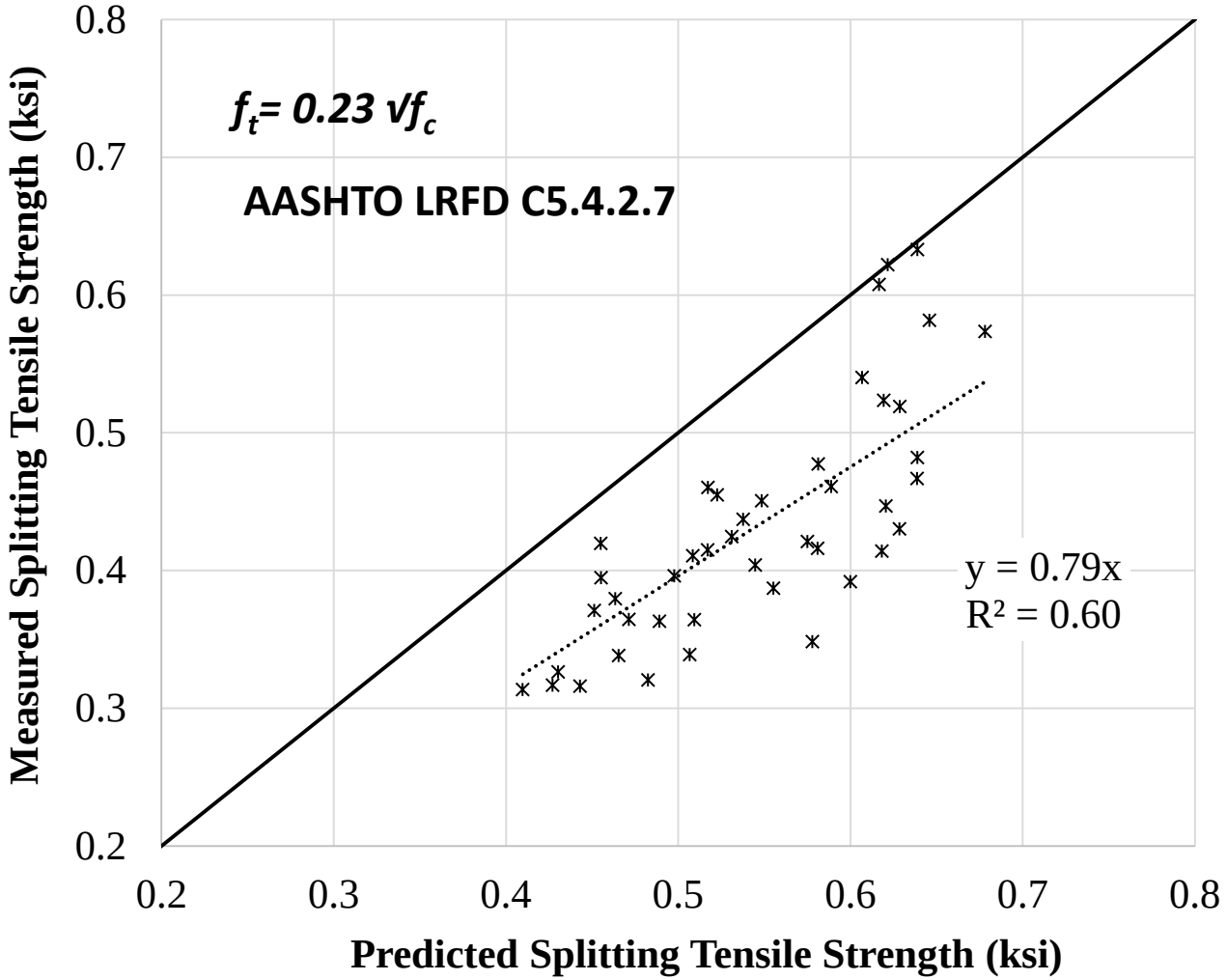
Modulus of Elasticity (MOE) (ASTM C469)

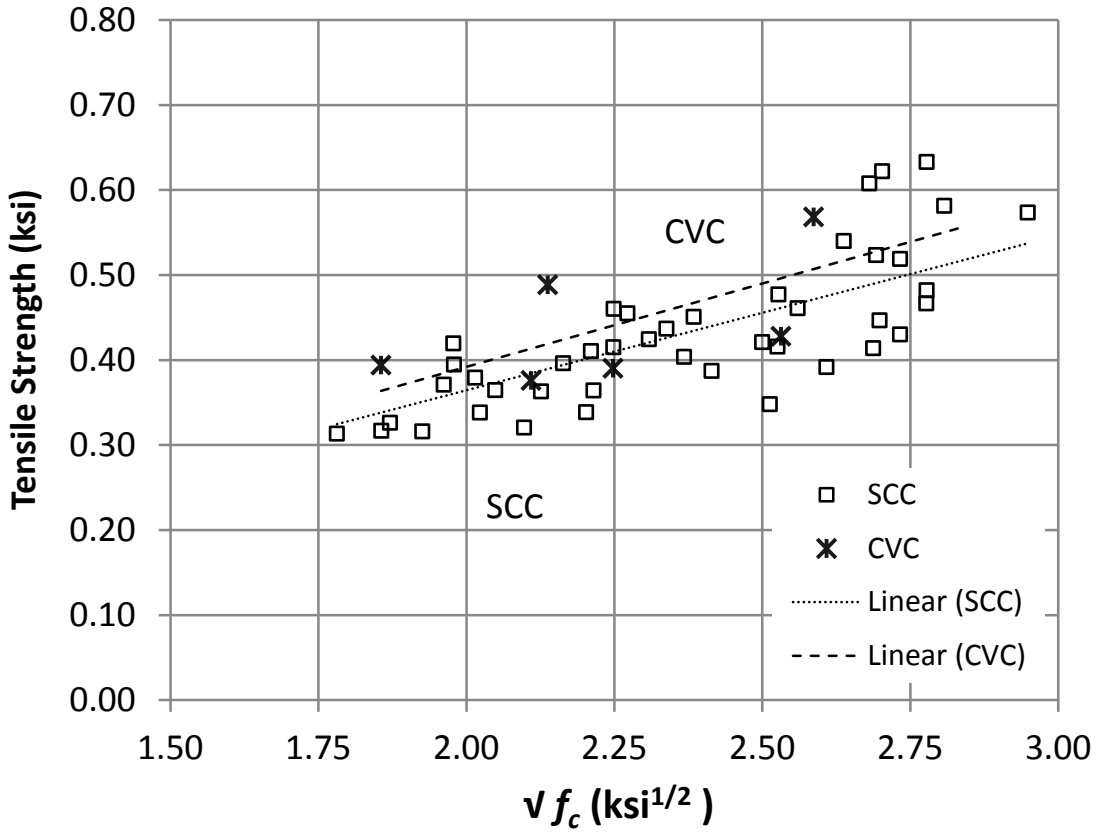




0.96 Modification Factor

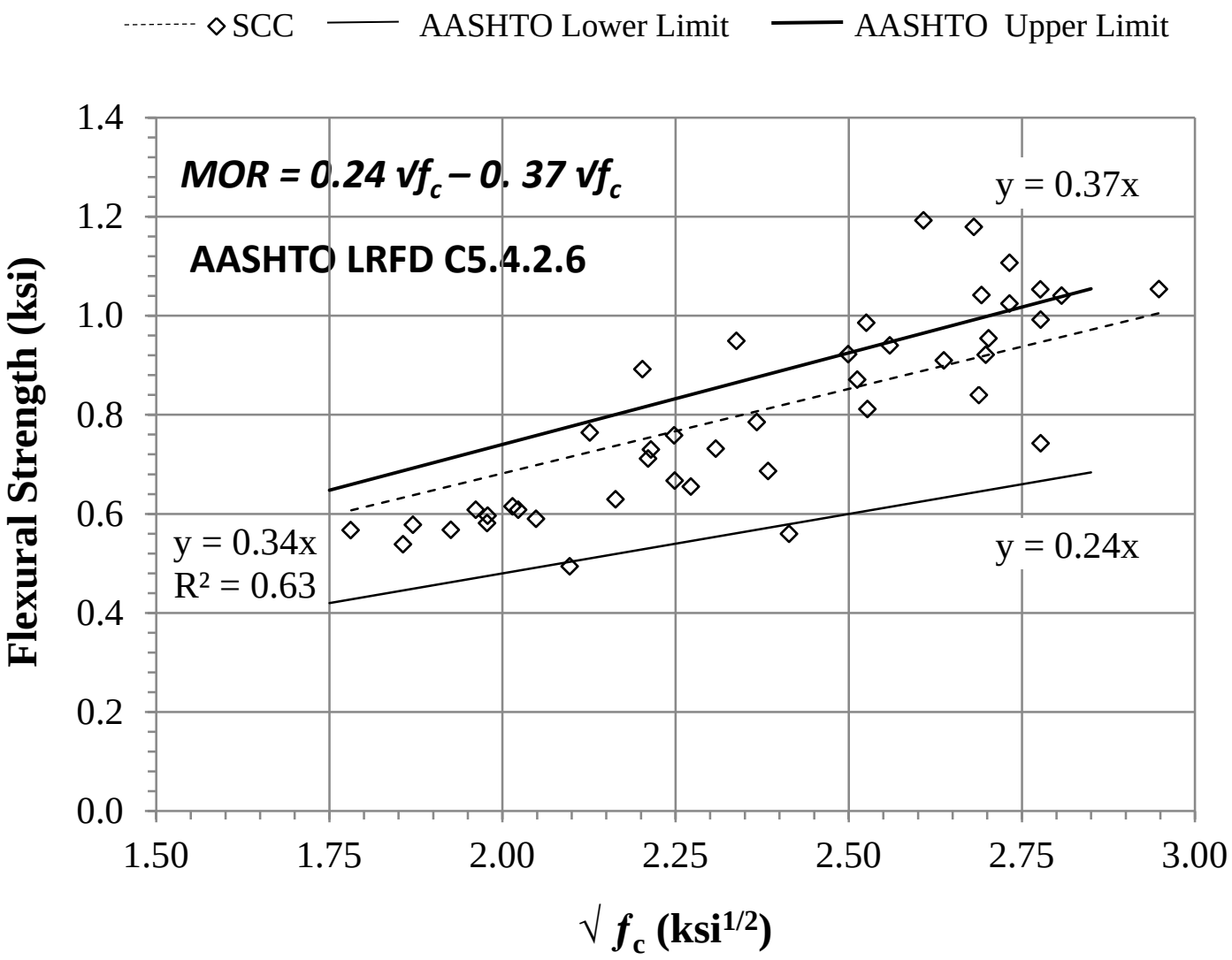
Splitting Tensile Strength (AASHTO T198)

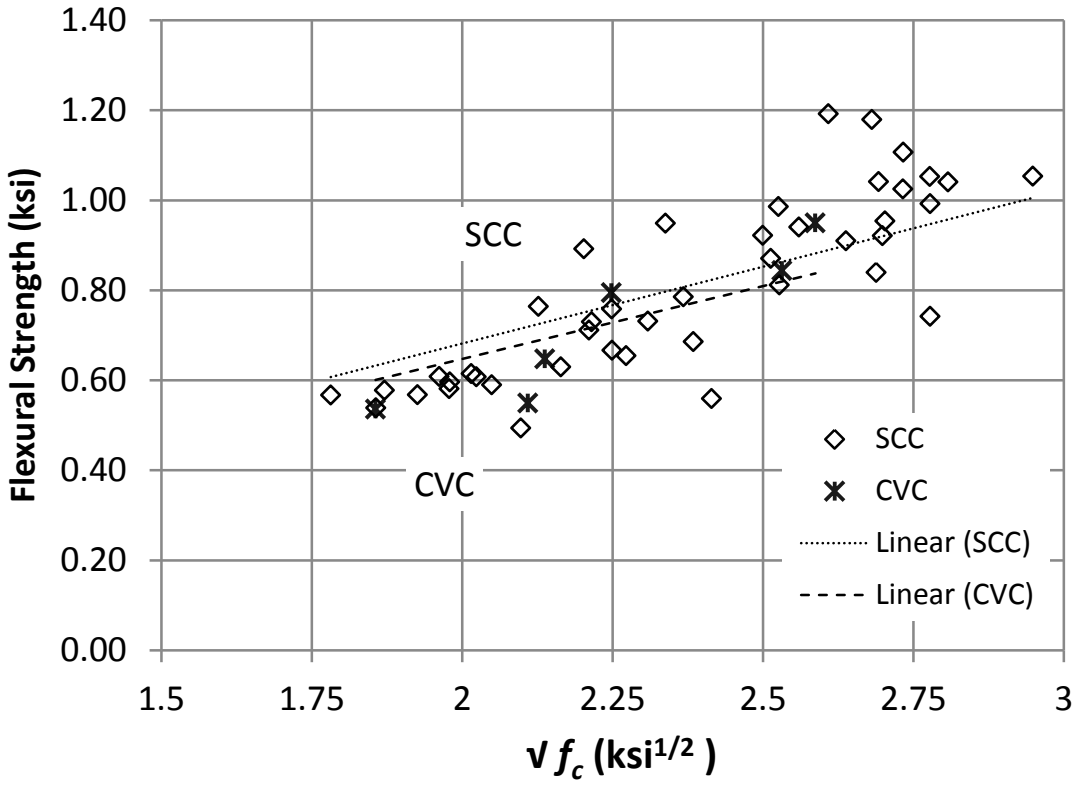




0.8 Modification Factor

Modulus of Rupture (MOR) **(AASHTO T97)**



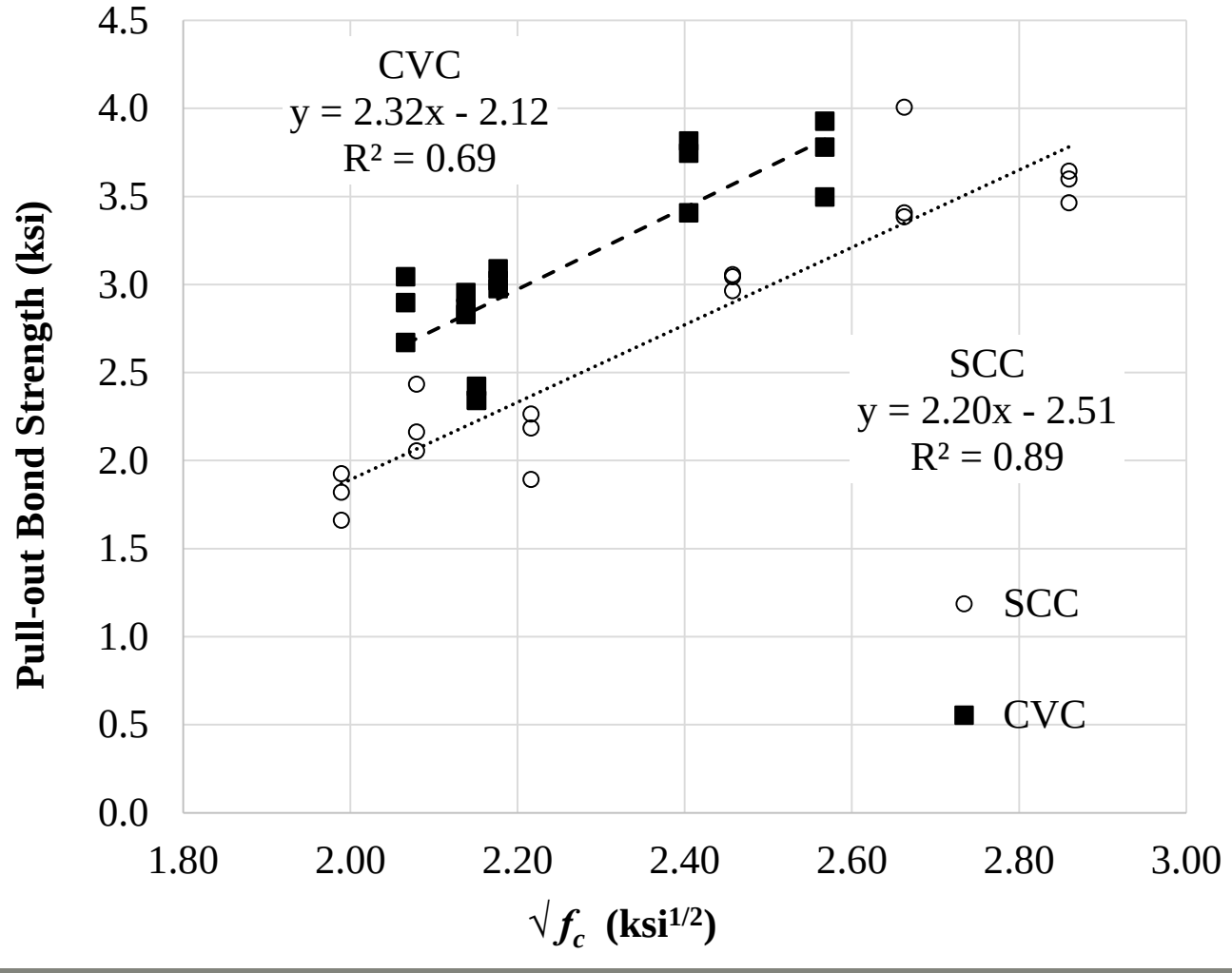


No Modification

Bond Strength

Pullout Test PHASE I (Rilem/CEB/FIB, 1970)

36 block specimens (18 SCC +18 CVC) with #6 vertical bars (Lab Mixed)

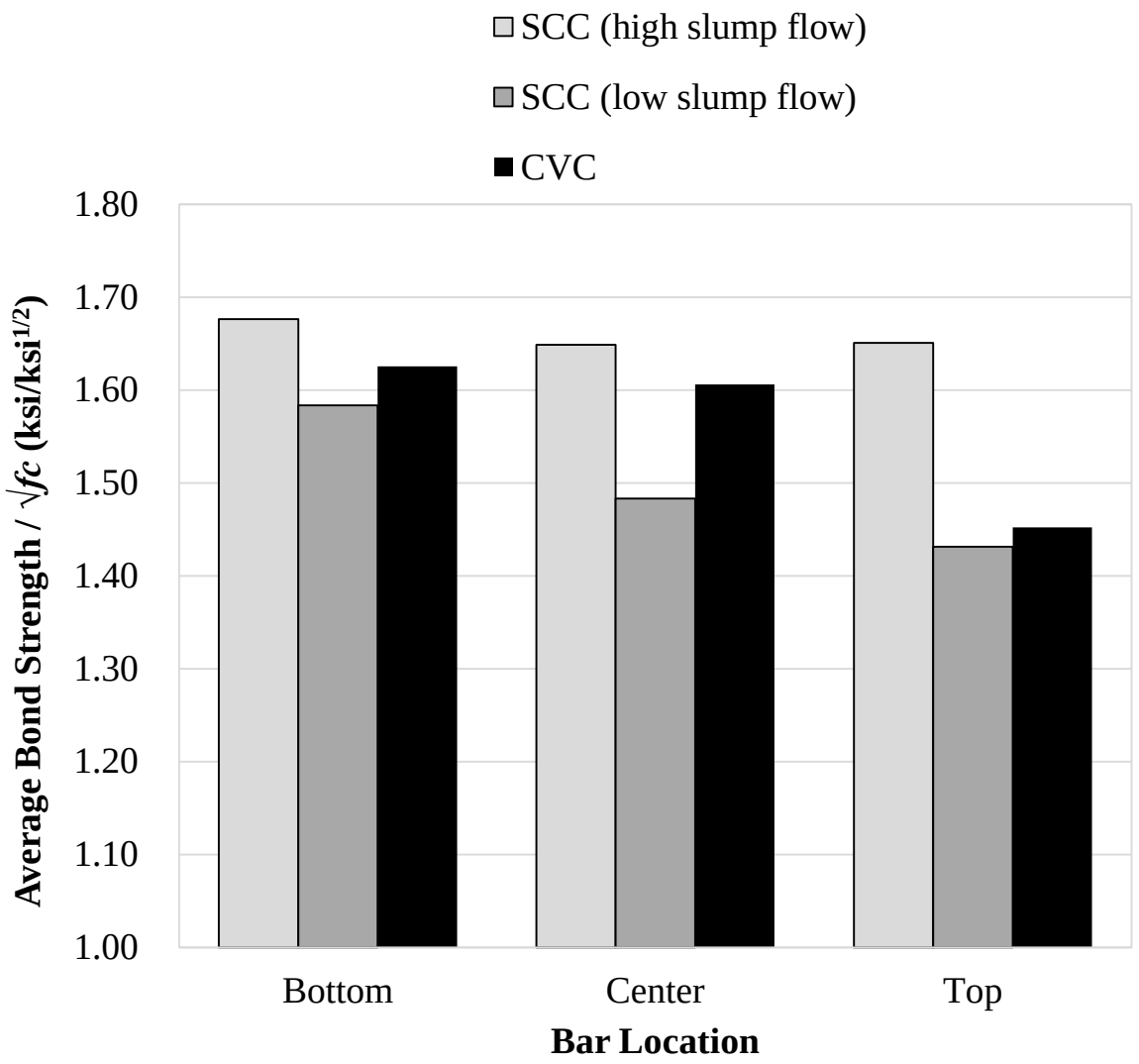


SCC Bond is 30% lower than that of CVC for vertical bars

Bond Strength

Pullout Test PHASE II (Rilem/CEB/FIB, 1970)

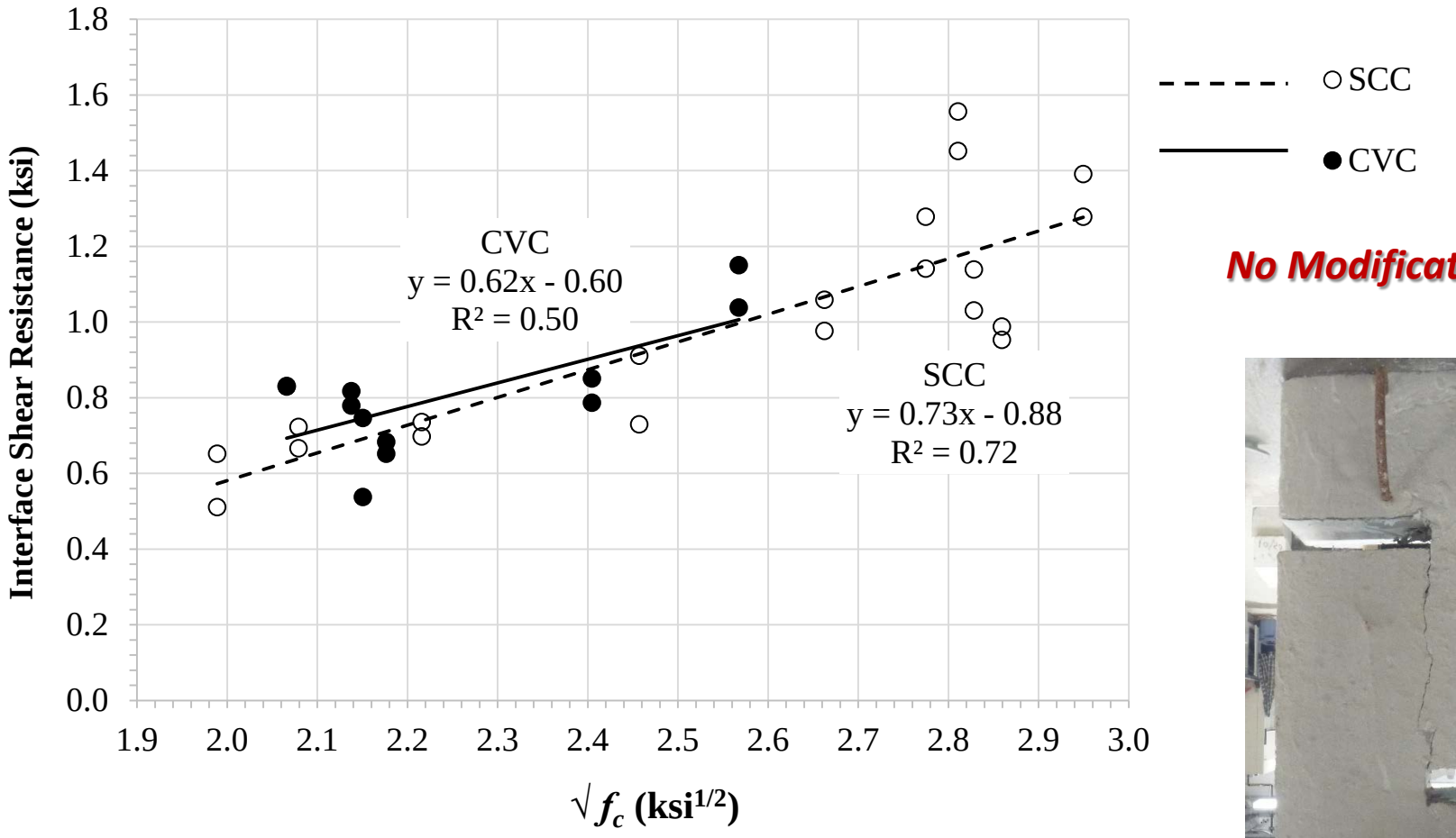
54 tests to evaluate bond and top bar effect of horizontal bars in wall specimens (Ready Mixed)



Top bar effect in SCC depends on slump flow

Shear Resistance

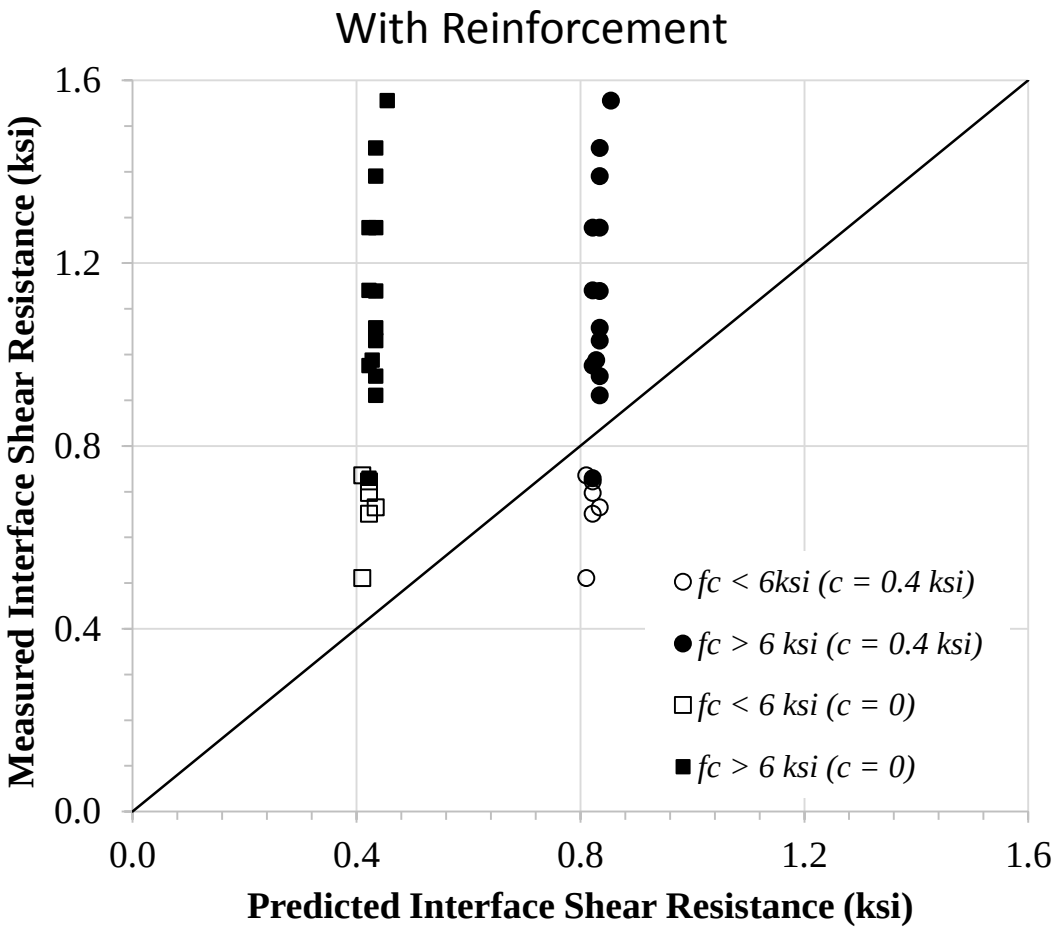
- Push off Tests for interface shear **(Mattock and Hawkins, 1972)**
  - 24 specimens (12 CVC+ 12 SCC) with 2#3 reinforcement - Lab mixed

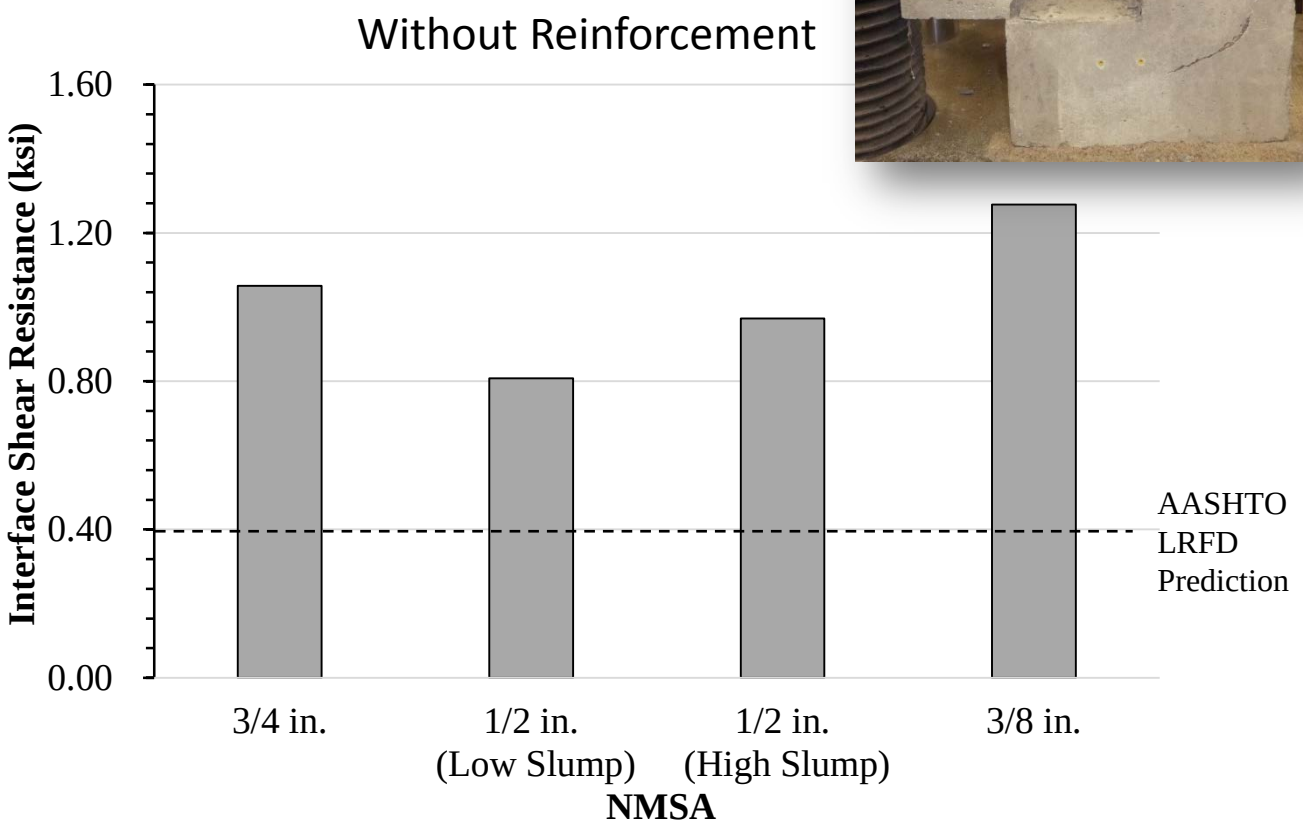


No Modification

Shear Resistance

Ignore c when f_c < 6 ksi



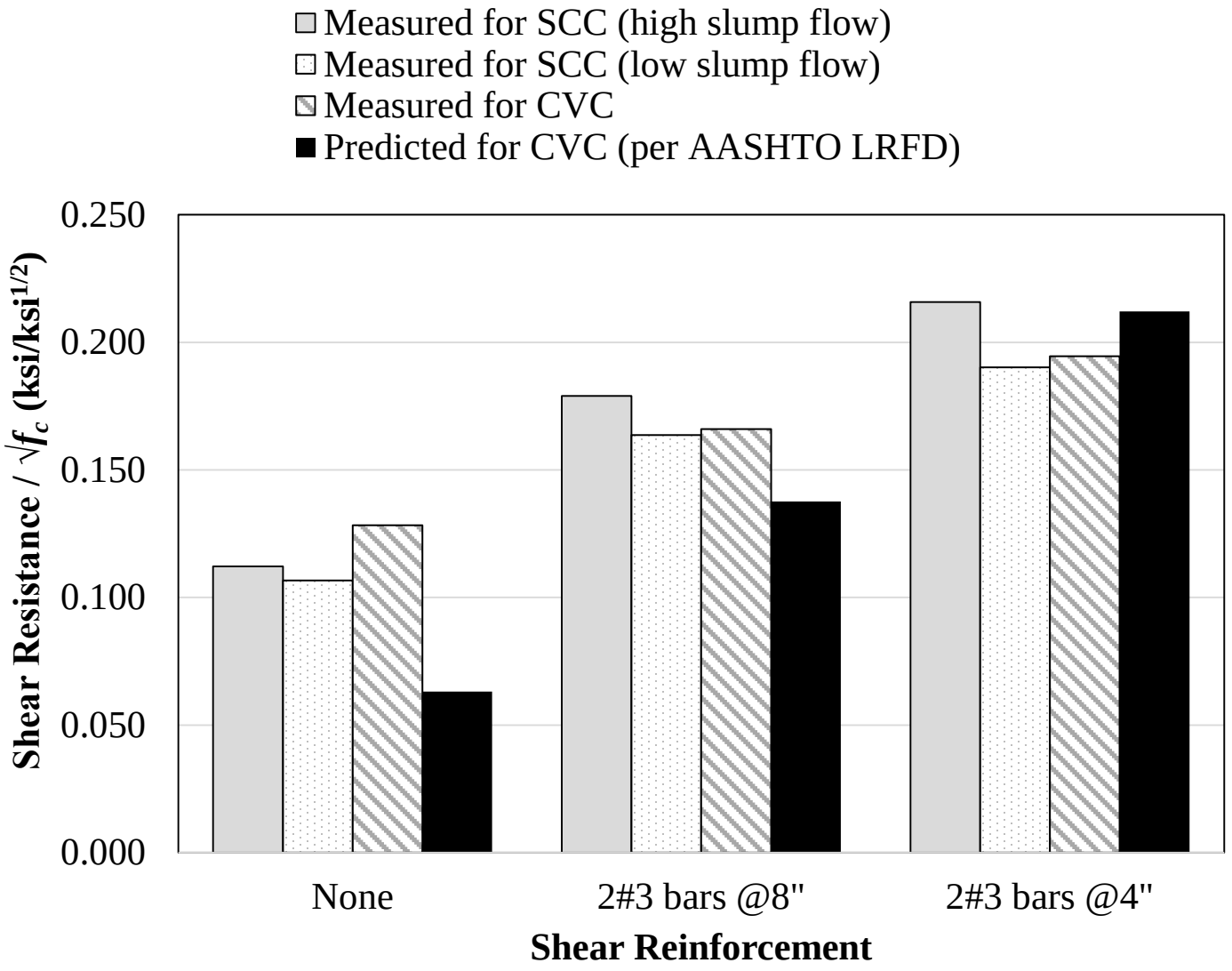


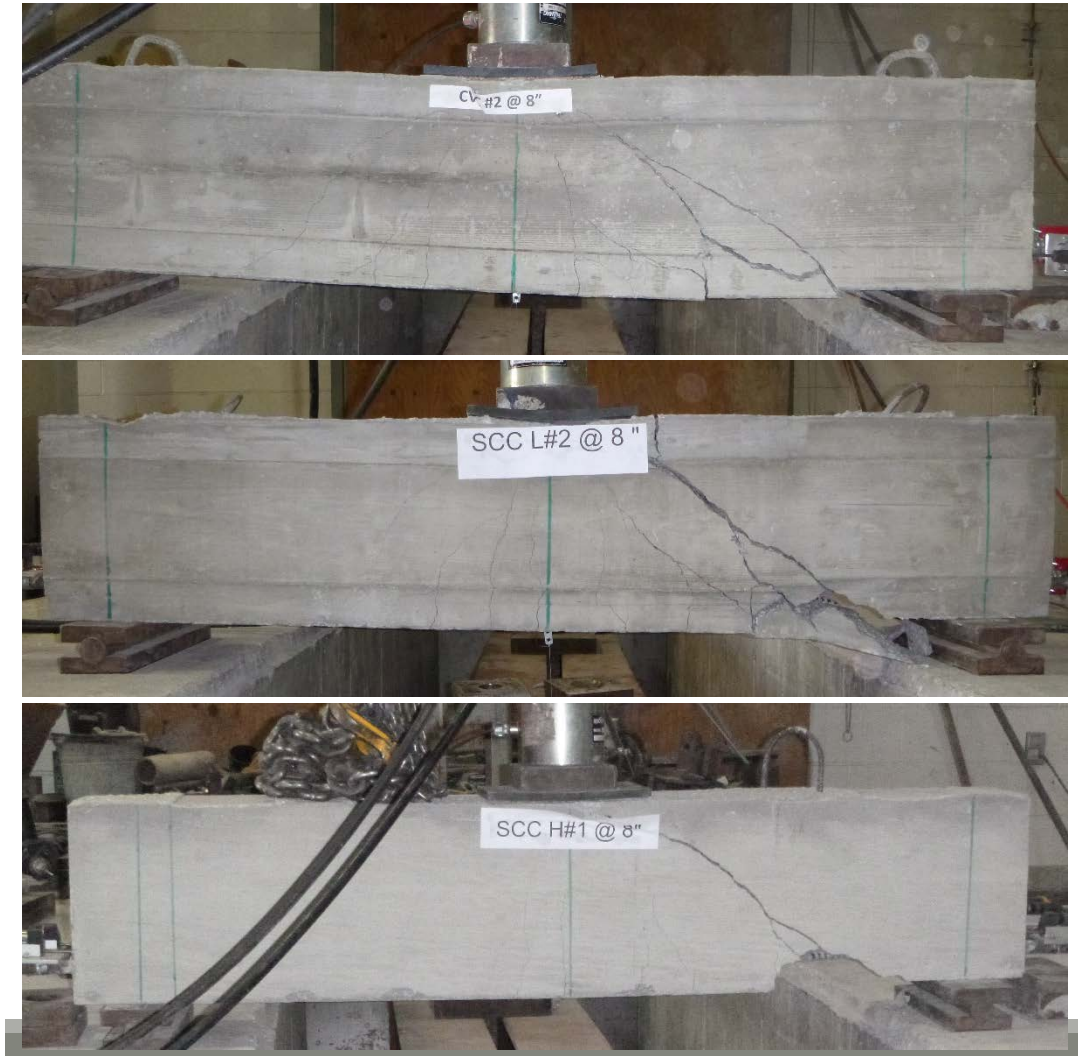
$$V_{ni} = c\,A_{cv} + \mu\,(A_{vf}\,f_y + P_c)$$ **AASHTO LRFD 5.8.4.1-3**

Shear Resistance

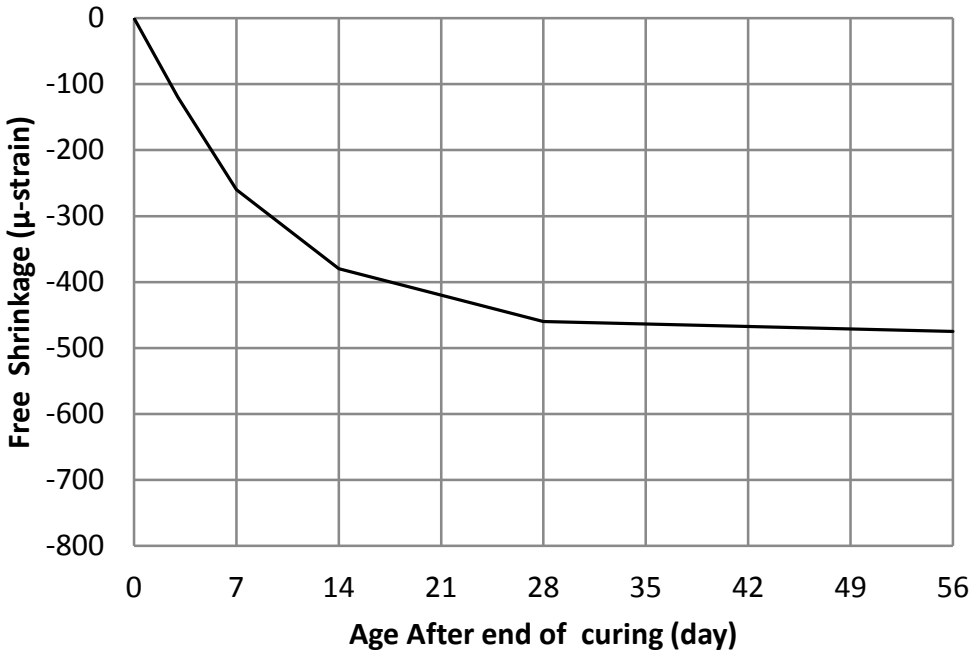
18 Beam tests (6 CVC + 6 low slump SCC + 6 high slump SCC)

No Modification

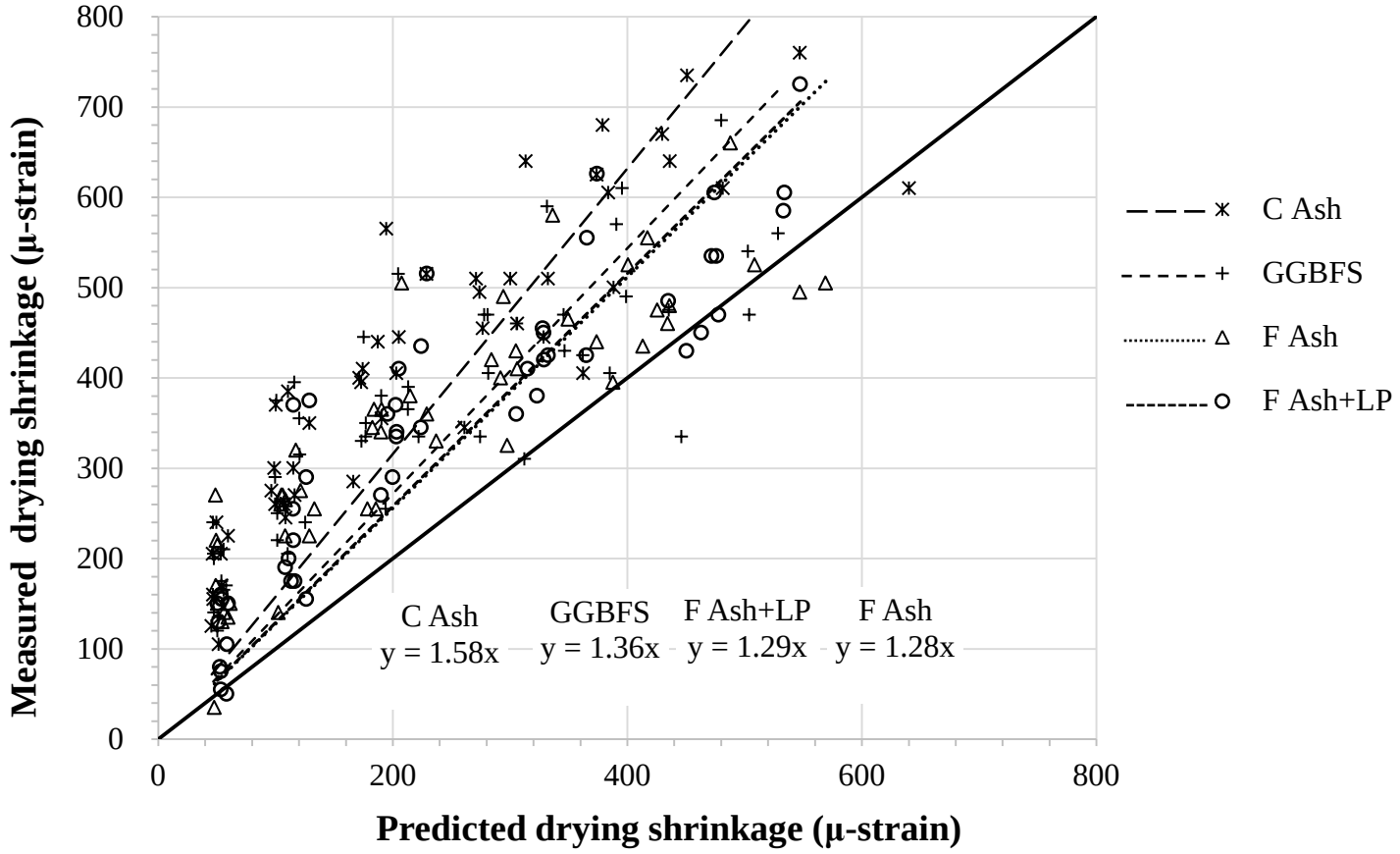




Drying (Free) Shrinkage **(AASHTO T160)**

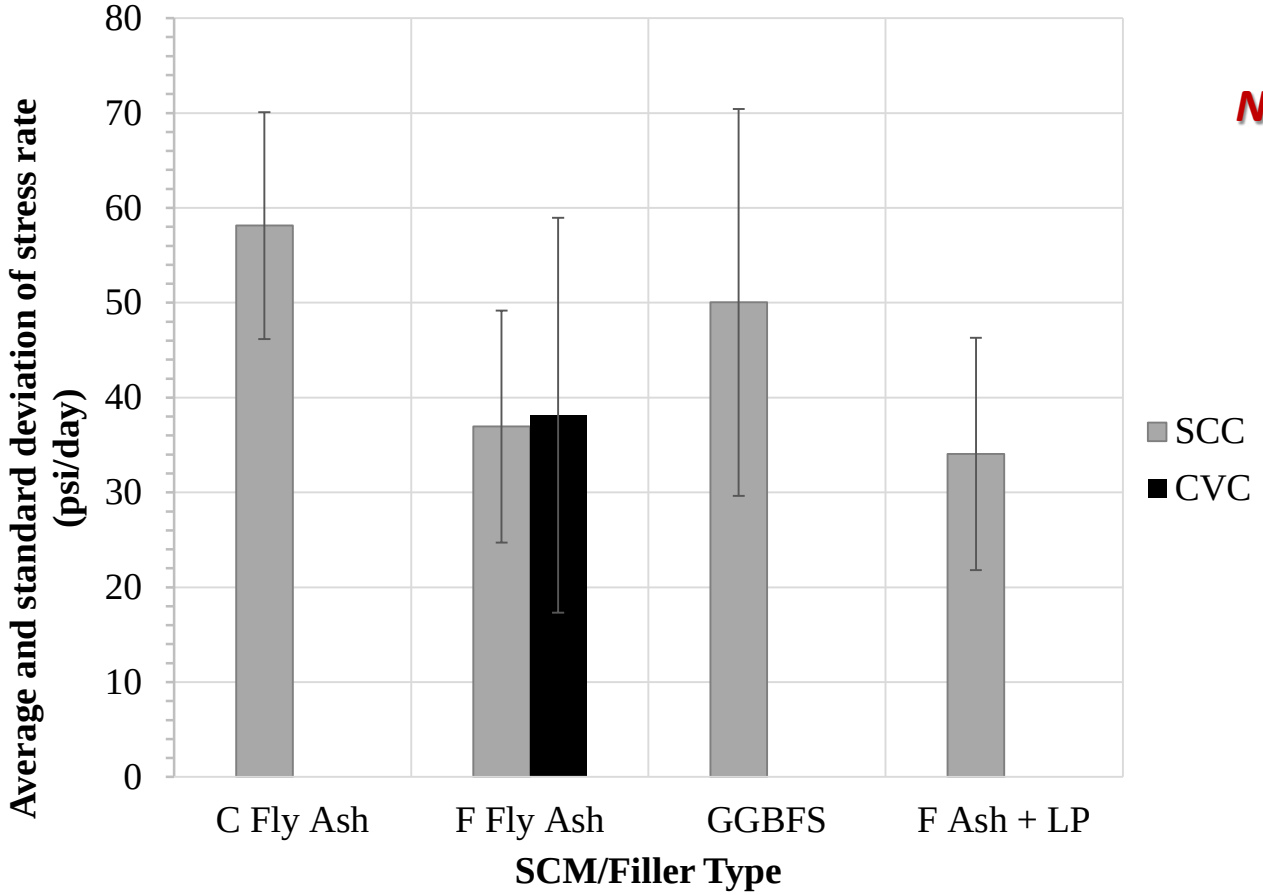


AASHTO LRFD 5.4.2.3.3-1

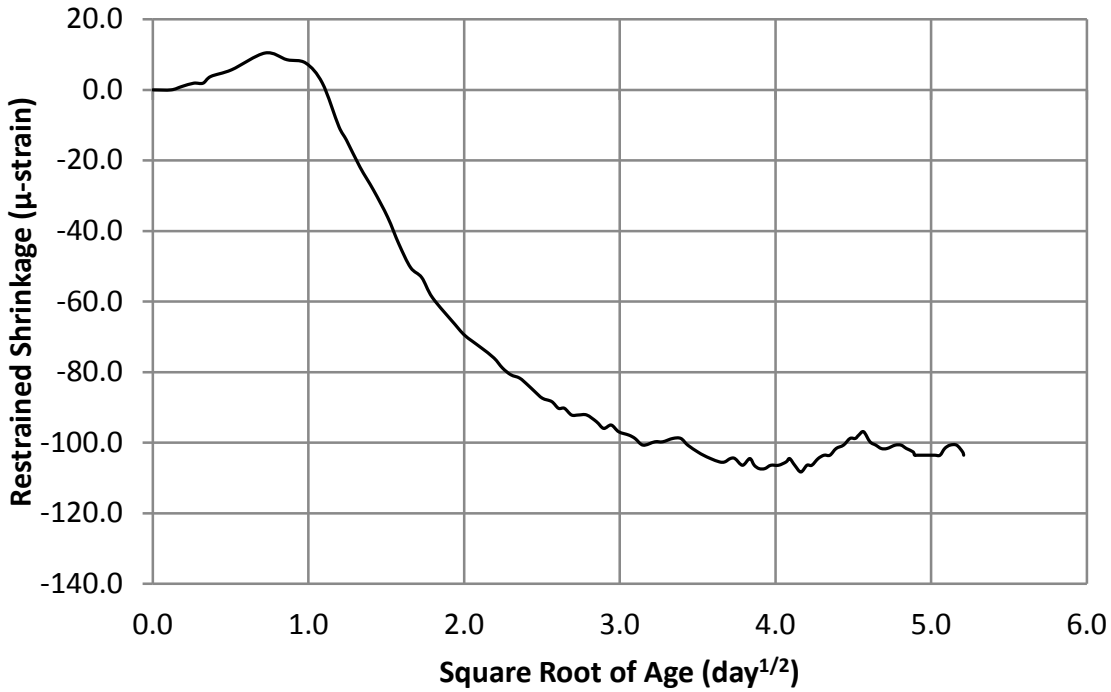


Several Modification Factors:
1.6 for C Ash
1.4 for GGBFS
1.3 for F Ash

Restrained Shrinkage (ASTM C1581)



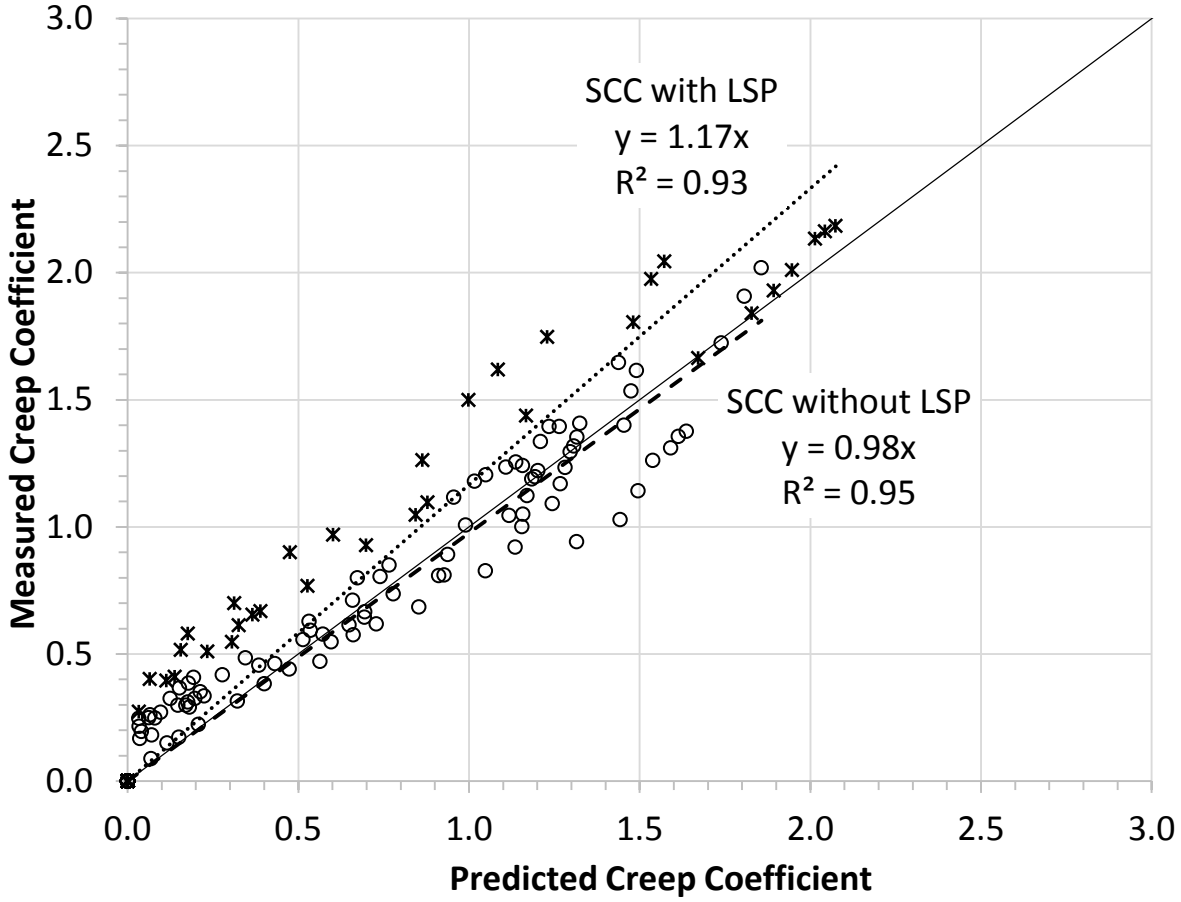
No Difference

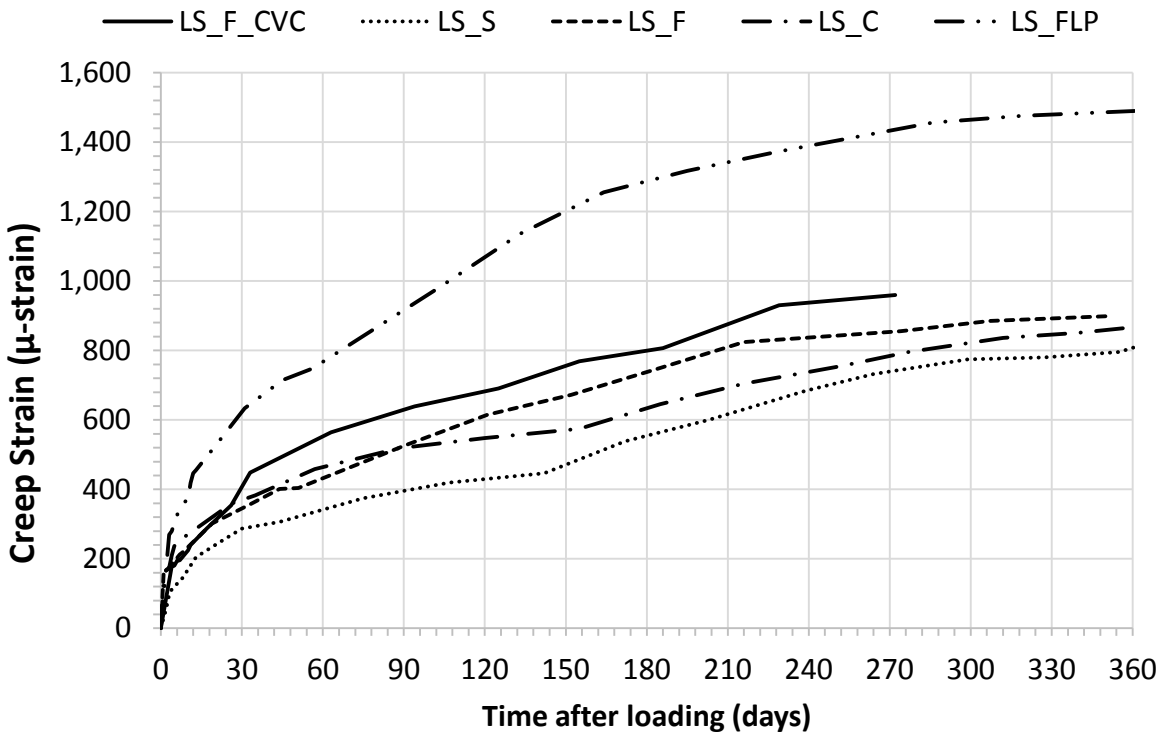


Creep (ASTM C512)

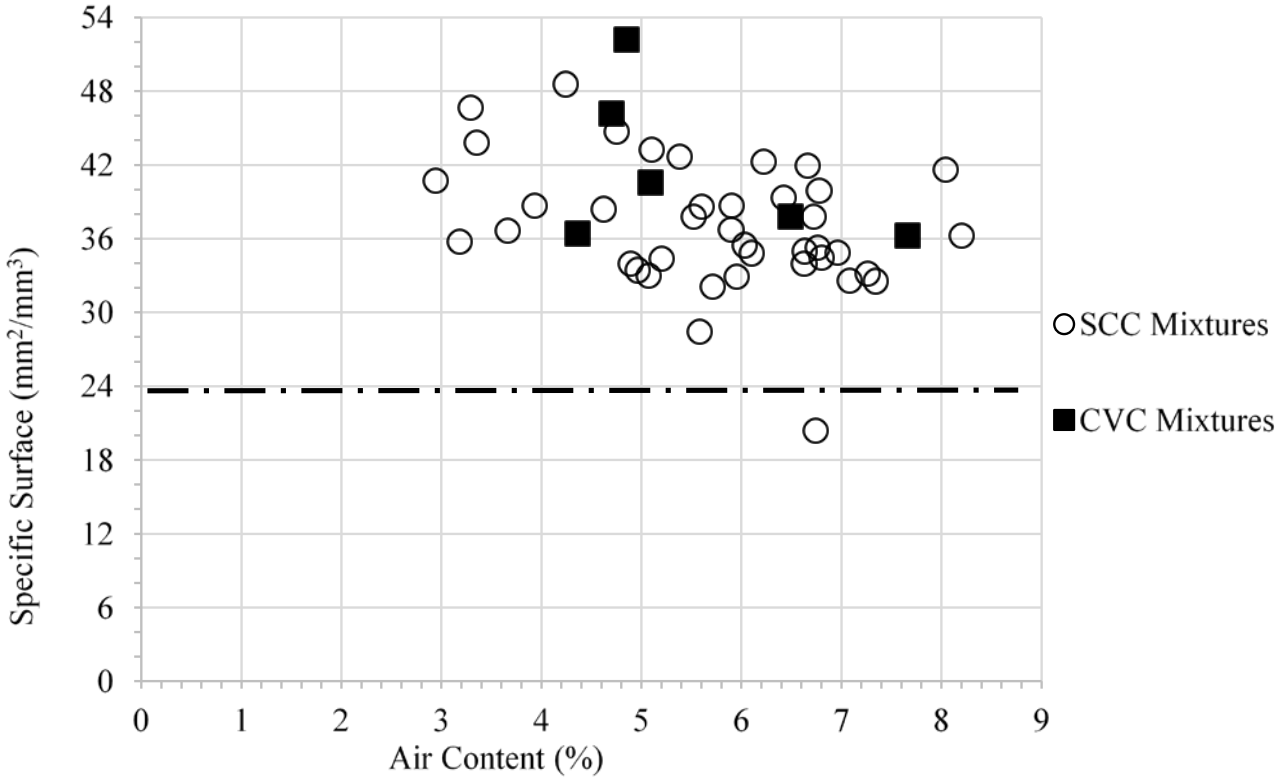
Modification Factor 1.2 for LSP

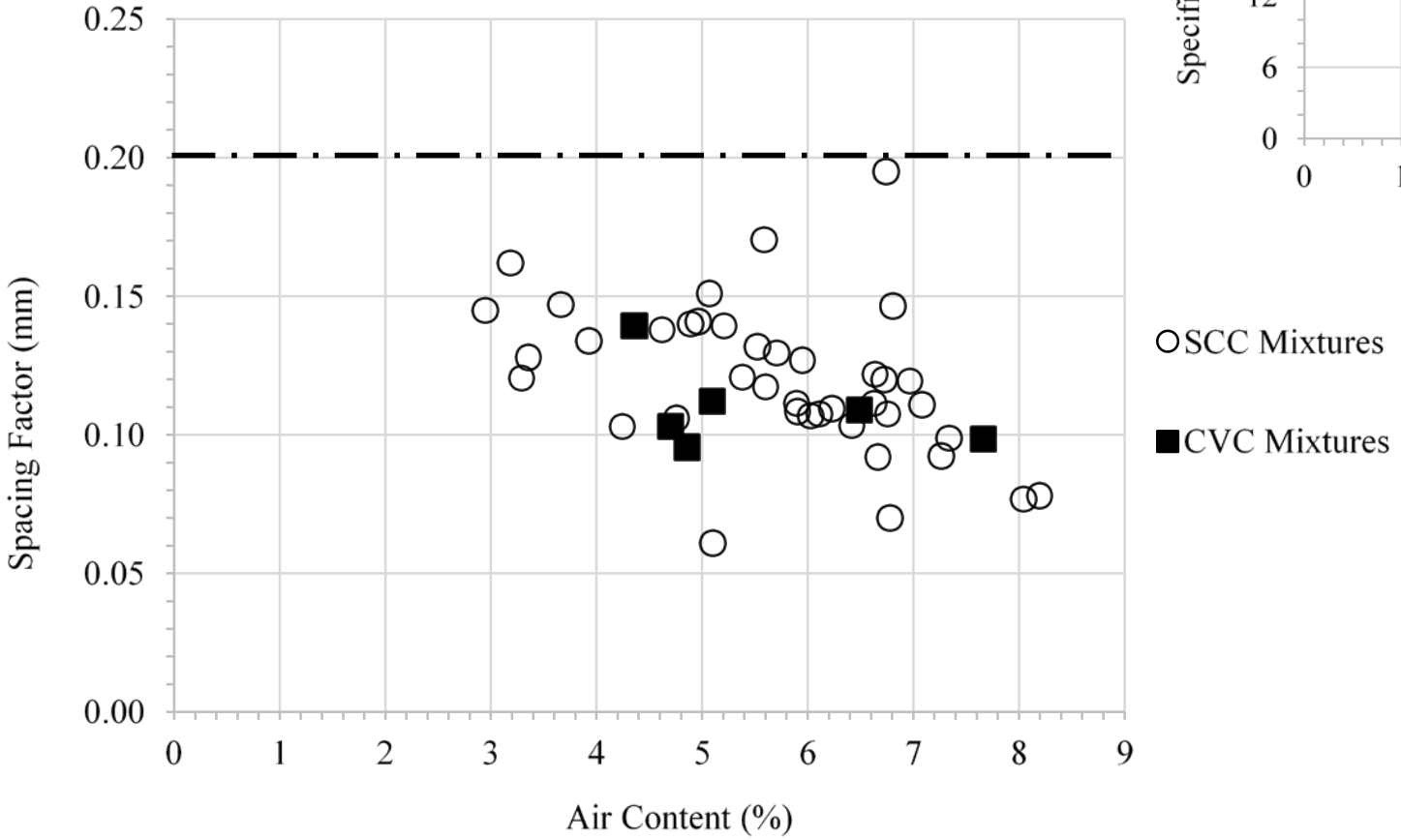
AASHTO LRFD 5.4.2.3.2-1





Air Void System (ASTM C457)





No Difference

Surface Resistivity (AASHTO TP 95)

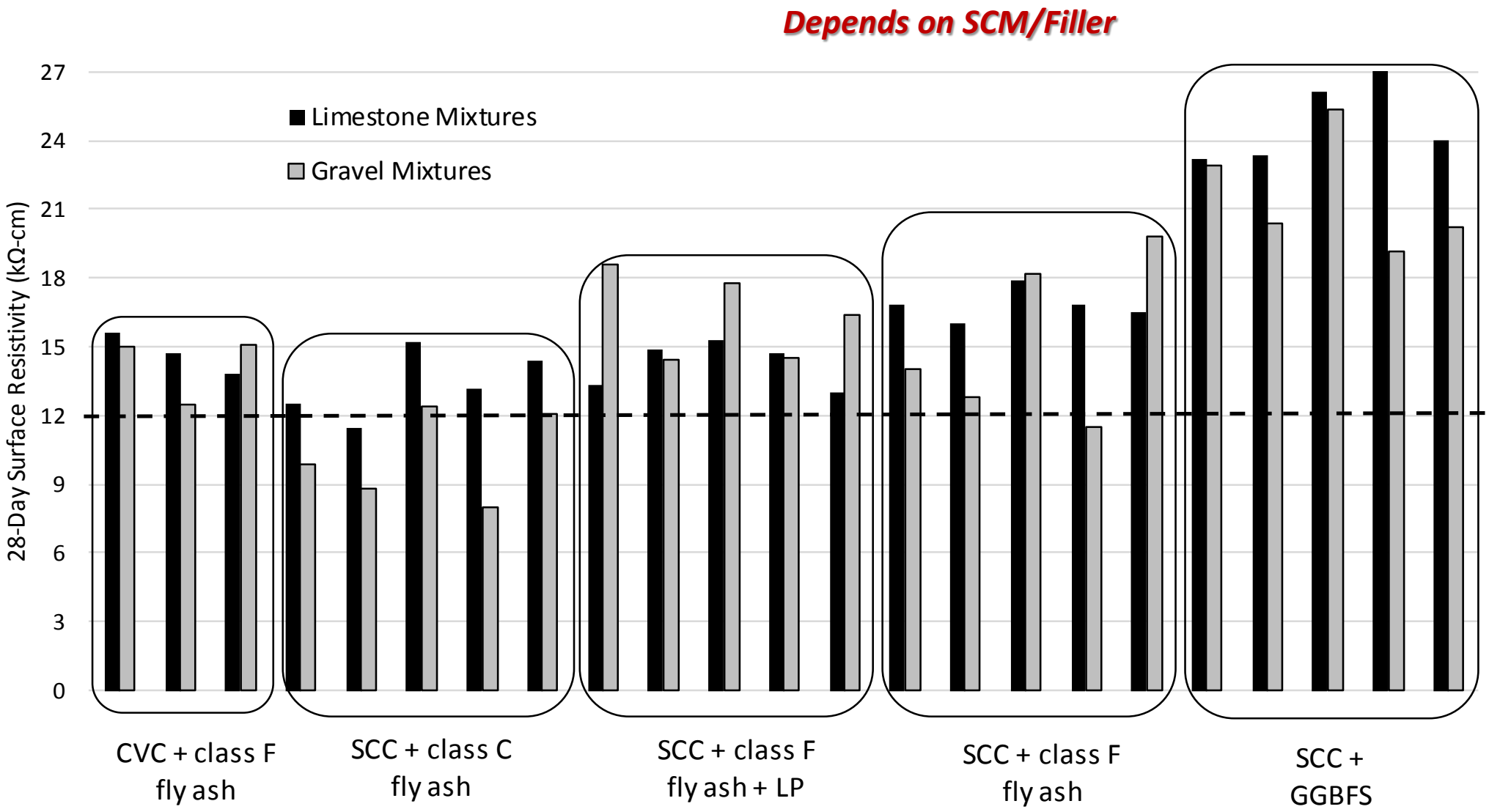


Table of Content

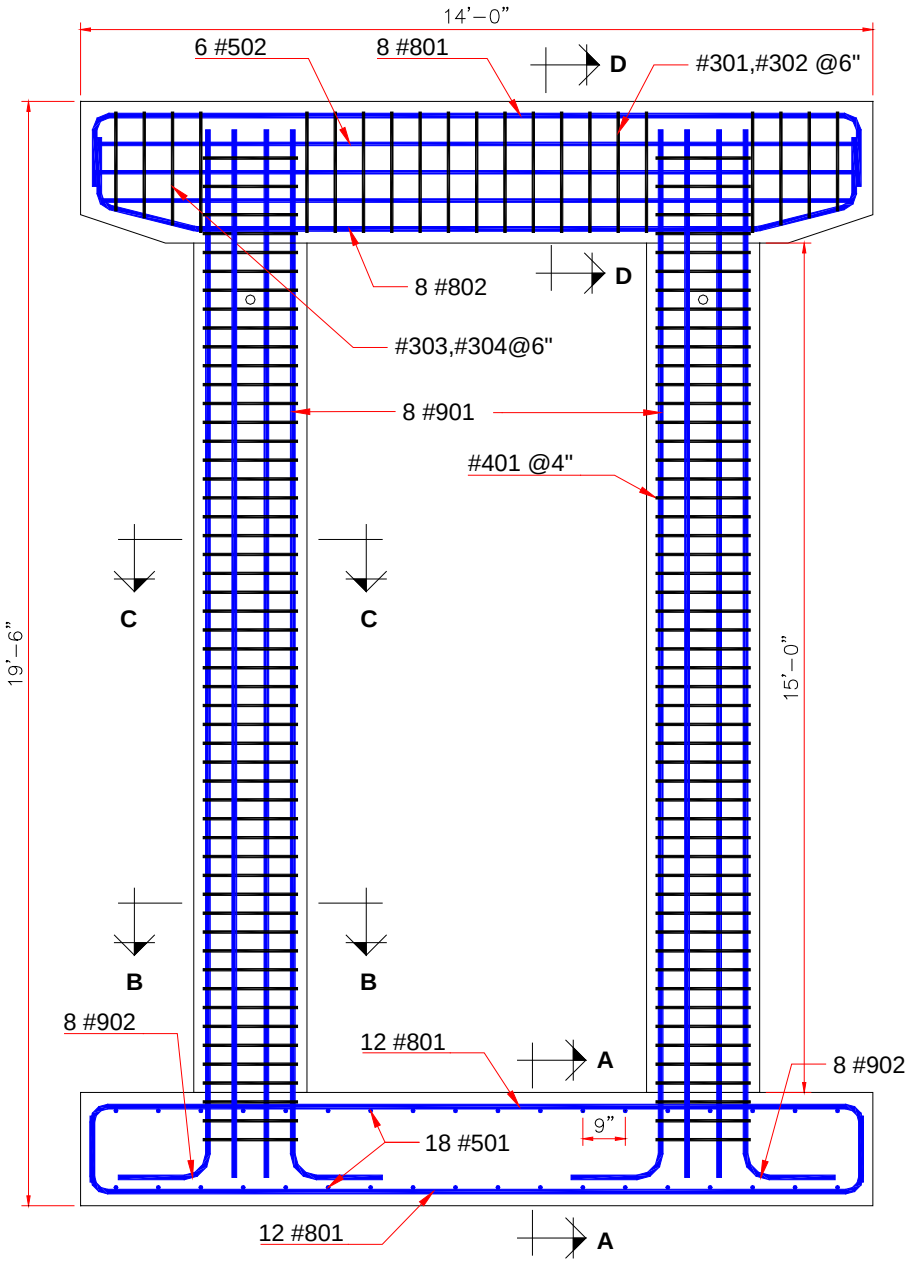
1. Definition
2. Problem Statement
3. Research Objectives and Scope
4. Research Approach **(chapter 1)**
5. Research Results **(chapter 2)**
   - Small-scale specimens
   - Full-scale specimens
6. Conclusions **(chapter 3)**

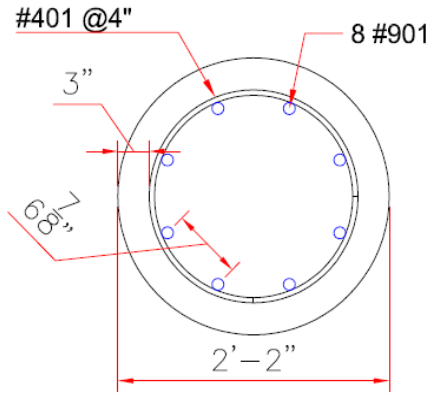
Research Results

- **From Small-Scale Lab-Mixed Concrete Specimens:**
  - Fresh concrete properties
  - Early-age concrete properties
  - Hardened concrete properties

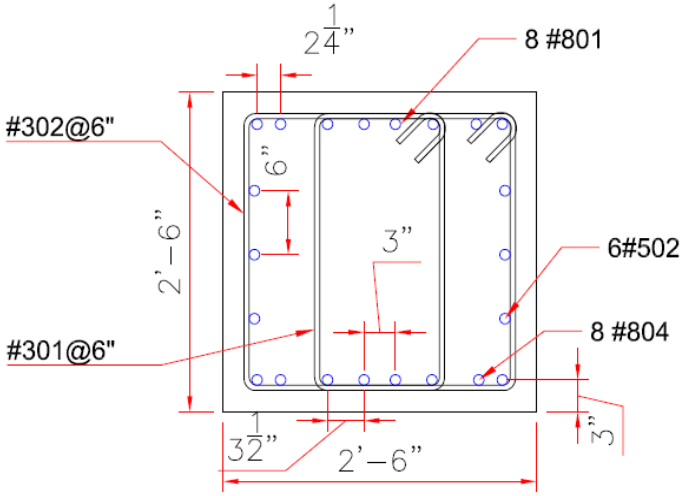
- **From Full-Scale Ready-Mixed Concrete Specimens:**
  - Constructability
  - Structural Performance

Full-Scale Substructure Component

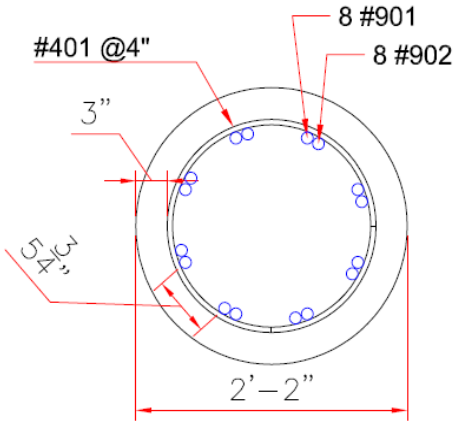




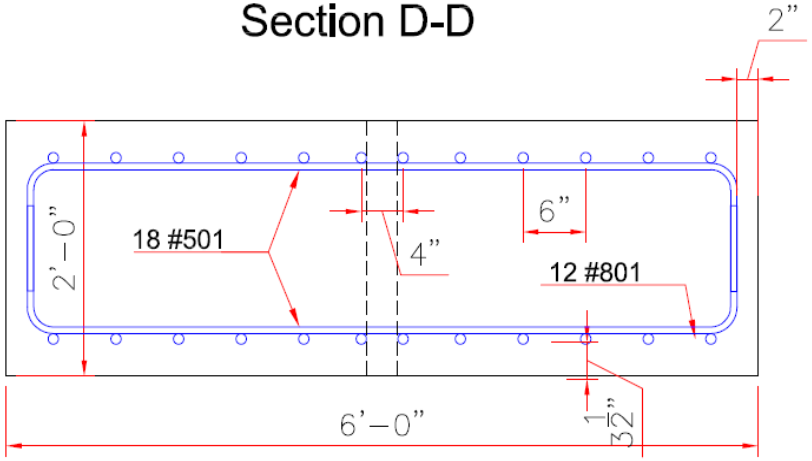
Section C-C



Section D-D



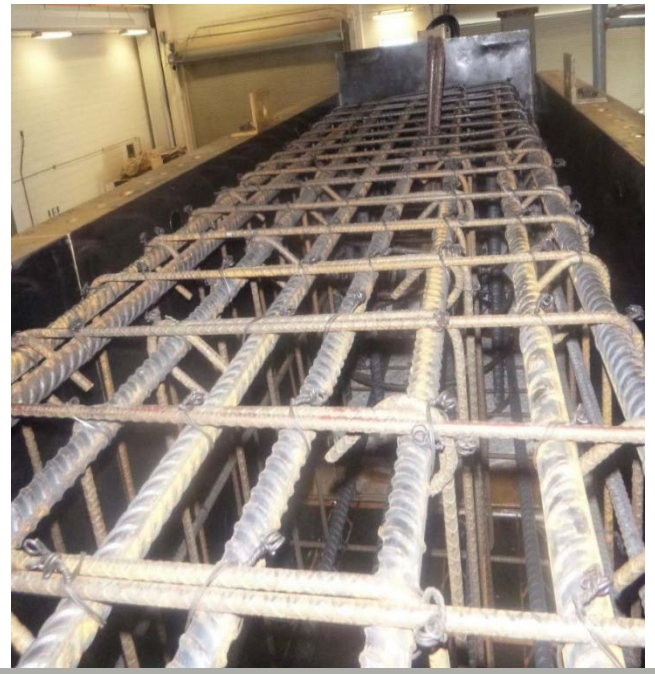
Section B-B



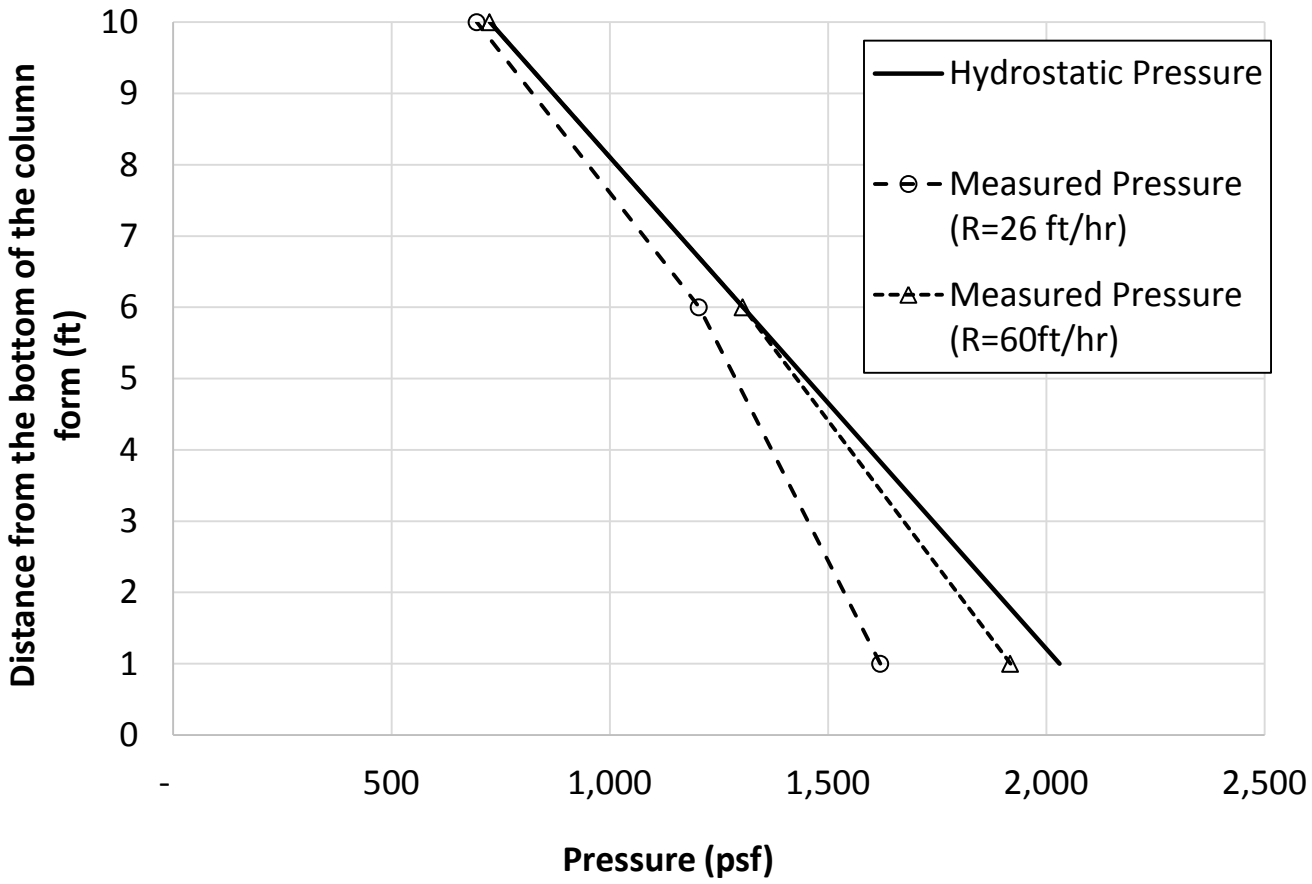
Section A-A

Full-Scale Substructure Component

Component	NMSA (in.)	Ordered Quantity (cy)	Required Quantity (cy)	Duration of Casting (min.)	Placement	
					Method	Rate
Footing	3/4	7	6.2	5	Truck Chute	1.3 cy/min.
First Column	1/2	3	2.05	35	Bucket and Tremie Pipe	26 ft/hr (0.06 cy/min)
Second Column	1/2	3	2.05	15	Bucket (free fall)	60 ft/hr (0.14 cy/min)
Pier Cap	1/2	4	3.15	45	1/2 cy Bucket	0.07 cy/min



Formwork Pressure



Surface Void Ratio *ACI 347.3R-13 Guide to Formed Concrete Surfaces*

Formed Concrete Surface	Max. Void Diameter (D_{max}), in.	% of D_{max}	Total % of void area	Surface Void Ratio Class
Footing (short side)	3/8	27.6%	0.16%	SVR3
Footing (long side)	3/8	14.0%	0.31%	SVR3
First Column (at 1.5 ft from the bottom)	3/8	35.3%	0.14%	SVR3
First Column (at 11.3 ft from the bottom)	3/8	8.7%	0.25%	SVR3
Second Column (at 8.5 ft from the bottom)	5/8	78.3%	0.19%	SVR2
Second Column (at 10 ft from the bottom)	5/8	14.0%	0.31%	SVR2
Pier Cap (at the pour Line)	5/8	12.0%	0.68%	SVR2
Pier Cap (away from the pour Line)	5/8	8.1%	0.54%	SVR2

Stability *HVSI AASHTO PP 58*

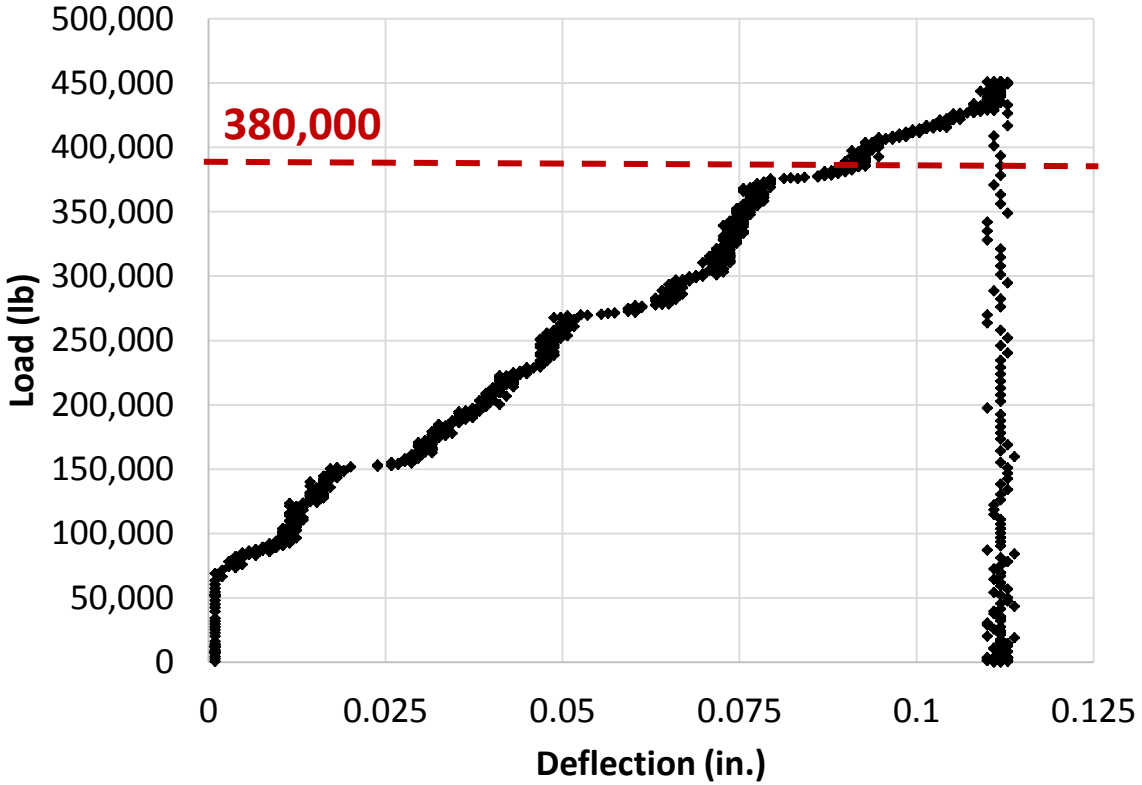
Location	Bottom	Middle	Top
First Column			
Second Column			

Stability *HVSI AASHTO PP 58*

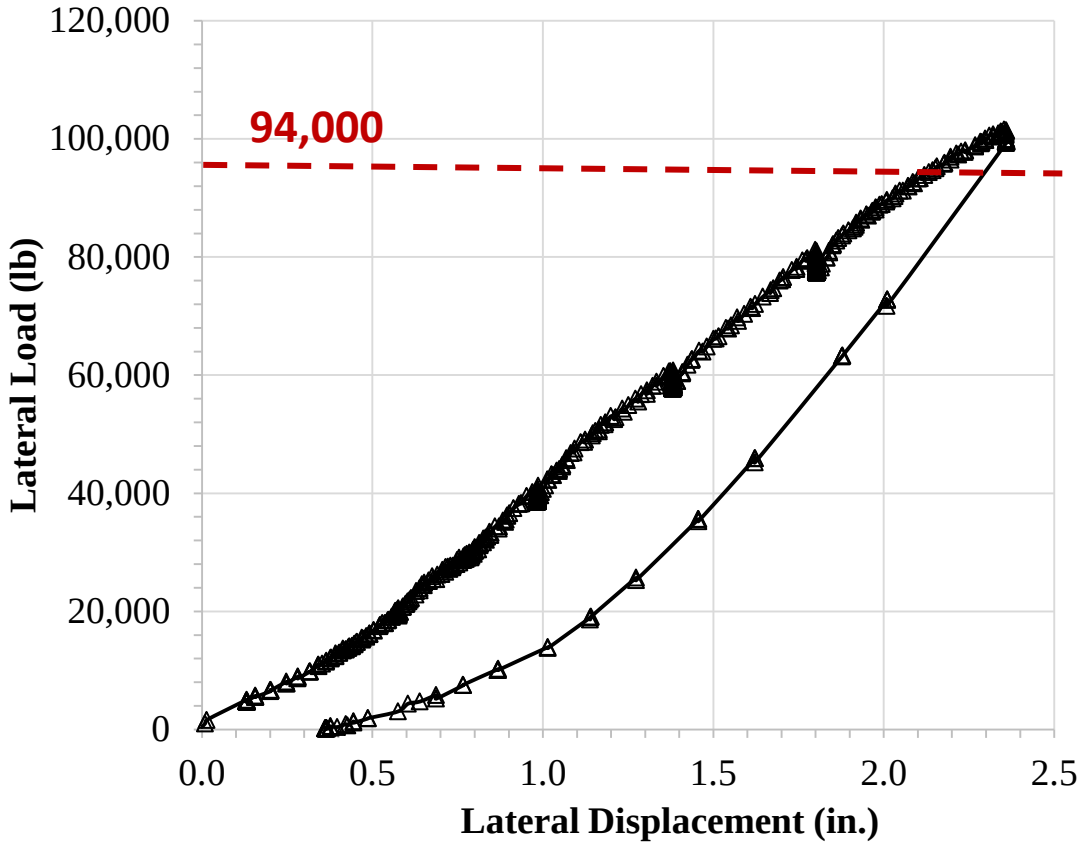
HVSI = 0

HVSI = 1

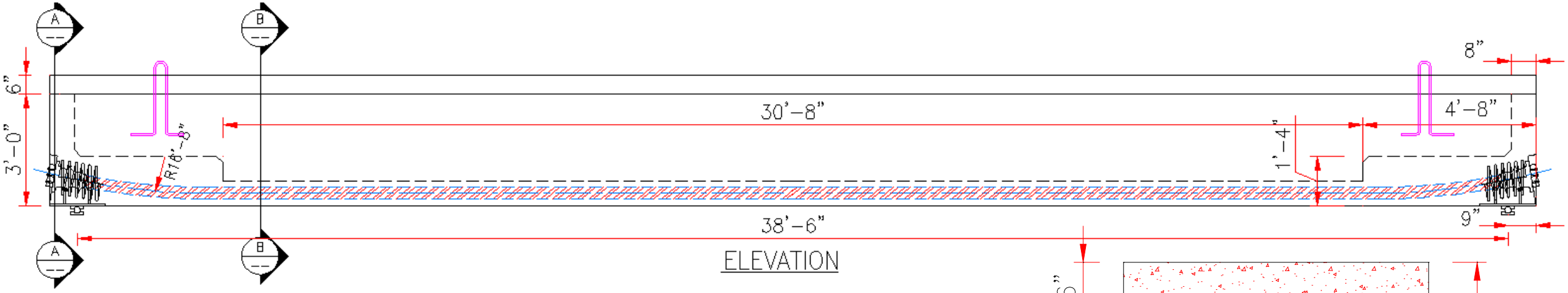
Strut-and-Tie Resistance

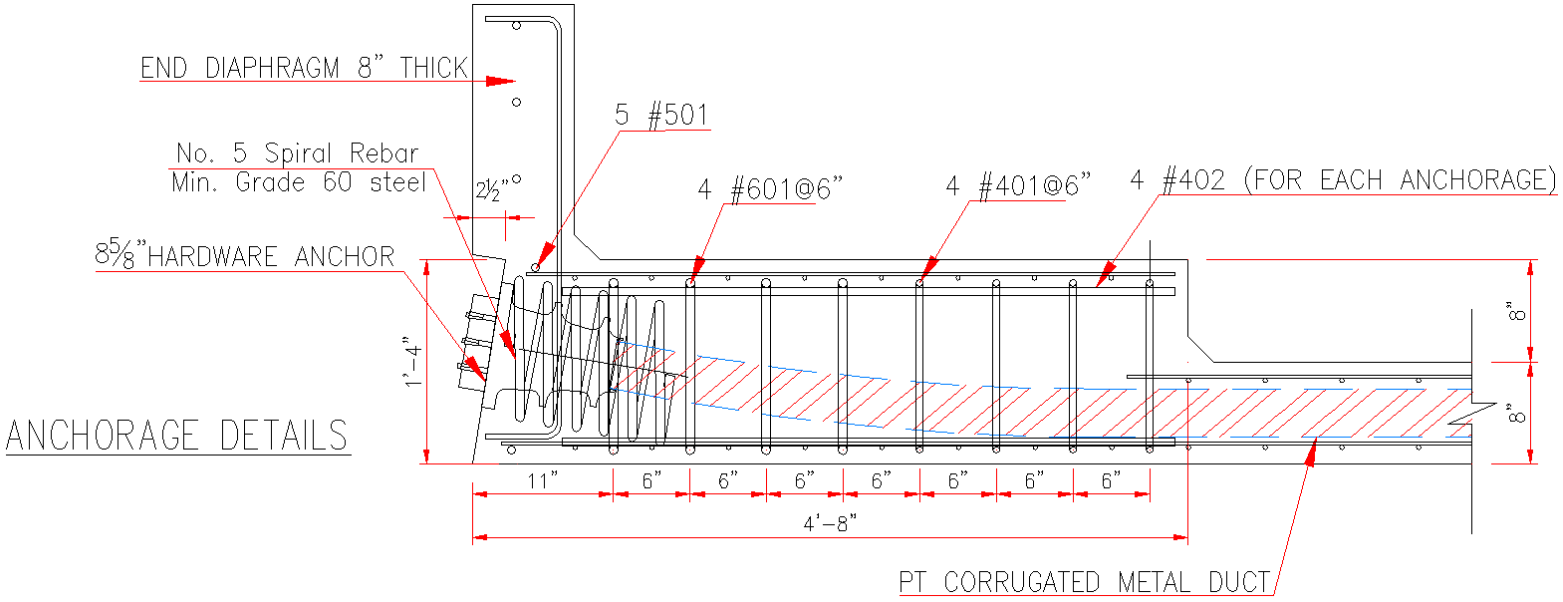


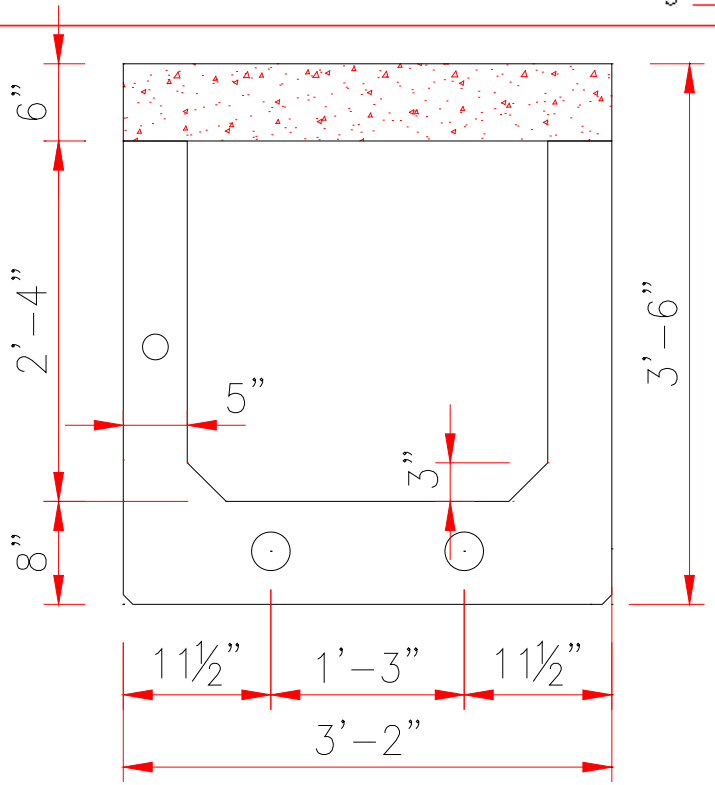
Flexural Resistance



Full-Scale Superstructure Component







Full-Scale Superstructure Component

Component	NMSA (in.)	Ordered Quantity (cy)	Required Quantity (cy)	Duration of Casting (min.)	Placement	
					Method	Rate
Box Girder	3/8	7	5	40	Pumping (2"and 3" hose)	0.13 cy/min
Top Flange	3/8	7	3.35	25	Pumping (3" hose)	0.13 cy/min

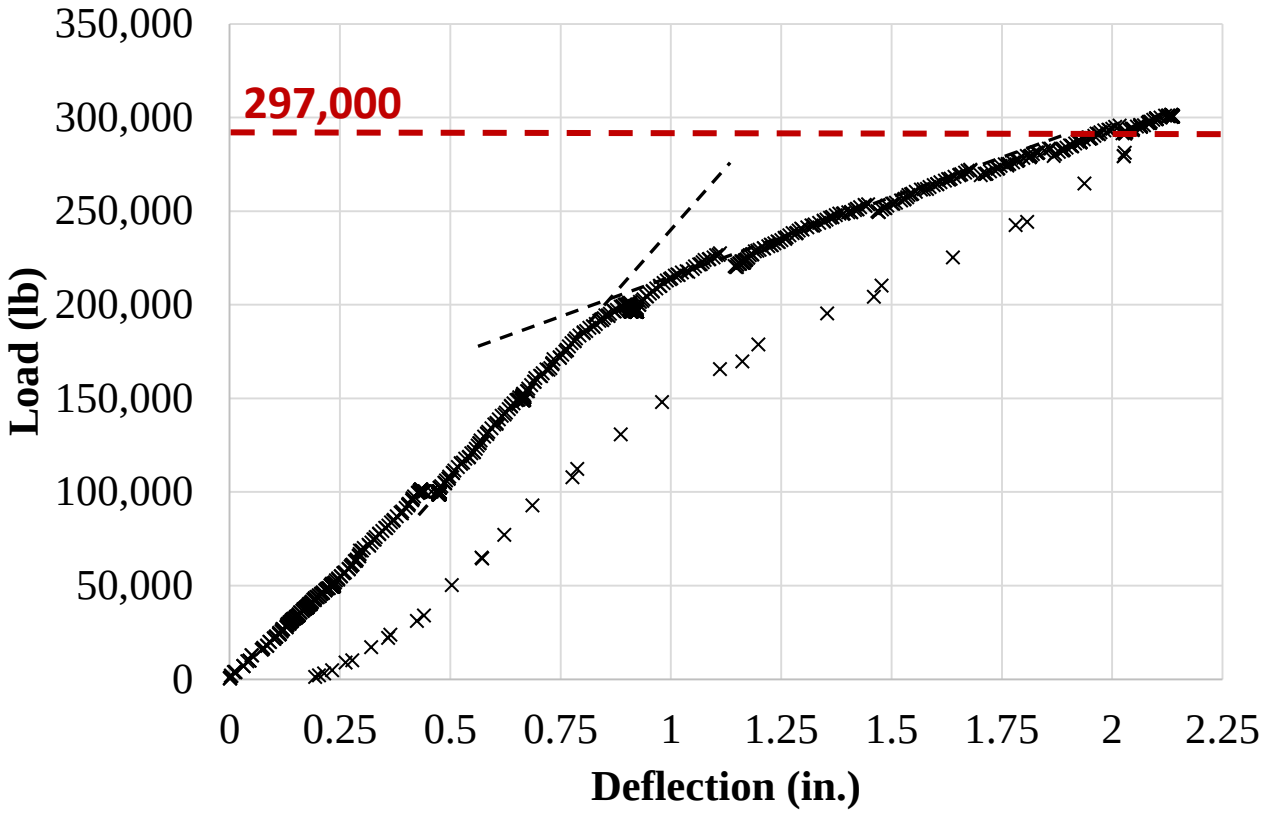
Surface Void Ratio *ACI 347.3R-13 Guide to Formed Concrete Surfaces*

Formed Concrete Surface	Max. Void Diameter (D_{max}), in.	% of D_{max}	Total % of void area	Surface Void Ratio Class
Top of the Girder (pouring side)	1/2	16.1%	0.40%	SVR3
Bottom of the Girder (pouring side)	1/2	37.2%	0.51%	SVR3
Bottom of the Girder (opposite side)	1/4	10.8%	0.20%	SVR4
Girder End (at the construction joint)	1/4	25.0%	0.02%	SVR4

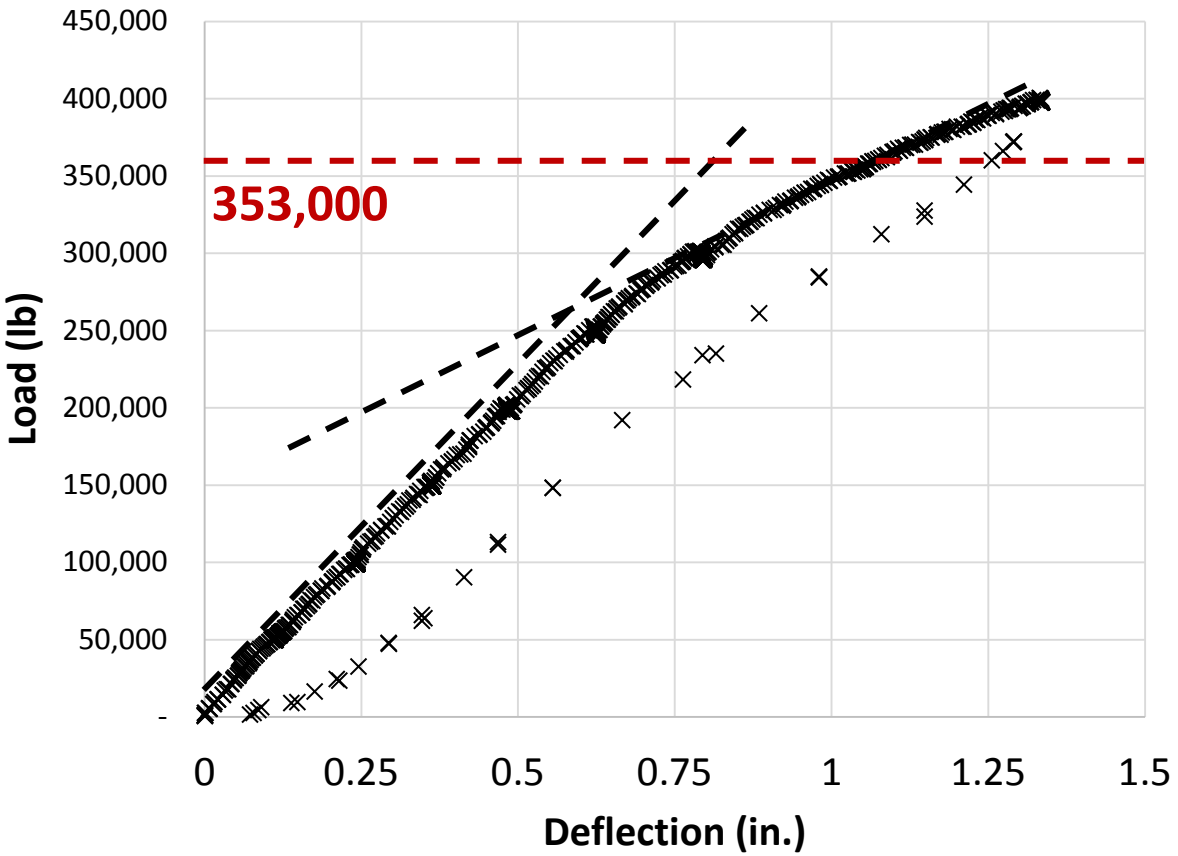
Stability *HVSI AASHTO PP 58*

HVSI = 0

Flexural Resistance



Shear Resistance



Air Void System

Batch ID	% Air Content in fresh concrete at plant*	Additional dosage of HRWRA (oz/cwt)	% Air Content in fresh concrete at site	Placement Method	Air Void System in Hardened Concrete					
					Measured from 4x8 Cylinders			Measured from Extracted Cores		
					Air content, %	Spacing factor, mm	Specific surface, mm^{-1}	% Air content	Spacing factor, mm	Specific surface, mm^{-1}
Footing	4.5	2.3	2.5	Truck Chute	4.1	0.17	32.8	2.9	0.23	22.5
First Column	4.5	2.0	4.0	Bucket and Tremie Pipe	5.7	0.17	26.4	4.2	0.18	31.0
Second Column	6.2	1.0	4.0	Bucket (free fall)	4.9	0.15	27.2	5.2	0.15	32.7
Pier Cap	6.4	4.0	4.0	1/2 cy Bucket	4.3	0.22	24.3	-	-	-
Box Girder	6.0	1.5	4.5	Pumping (2 and 3 in.hose)	4.0	0.16	34.0	5.2	0.14	29.0
Top Flange	4.5	1.5	3.5	Pumping (3 in. hose)	5.0	0.13	33.1	4.6	0.17	31.9
Average	**5.35**	**2.05**	**3.75**	-	**4.7**	**0.17**	**29.6**	**4.4**	**0.18**	**29.4**

* Measured by plant technician

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Conclusions

Component Category	Bridge Component	Component Geometric Characteristics												SCC Workability Targets					
		Length		Depth		Thickness		Shape Intricacy		Formed Surface Quality		Level of Reinforcement		Filling Ability		Segregation Resistance*		Passing Ability	
		Short	Long	Shallow	Deep	Thin	Thick	Simple	Complex	Low	High	Low	High	FA1	FA2	SR1	SR2	PA1	PA2
Substructure	Footing	■		■			■	■		■		■		■		■		■	
	Pile Cap	■		■			■	■		■			■	■		■			■
	Wing Wall	■		■			■	■		■		■		■		■		■	
	Abutment Wall		■		■		■	■		■		■		■			■	■	
	Pier Wall		■		■		■		■		■	■			■		■	■	
	Pier Column	■			■		■	■			■		■		■		■		■
	Strut or Tie	■		■			■	■			■	■			■		■	■	
	Pier Cap	■		■			■	■			■		■		■	■			■
Superstructure	Box Girder		■	■		■			■				■		■		■		■
	Stringer	■		■			■	■		■			■	■		■			■
	Floor Beam	■		■			■	■		■		■		■		■		■	
	Girder		■	■		■		■			■		■		■		■		■
	Arch		■		■		■	■			■	■			■		■	■	

* For deep/long components, SR1 could be acceptable if free-fall height/free-travel distance are controlled (e.g., tremie pipe).

Conclusions

1. SCC mixtures for CIP bridge components can be proportioned with:
   - water-powder ratio 0.37 – 0.44
   - powder content 650 – 760 lb/cy
   - sand-to-aggregate ratio 0.45 – 0.5
   - NMSA 3/4 , 1/2, 3/8 in. (limestone and gravel)
   - SCM/filler: C ash, F ash, GGBFS, Limestone powder
2. The rate of workability loss of SCC mixtures is directly proportional to the initial slump.
3. Time of initial setting of SCC mixtures depends on temperature, SCM/filler, and slump flow.
4. Heat of hydration of SCC mixture is similar to that of CVC, but with slight delay in reaching the peak temperature/energy.
5. Formwork pressure of SCC mixture is less than full hydrostatic pressure depending on the placement rate, thixotropy, and yield stress.

Conclusions

6. ACI 209 adequately predict SCC compressive strength development.
7. AASHTO LRFD slightly overestimates SCC MOE.
8. AASHTO LRFD overestimates SCC splitting tensile strength.
9. AASHTO LRFD adequately predict SCC MOR.
10. SCC has lower bond strength with vertical bars than CVC
11. SCC top bar effect depends on slump flow and could be less than that of CVC.
12. AASHTO LRFD overestimates interface shear resistance for low strength SCC.
13. SCC has similar nominal shear resistance to that of CVC at different reinforcement levels, which can be accurately predicted by AASHTO LRFD.

Conclusions

14. Drying shrinkage of SCC is higher than predicted by AASHTO LRFD and highly depended of the type of SCM/filler used.
15. Restrained shrinkage of SCC is highly depended of the type of SCM/filler used, but not significantly different from that of CVC.
16. Creep coefficient of SCC can be accurately predicted by AASHTO LRFD except SCC mixtures containing LSP (higher creep coefficient).
17. Air void system of SCC is not significantly different from that of CVC. However, variations in HRWRA dosage can result in differences between fresh and hardened conditions.
18. Surface resistivity of SCC is highly depended of the type of SCM/filler used, but not significantly different from that of CVC.

Thank You

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