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Entrained Air-Void Systems for Durable Highway Concrete

October 26, 2021

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Learning Objectives

1. Identify requirements for the air-void system parameters of concrete

2. Discuss innovative test methods for effectively characterizing the air system

Air Void System Requirements for a Durable Paving Concrete

Peter Taylor, Hamed Sadati, John Kevern

Iowa State University
Institute for Transportation

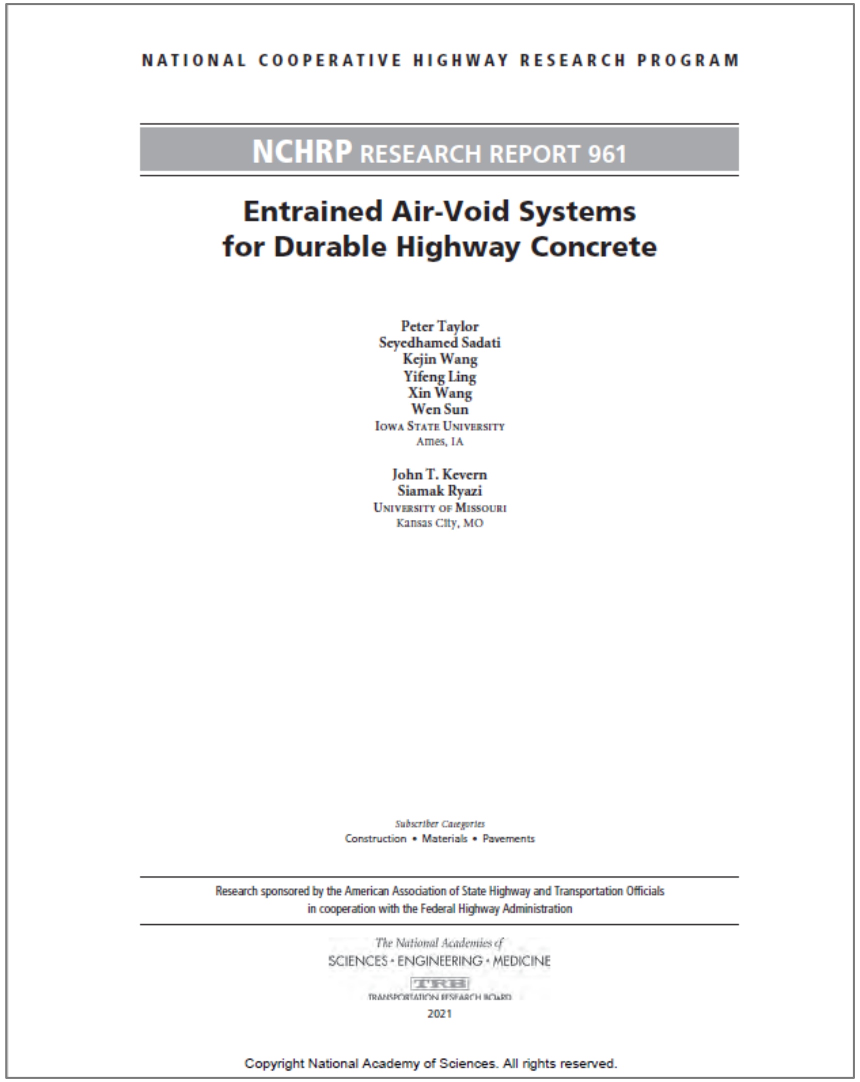
National Concrete Pavement Technology Center
CP Tech Center

Air Void System for F-T Durability…

- NCHRP Research Report 961
- Project 18-17

- Dr Amir Hanna

- Peter Taylor
- Seyedhamed Sadati
- Kejin Wang
- Yifeng Ling
- Xin Wang
- Wen Sun


NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP RESEARCH REPORT 961

Entrained Air-Void Systems for Durable Highway Concrete

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Subscriber Categories
Construction • Materials • Pavements

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2021

Air Void System for F-T Durability…

- Panel
  - Donald J. Janssen (Chair)
  - Mick S. Syslo
  - Darin Hodges
  - Paul D. Krauss
  - James M. Krstulovich, Jr.
  - Patricia I. Baer
  - Tyson D. Rupnow
  - Kenny Seward
  - Ahmad A. Ardani

Air Void System for F-T Durability…

- Objectives
  - Identify the characteristics of the entrained air-void system required for F-T durability of highway concrete
  - Identify and develop new or modified test methods for measuring these characteristics
  - Identify and develop new or modified test methods for evaluating F-T durability

Air Void System for F-T Durability…

- Background
  - A proper air-void system is needed to ensure longevity of pavements in cold weather regions
    - But what is a proper system
    - How do we measure it

Air Void System for F-T Durability…

- Work plan
  - Review performance and properties of field samples
  - Compare data from AVS test methods of a variety of mixtures with different
    - Cement type
    - Fly ash performance
    - AEA type
    - WRA Type
    - Aggregate mineralogy
  - Compare performance of a range of mixtures using alternative test methods

Air Void System Requirements for a Durable Paving Concrete

IOWA STATE UNIVERSITY
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National Concrete Pavement Technology Center
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Air Void System for F-T Durability

Long-term field performance:

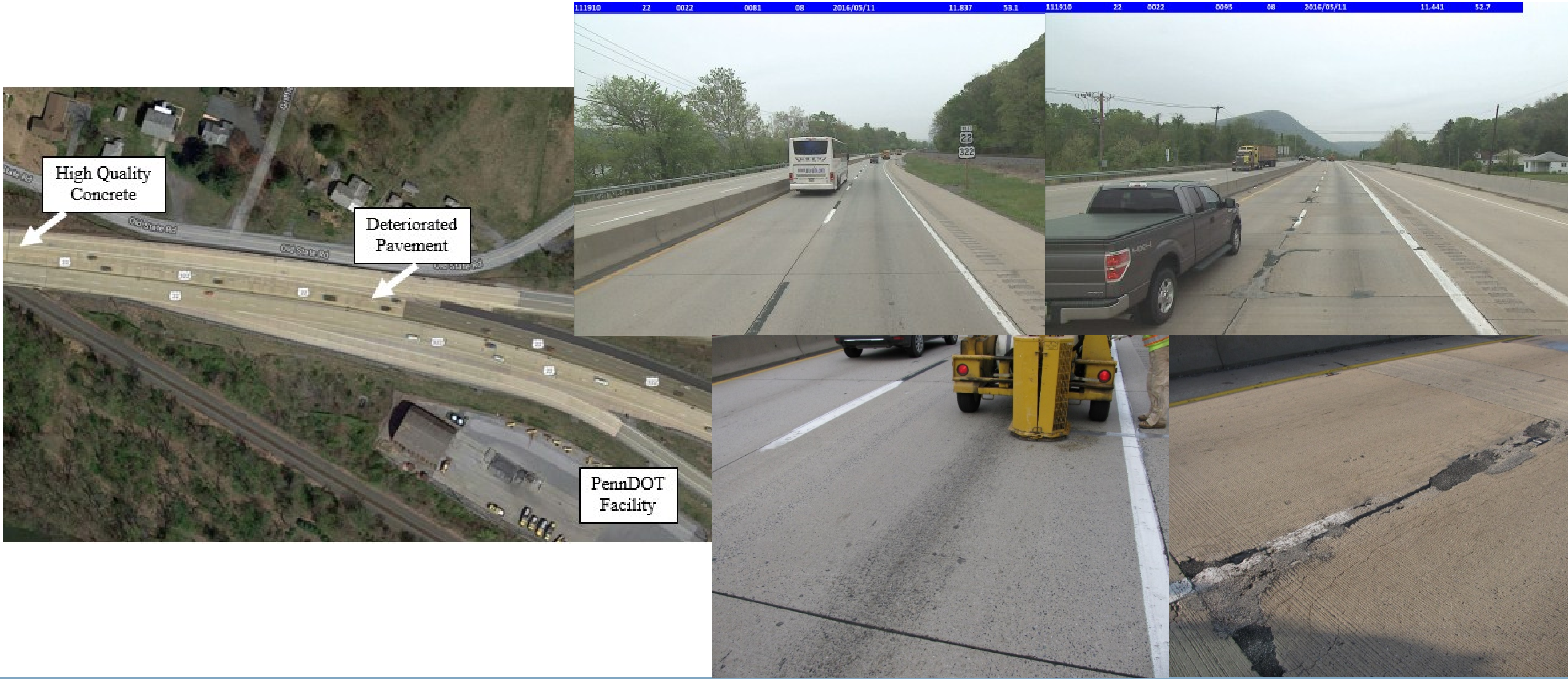
- *What are the hardened air void system properties of the pavements exhibiting good, marginal, and poor durability?*

Laboratory investigation:

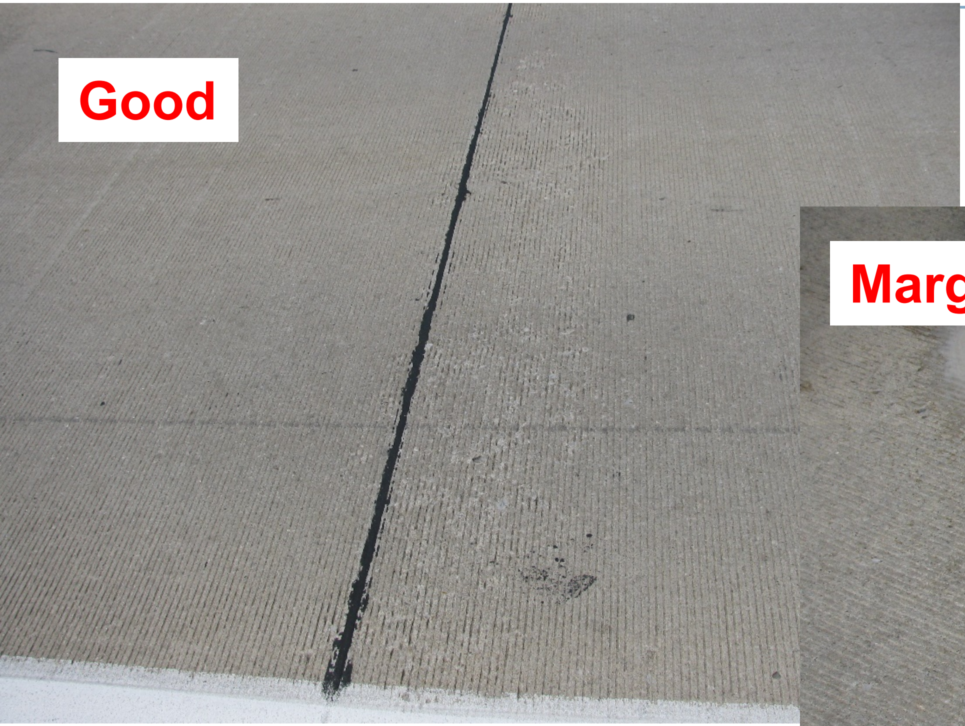
- *What are the correlations between fresh and hardened air void system?*

- *How do these requirements compare to performance in different accelerated F-T tests?*

Field Performance

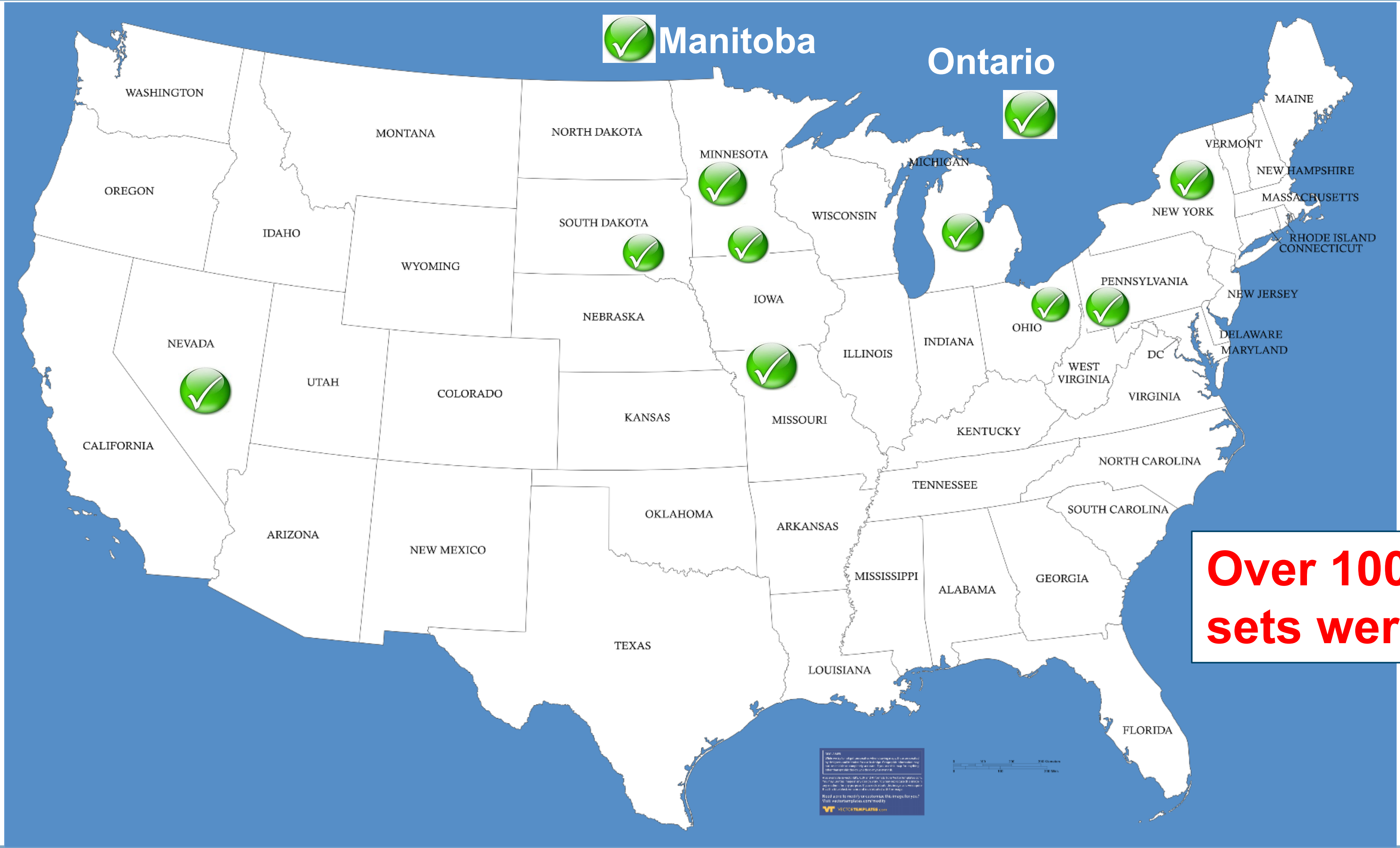


Field Performance



HWY 63, MISSOURI

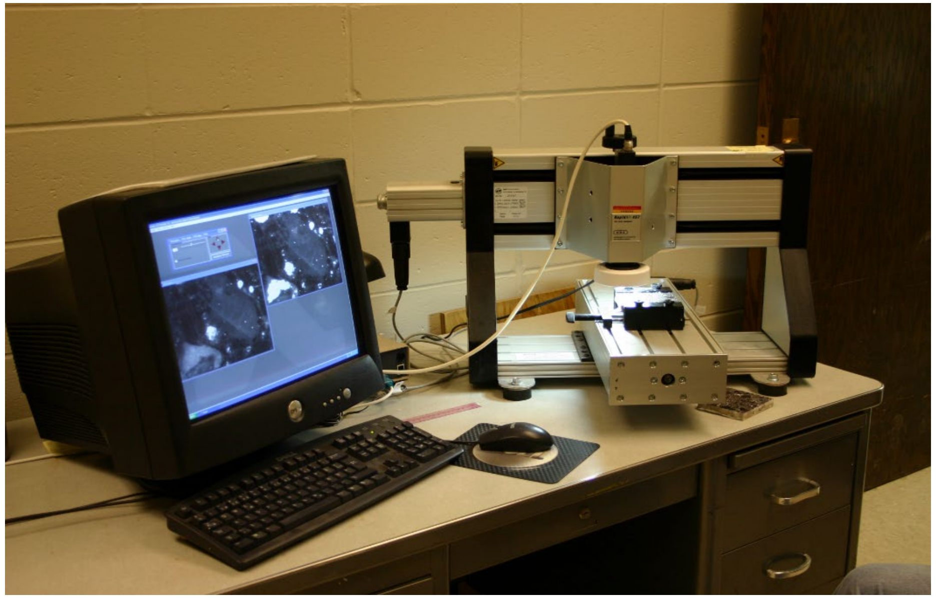
Field investigation…



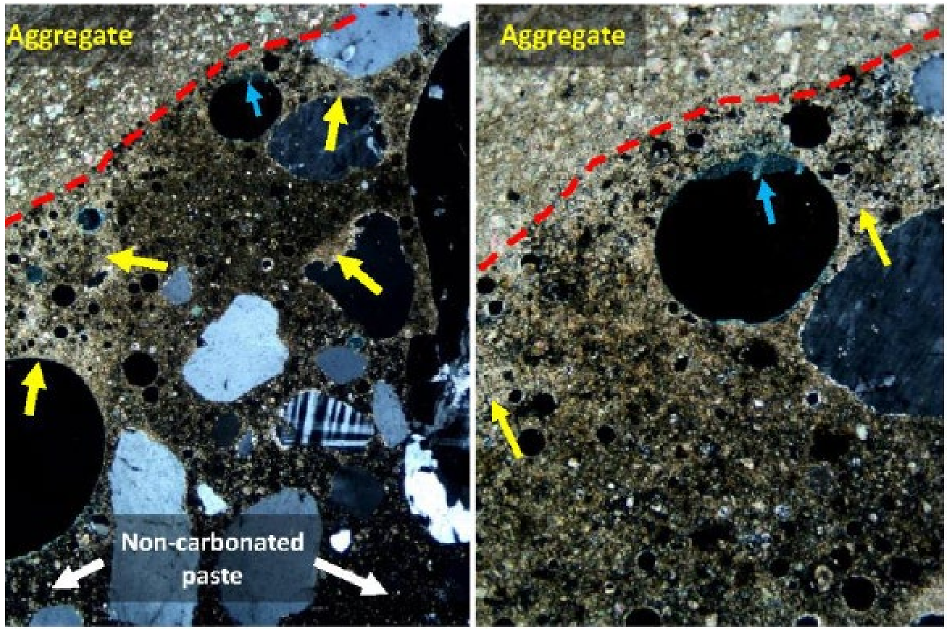
Over 100 cores/data sets were gathered…

For core specimens…

- Test for air void system of hardened concrete
- Petrography (selected samples)



Rapid Air



Petrography

Air Void System for F-T Durability…

Expected performance based on hardened air void system…

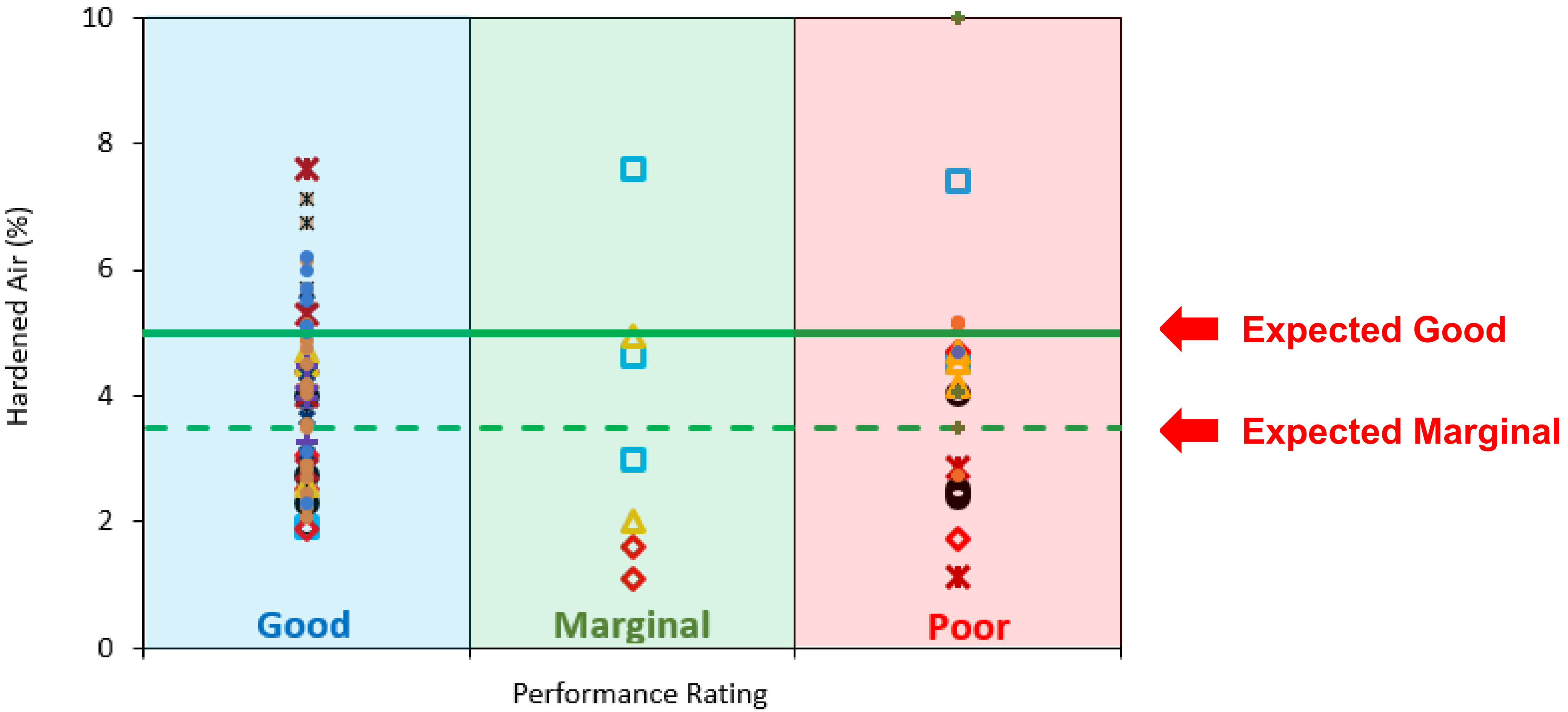
Property	Hardened Air (%)	Spacing Factor (in.)	Specific Surface (in.$^{-1}$)
Good	> 5.0	<0.008	>600
Marginal	3.5 – 5.0	0.008-0.011	400-600
Poor	<3.5	>0.011	<400

ACI 201 recommendations & STD/COV values from ASTM C457

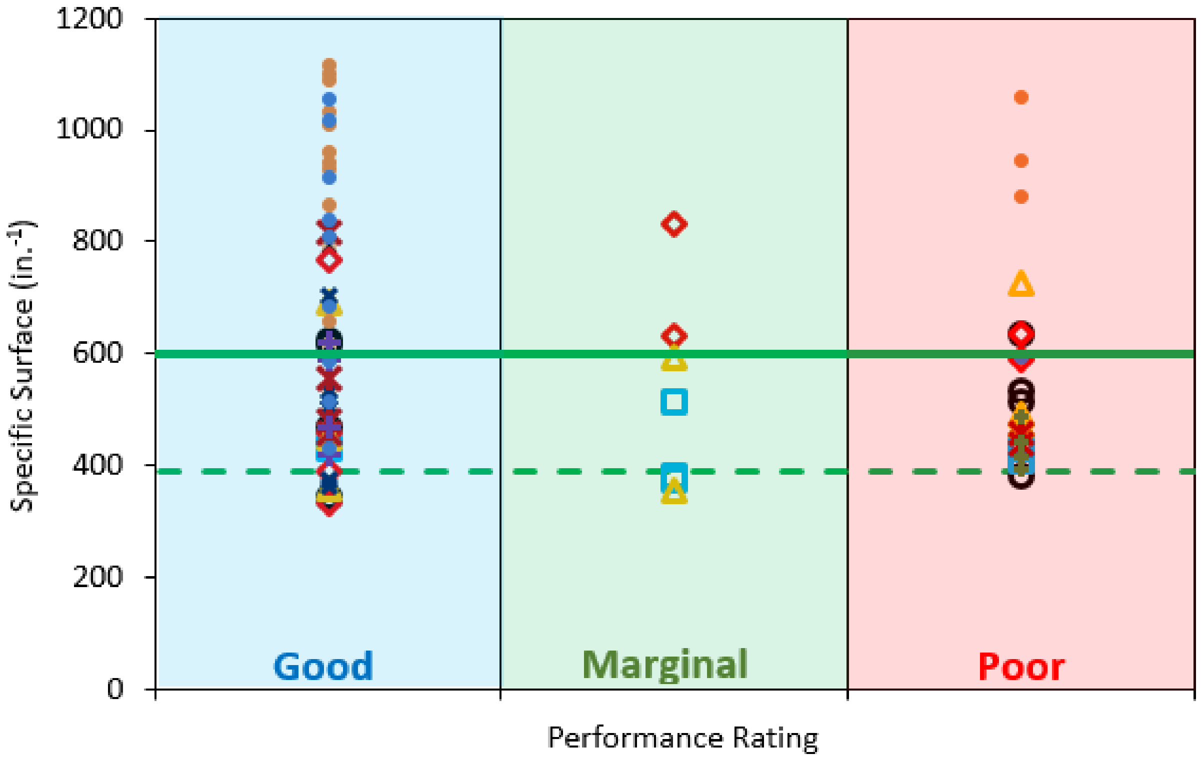
Performance Rating

Geographic Location	Core #	Type of Distress	Scaling Rating (ASTM C672)	Overall Performance
Pennsylvania	1-E	F-T, D-Cracking, Scaling	3	Poor
	3-E	F-T, D-Cracking, Scaling	3	Poor
	4-E	F-T, D-Cracking, Scaling, ASR	3	Poor
	5-E	F-T, D-Cracking, Scaling	3	Poor
	1-C	Abrasion, Scaling	2	Good
	2-C	Abrasion, Scaling	2	Good
	4-C	Abrasion, Scaling, ASR	2	Good
	5-C	Abrasion, Scaling	2	Good
New York	5	Scaling	2-3	Good
	6	Scaling	2-3	Good
	7	Scaling	2-3	Good
	8	Scaling	2-3	Good
	9	Scaling	2-3	Good
Nevada	3	F-T, D-Cracking, Scaling, ASR	2	Poor
	5	F-T, D-Cracking, Scaling	2	Marginal
	6	F-T, D-Cracking, Scaling, ASR	2	Marginal
	7	F-T, Scaling	2	Good
Missouri	1	F-T, D-Cracking, Scaling, ASR, ACR	1-2	Poor
	2	F-T, Scaling	1-2	Marginal
	3	F-T, Scaling, ASR, ACR	1	Good
	4	F-T, Scaling	1-2	Good
	5	F-T, Scaling	2-3	Poor
	6	F-T, Scaling	1	Good
	7	F-T, Scaling	1	Good

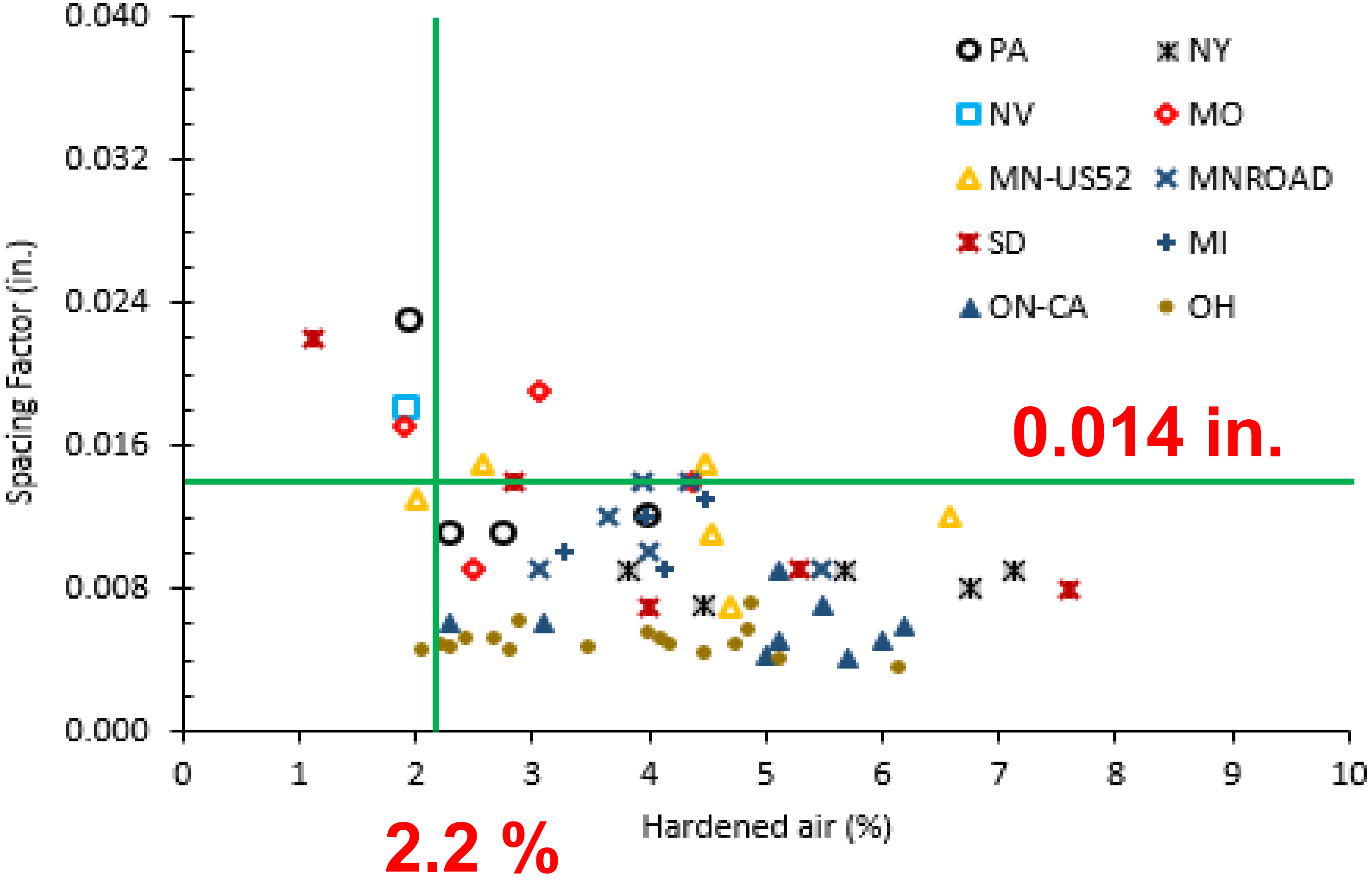
Performance Rating vs. Hardened Air



Performance Rating vs. Specific Surface

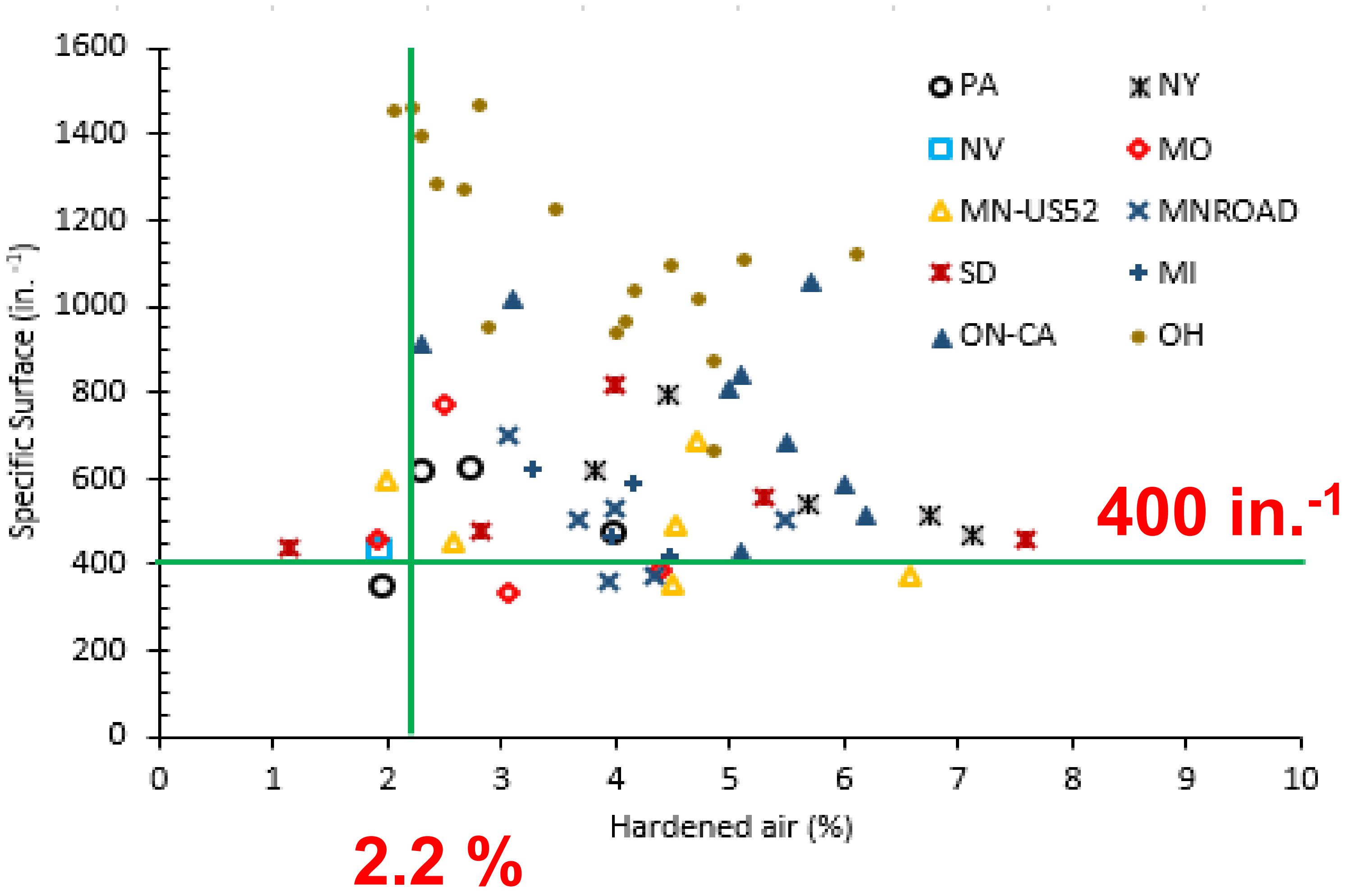


F-T Durable Pavements…



S.F. vs. Air for pavements with good durability

F-T Durable Pavements…



S.S. vs. Air for pavements with good durability

Initial Results…

Majority of pavements with acceptable durability:

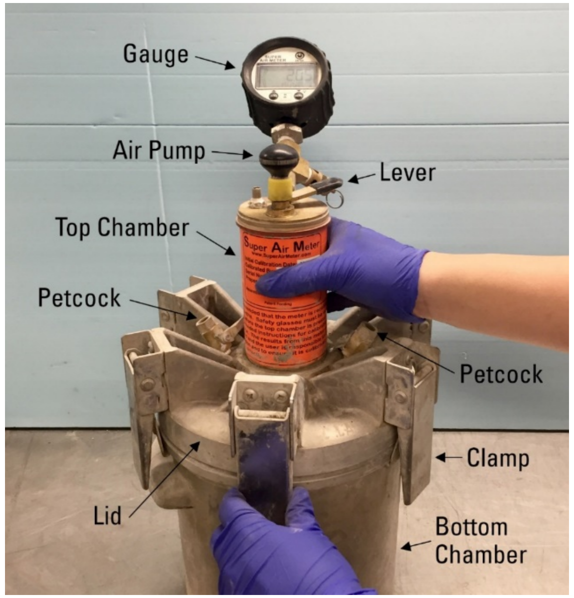
- Hardened air content higher than 2.2%
- Spacing factor lower than 0.014 in.
- Specific surface higher than 400 $in.^{-1}$

In Laboratory…

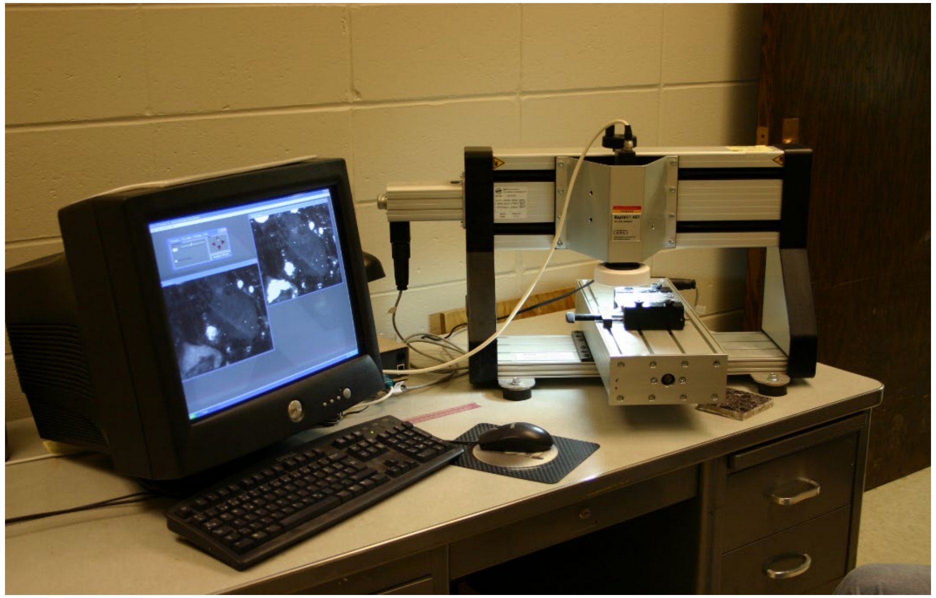
Factor	Variant	# of variants	Total combinations
Cement Type	Low-alkali (LA)	3	**144 combinations for full parametric study**
	High-alkali (HA)		
	Type IL portland-limestone (TIL)		
SCM Type	Low-quality fly ash	3	
	High-quality fly ash		
	Natural pozzolan		
AEA	Stable (S)	2	
	Unstable (U)		
WRA	Compatible (C)	2	
	Incompatible (I)		
Design Fresh Air	Low (L)	2	
	High (H)		
Fine Aggregate	River sand (S)	2	
	Manufactured sand (M)		
Coarse Aggregate	Crushed limestone (L)	1	

In Laboratory…

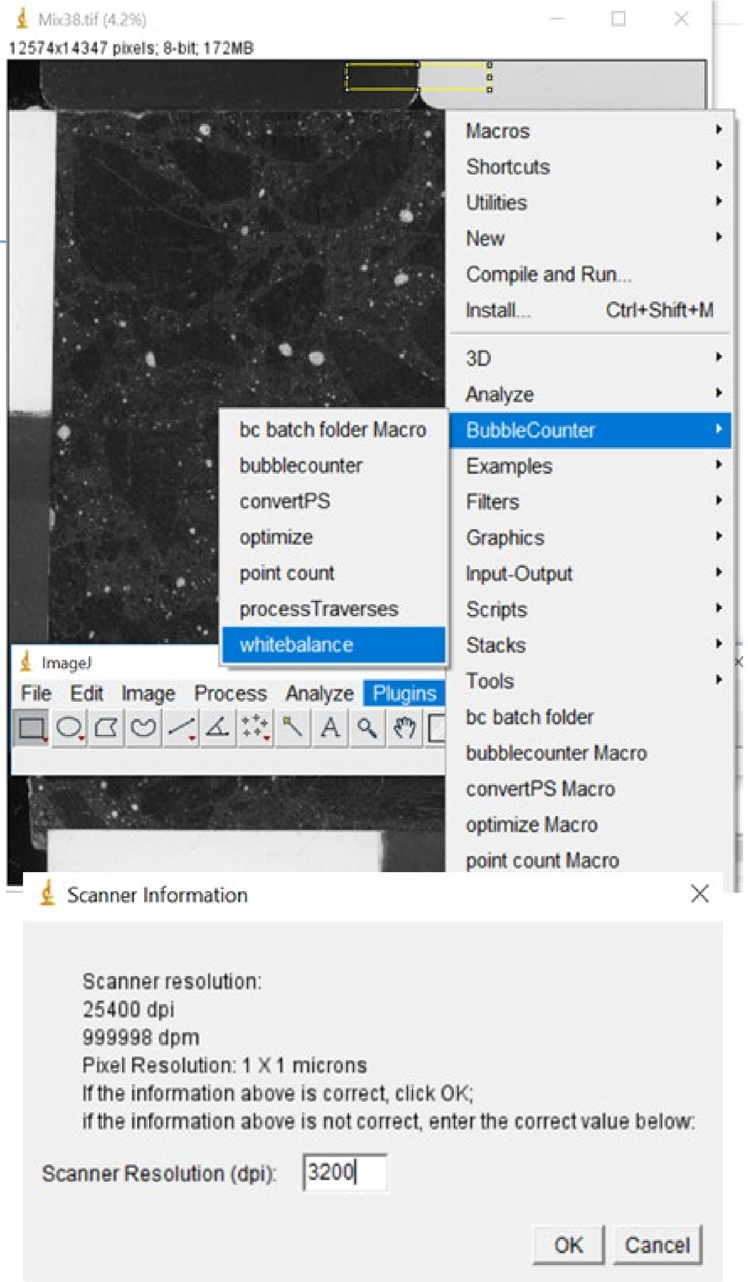
- Develop 144 mixtures
- Test for air void system in fresh state
- Test for air void system of hardened concrete



SAM Testing

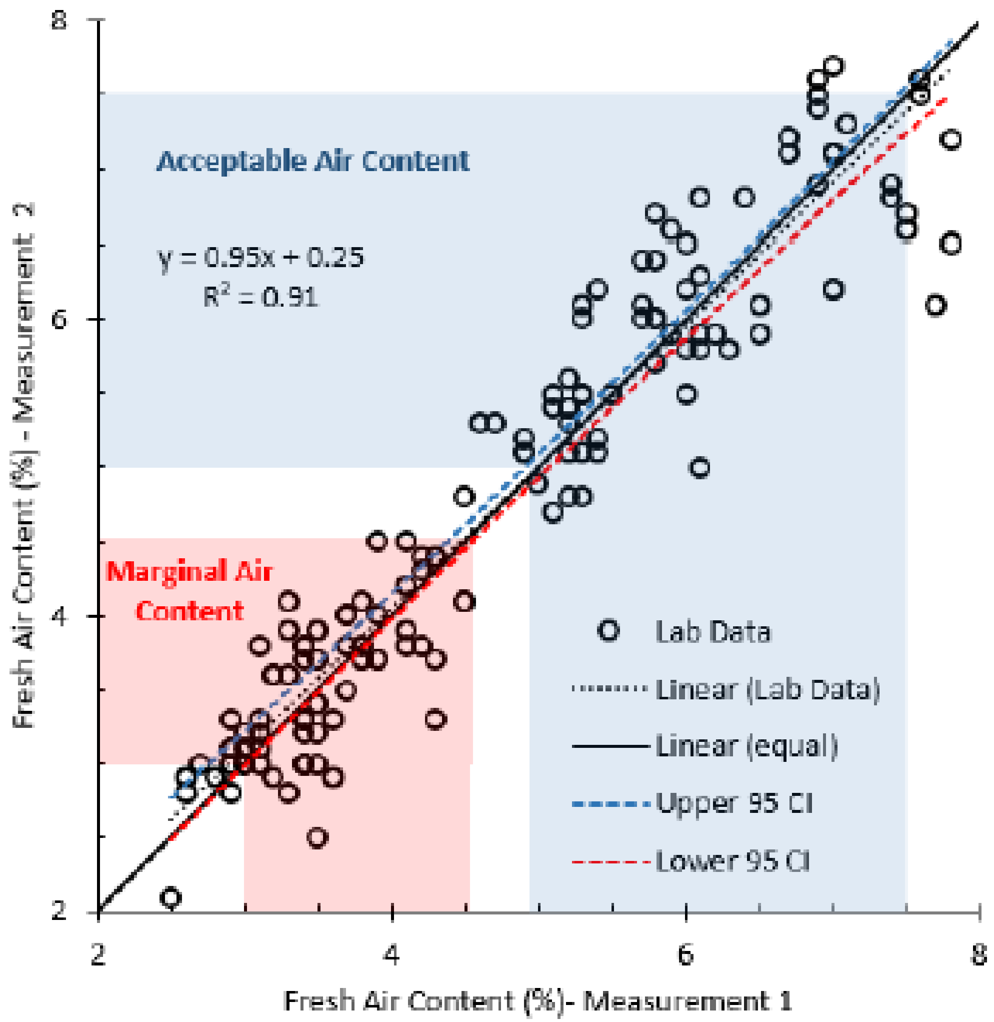


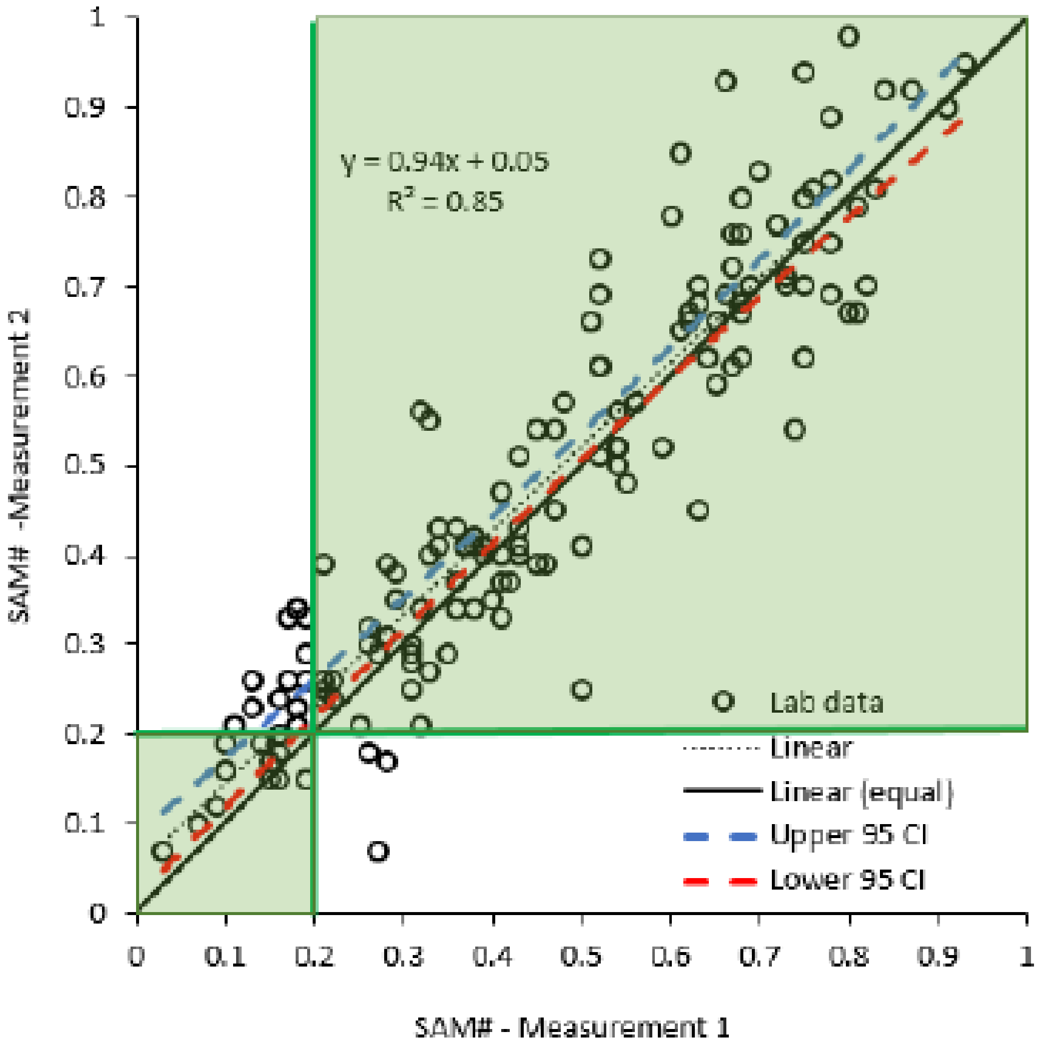
Rapid Air



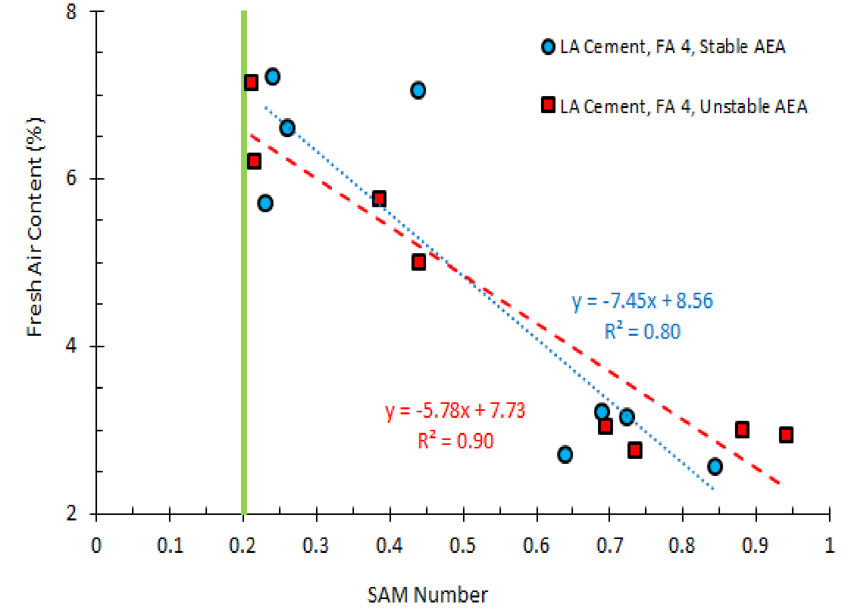
Flatbed Scanner

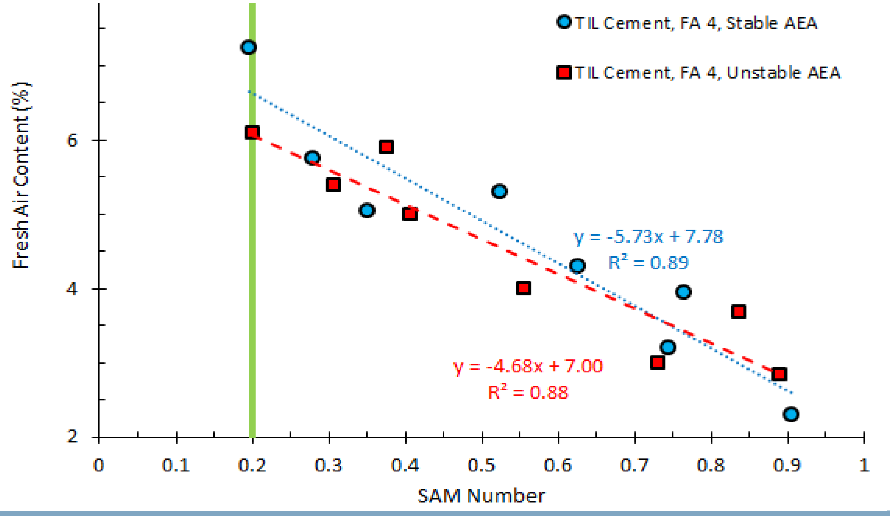
Measurement; Fresh Concrete

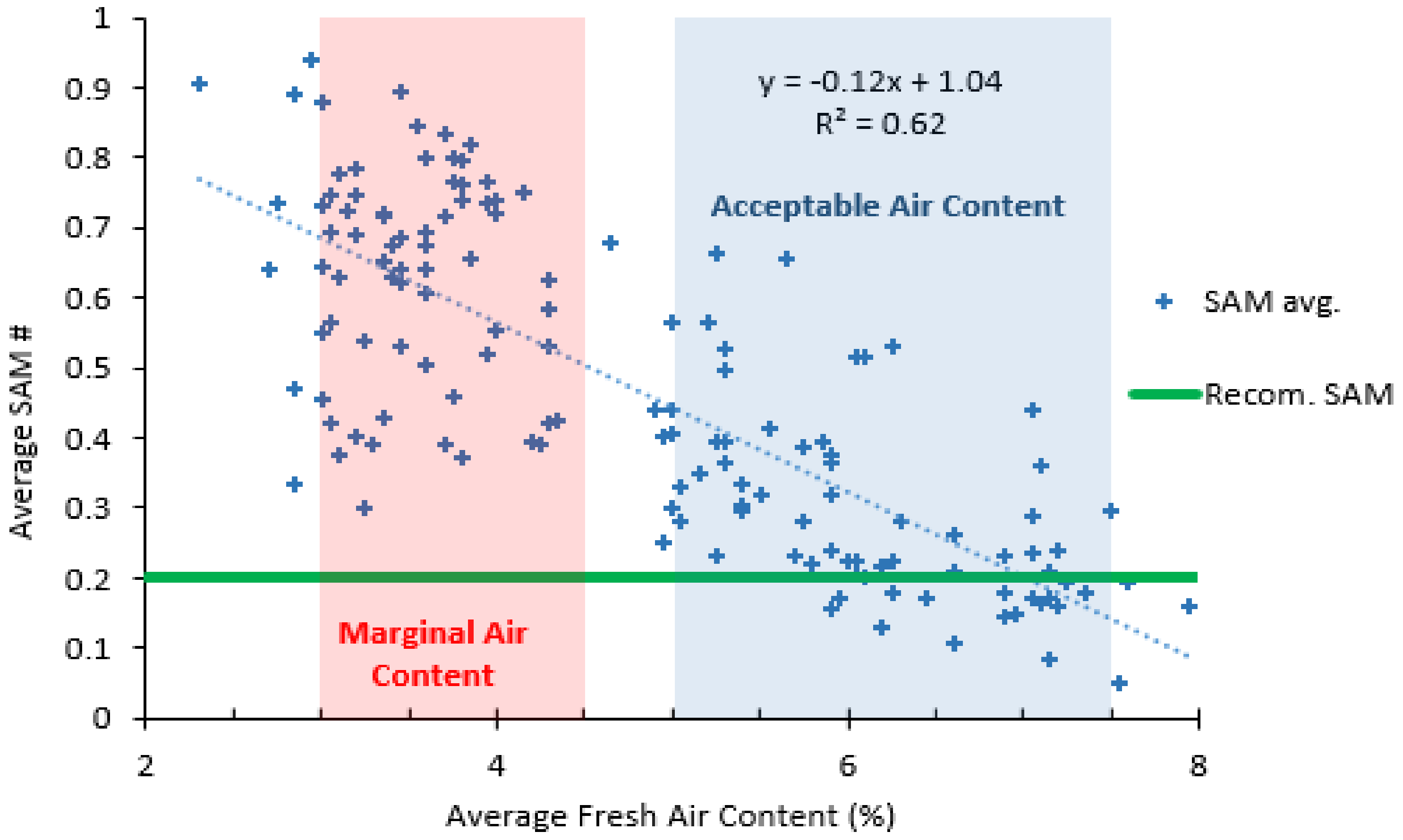




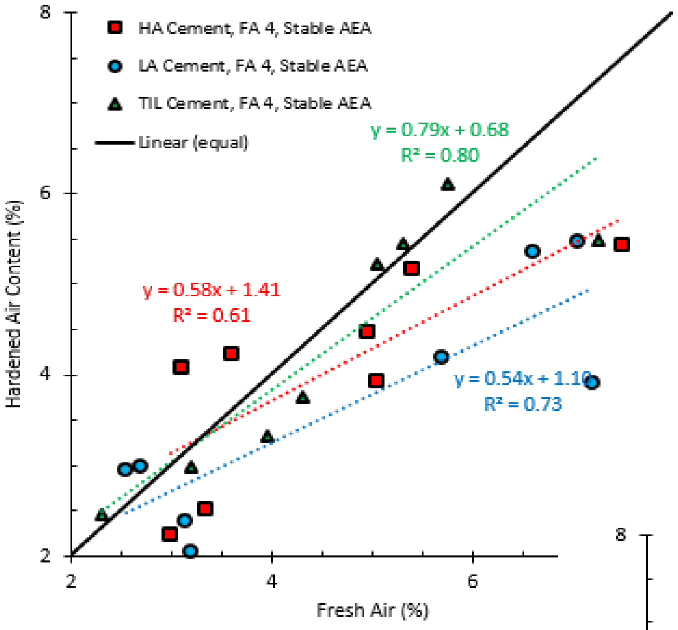
SAM vs. Fresh Air…

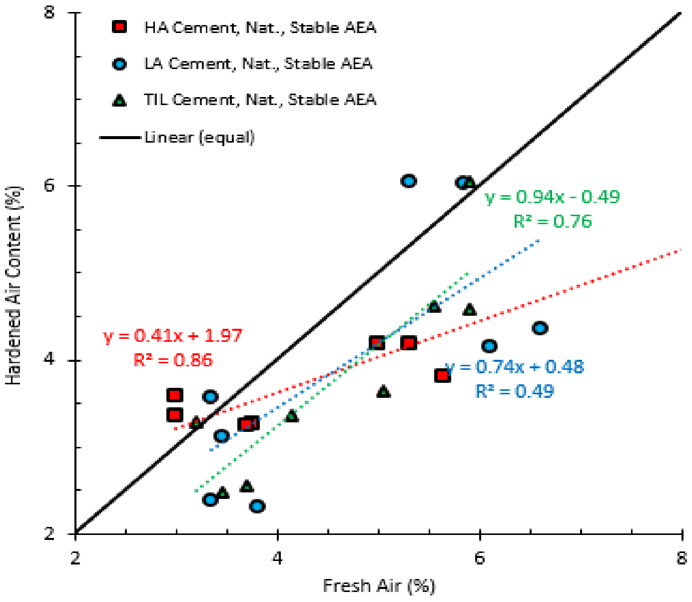


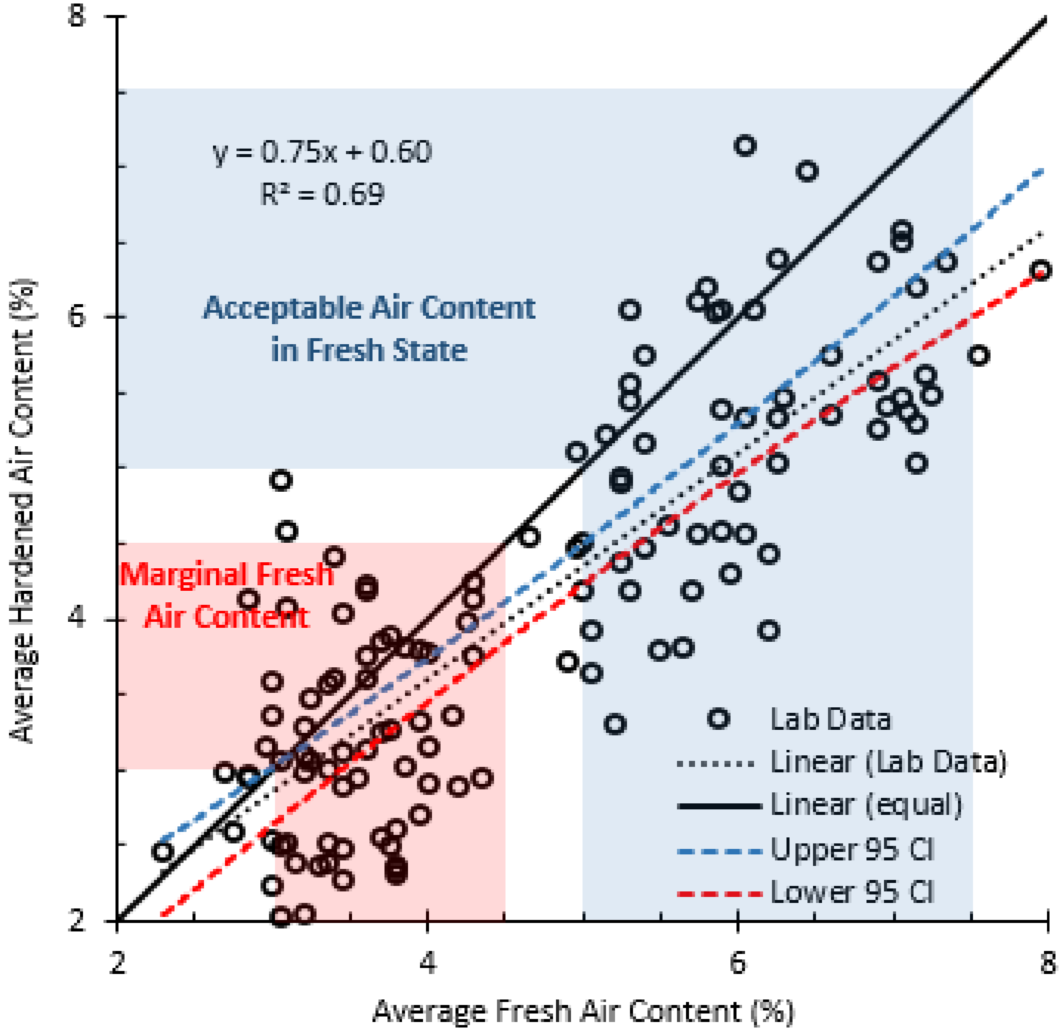




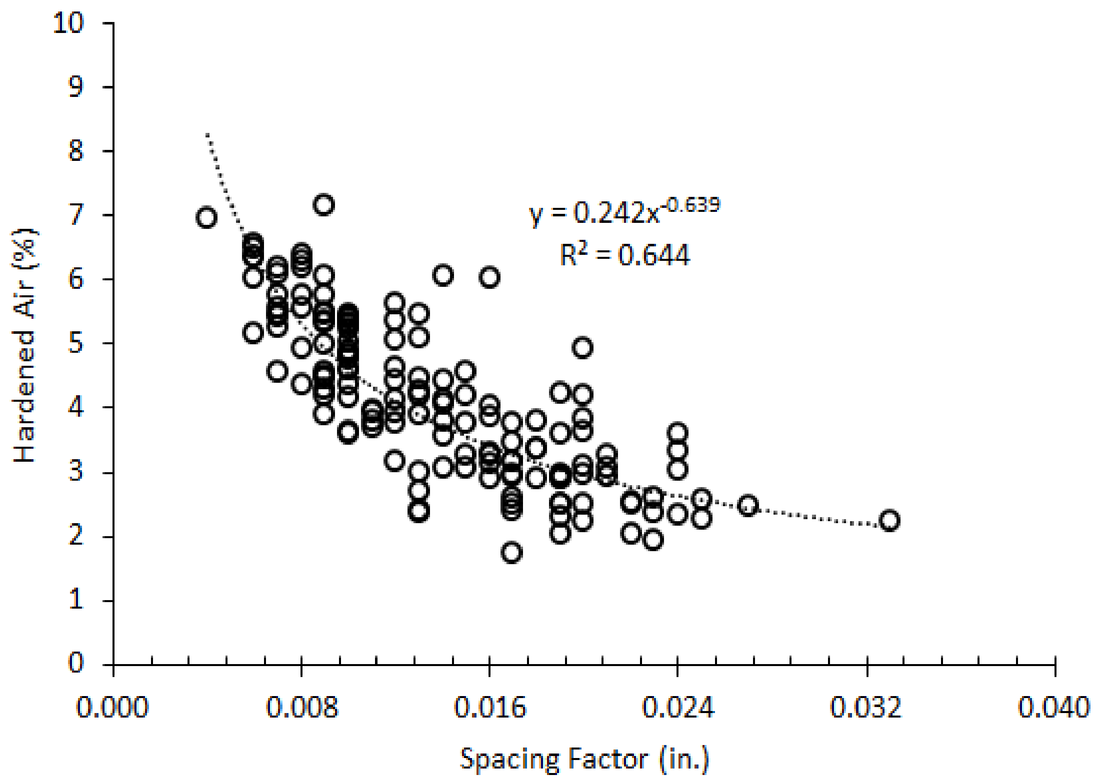
Fresh vs. Hardened

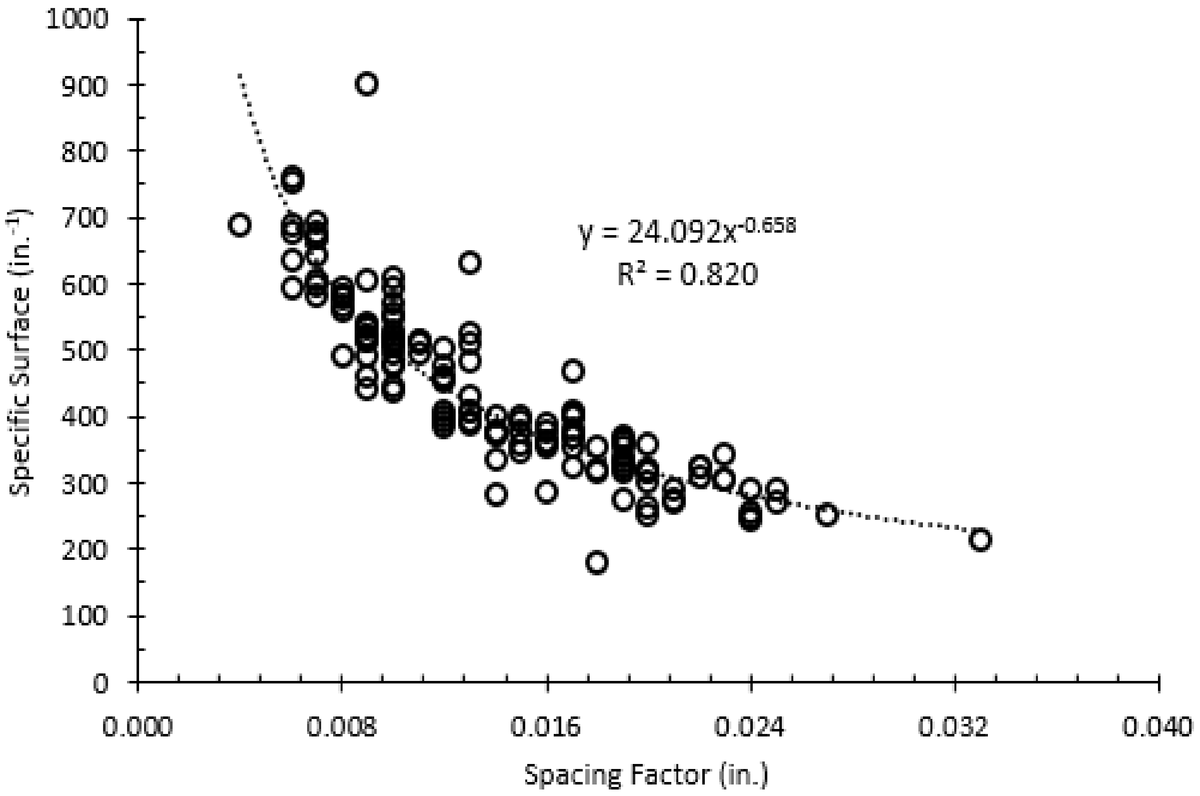




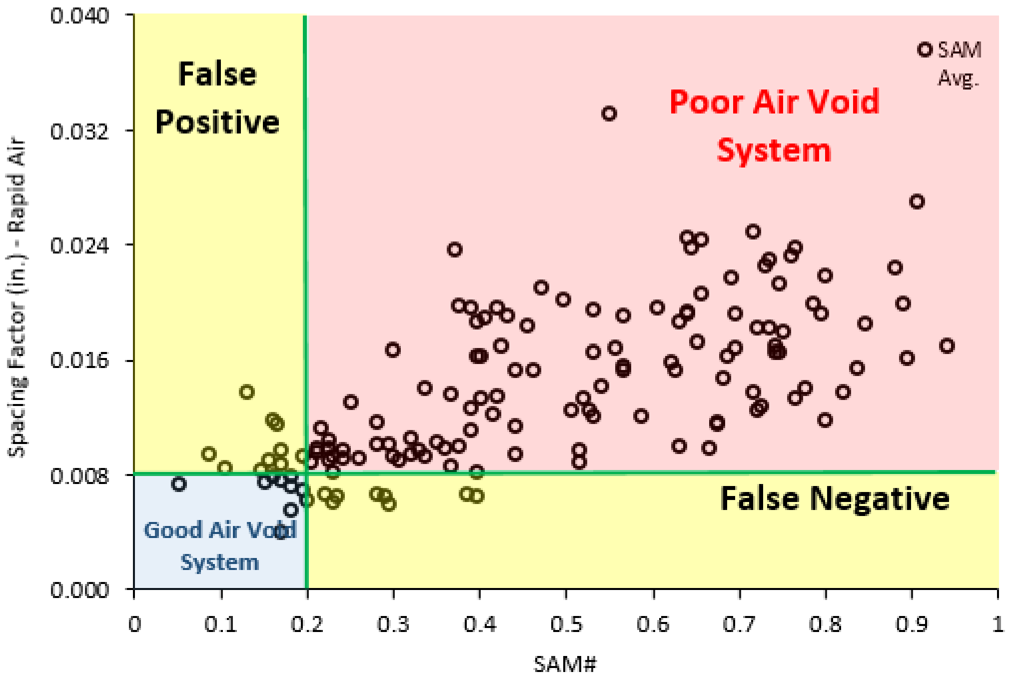


Hardened Air Void System

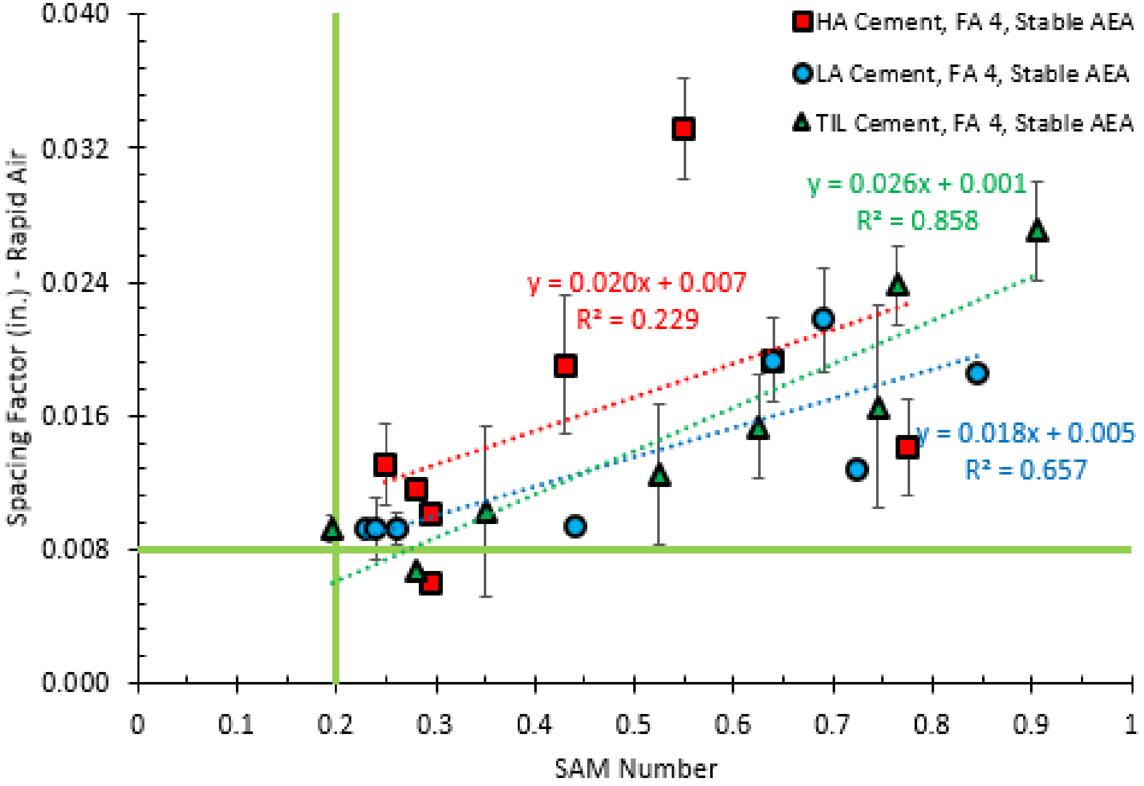




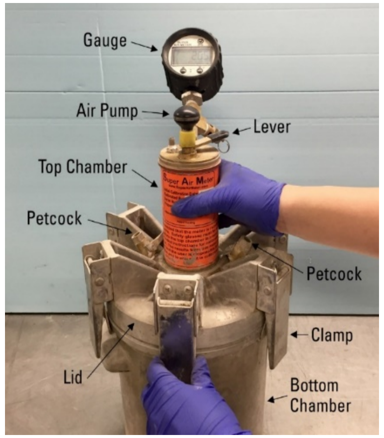
Fresh vs. Hardened



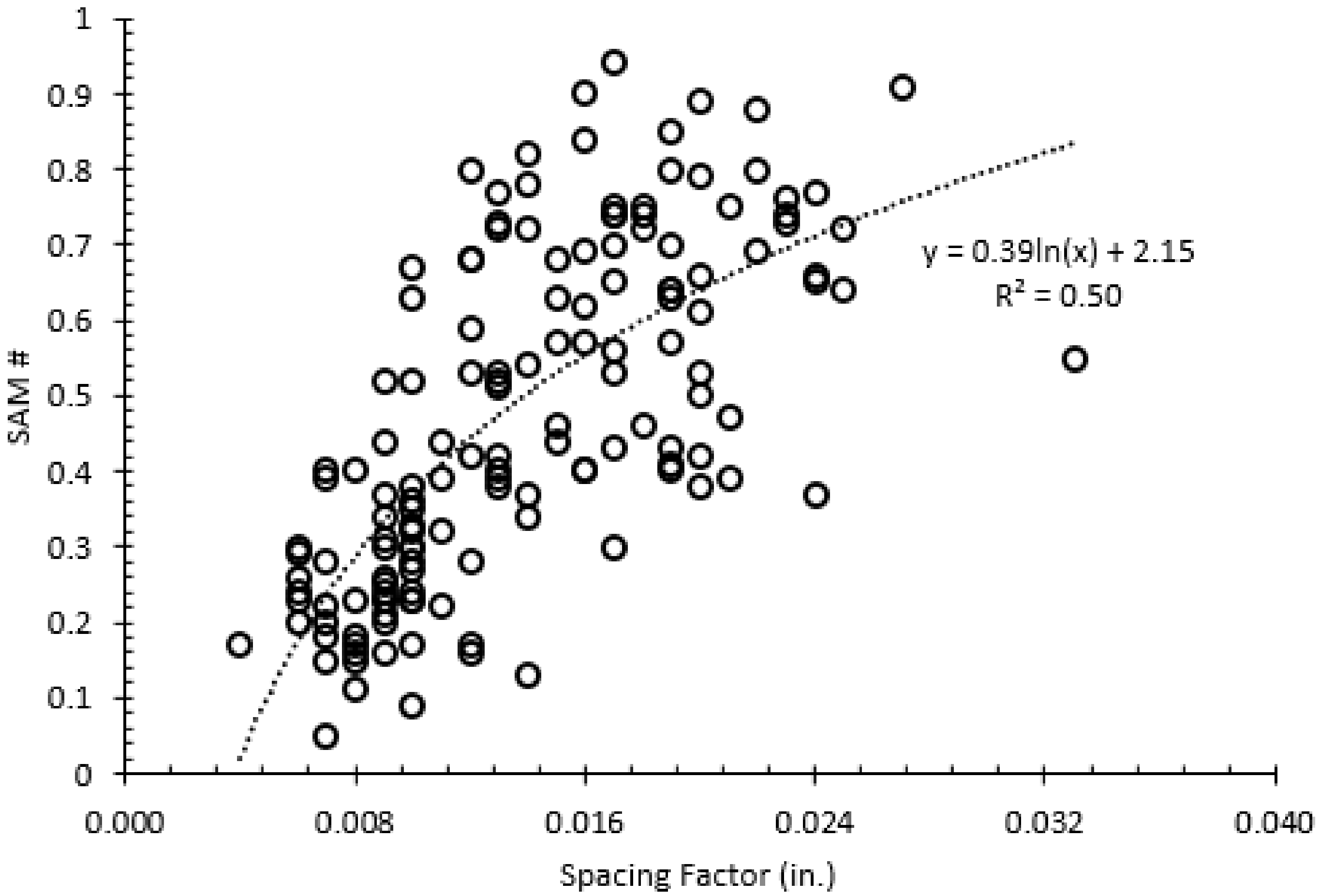
SAM Limit	Good Air Agreement	Poor Air Agreement	False Negative	False Positive
0.20	7 (5%)	116 (81%)	9 (6%)	12 (8%)
0.25	11 (8%)	105 (73%)	5 (3%)	23 (16%)
0.30	14 (10%)	100 (69%)	2 (1%)	28 (19%)
0.35	14 (10%)	92 (64%)	2 (1%)	36 (25%)
0.40	16 (11%)	79 (55%)	0 (0%)	49 (34%)

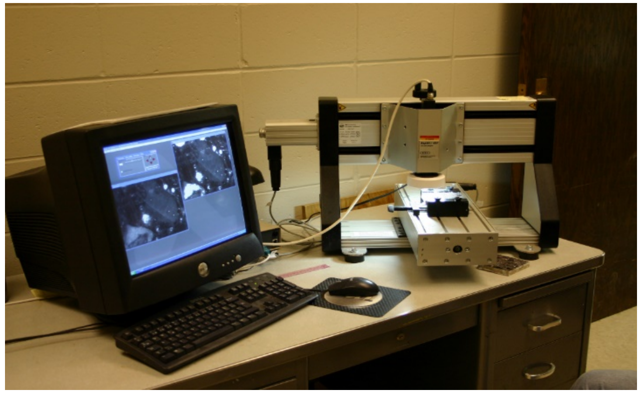


Fresh vs. Hardened



Minutes to finish...





More time/cost

From Laboratory…

Based on average laboratory measurements:

- Hardened air content: STD = 0.6 %
- Spacing factor: STD = 0.0026 in.
- Specific surface: STD = 64 in.$^{-1}$
- SAM: STD = 0.05

Combining Field & Lab

Spacing factor

- Maximum = 0.014 – 0.0026 = **0.0114 in.**

Specific surface

- Minimum = 400 + 64 = **464 in.$^{-1}$**
- Spacing factor of 0.0114 in. corresponded to 460 in.$^{-1}$

Hardened air

- Minimum hardened air content = 2.2 + 0.6 = 2.8%
- Spacing factor of 0.0114 in. corresponded to **4.2 % air**

Combining Lab & Field

SAM number

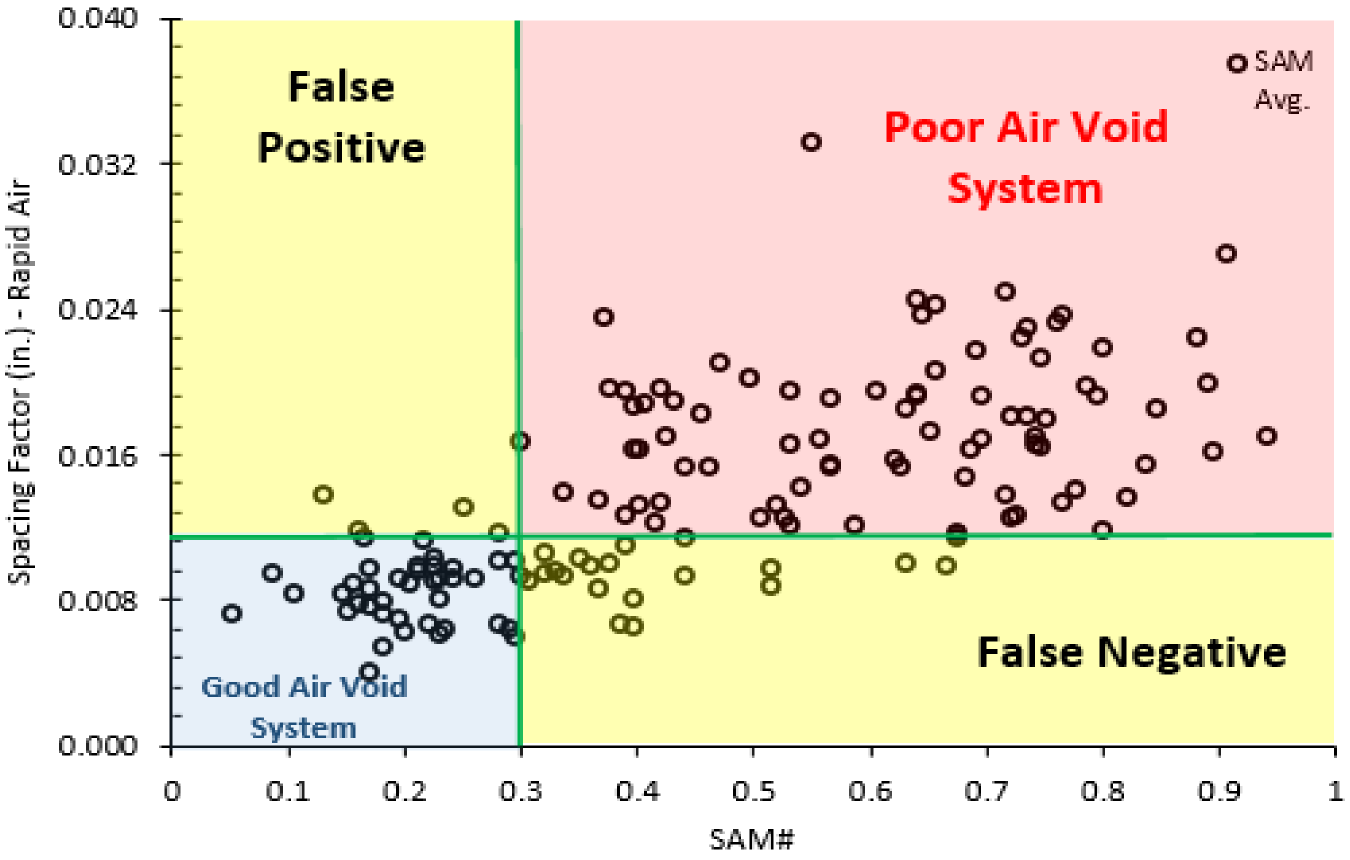
- Spacing factor of 0.0114 in. corresponded to SAM number of 0.42

Considering a safety factor equal to 2 STD (i.e., 2 × 0.05 = 0.10) for the SAM number ensures a 95% confidence interval.

- Maximum SAM number = 0.32 rounded to **0.30**
- Minimum fresh air = ~5%

SAM vs. Spacing Factor

- False negative: 13%
- False positive: 3%
- Agreement-good air-void system: 28%
- Agreement-poor air-void system: 56%
- Total agreement: 84%



Summary

- Minimum fresh air: 5.0%
- Maximum SAM number: 0.30
- Minimum hardened air: 4.5%
- Maximum spacing factor: 0.011 in.
- Minimum specific surface: 475 in.$^{-1}$

Maybe need to think again about the minimum AVS requirements…

Summary & Conclusions

- Quite challenging to identify pavements that only suffer from air void system. Air is not the only contributor…
- Field observations highlight the importance of transport properties and aggregate stability on F-T durability of pavements
- Premature joint distress is a major contributor
- Cut-off limits of 0.008 in. and 600 in.$^{-1}$ for the spacing factor and specific surface might be a bit too much

Acknowledgements

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- Dr. Tyler Ley, Oklahoma State University
- Dr. Larry Sutter, Michigan Technological University

Air Void System Requirements for a Durable Paving Concrete – Freeze-Thaw Evaluation

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Institute for Transportation

National Concrete Pavement Technology Center
CP Tech Center

Air Void System for F-T Durability

Laboratory investigation:

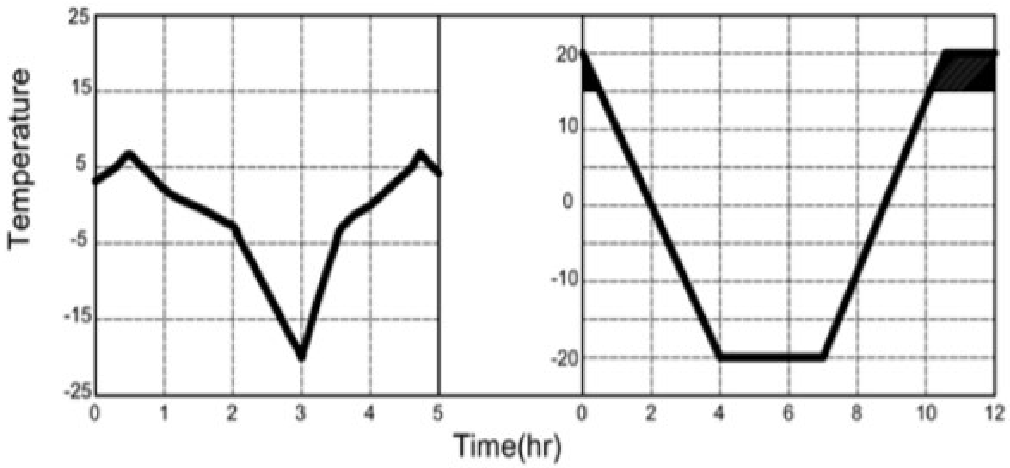
- *What are the correlations between fresh and hardened air void system?*
- *How do these requirements compare to performance in different accelerated F-T tests?*

Test	Specifications				Specifications (continued)			Evaluation
Method	State of test method	Sample condtioning	Testing environment	Testing fluid	Cooling Rate/Time	Heating	No. of	Evaluation
AASHTO T161; ASTM C666:A[15]	Current	14 days limewater	Saturated at ambient pressure for both freezing and thawing; "B" Saturated thawing, drained freezing	Tap Water (TW)	4.4° to -18°C, <75% of total time	-18° to 4.4°C, 2–5 hrs, >25% of total time	300	Internal damage/Dilation
ASTM C666:B[15]	Current				4.4° to -18°C, <80% of total time	-18° to 4.4°C, 2–5 hrs, >20% of total time	300	Internal damage/Dilation
ASTM C666:C	Formerly proposed				4.4° to -18°C, <80% of total time	-18° to 4.4°C, 2–5 hrs, >20% of total time	300	Internal damage/Dilation
SHRP-C-391[26]	Formerly proposed			3% NaCl	4.5° to -18°C, <75% of total time	-18° to 4.4°C, 2–5 hrs of total time	300	Internal damage/Dilation
ASTM C292[27]	Withdrawn 1965			Brine/ TP	23° to -18°C, 16° to 15°C/hr	-18° to 23°C, 18–24 hrs	100 brine/ 200water	Internal damage/Dilation
KTMR-22[28]	Current	67 days 100% relative humidity, 21 days 50% relative humidity, 24 hrs tap water at 70°F, 24 hrs tap water 40°F	Saturated at ambient pressure for thawing, frozen in drained condition	TW	4.4° to -18°C, <80% of total time	-18° to 4.4°C, 2–5 hrs, >20% of total time	660	Internal damage/Dilation
ASTM C310[29]	Withdrawn 1964	14 days limewater	Saturated at ambient pressure for thawing, frozen in drained condition	TW	4.4° to -18°C, -14.6° to 13.3°C/hr	-18° to 4.4°C, 5–7 hrs	300	Internal damage
ASTM C671[30]	Withdrawn 2003	14 days limewater, then maintained at 35°F	Saturated during freezing, thawed at 35°F	TW	23° to -17.5°C/hr, hold 8 hrs	NA	Until dilation constant	Mass and Dilation
ASTM C672[31]	Current	14 days 100% relative humidity, 14 days 50% relative humidity	Saturated at ambient pressure for both freezing and thawing	4%	-18°C for 16–18 hrs	23°C for 6–8 hrs	50	Surface scaling/ Mass
RILEM TC 117-FDC[32]	Current	0–24 hrs cured in molds covered with plastic, 24 hrs–7 days place in tap water bath @ 68°F, 7–21 days drying @ 68°F 50% RH, 21–26 days sealed with foil tape	Capillary suction, 5 sealed sides, 1 open side with ~1/4 in. solution level	3%,TW	20° to -20°C in 4 hrs; -20°C for 3hrs.	-20° to20°C, 4 hrs; 20°C 1 hr	28	Mass/Surface scaling
RILEM TC 117-FDC[32]	Current			3%,TW			28	Internal damage/ surface scaling
RILEM TC 176-IDC[33]	Current		Deicer scaling	3%			28/56	Internal damage/ surface scaling

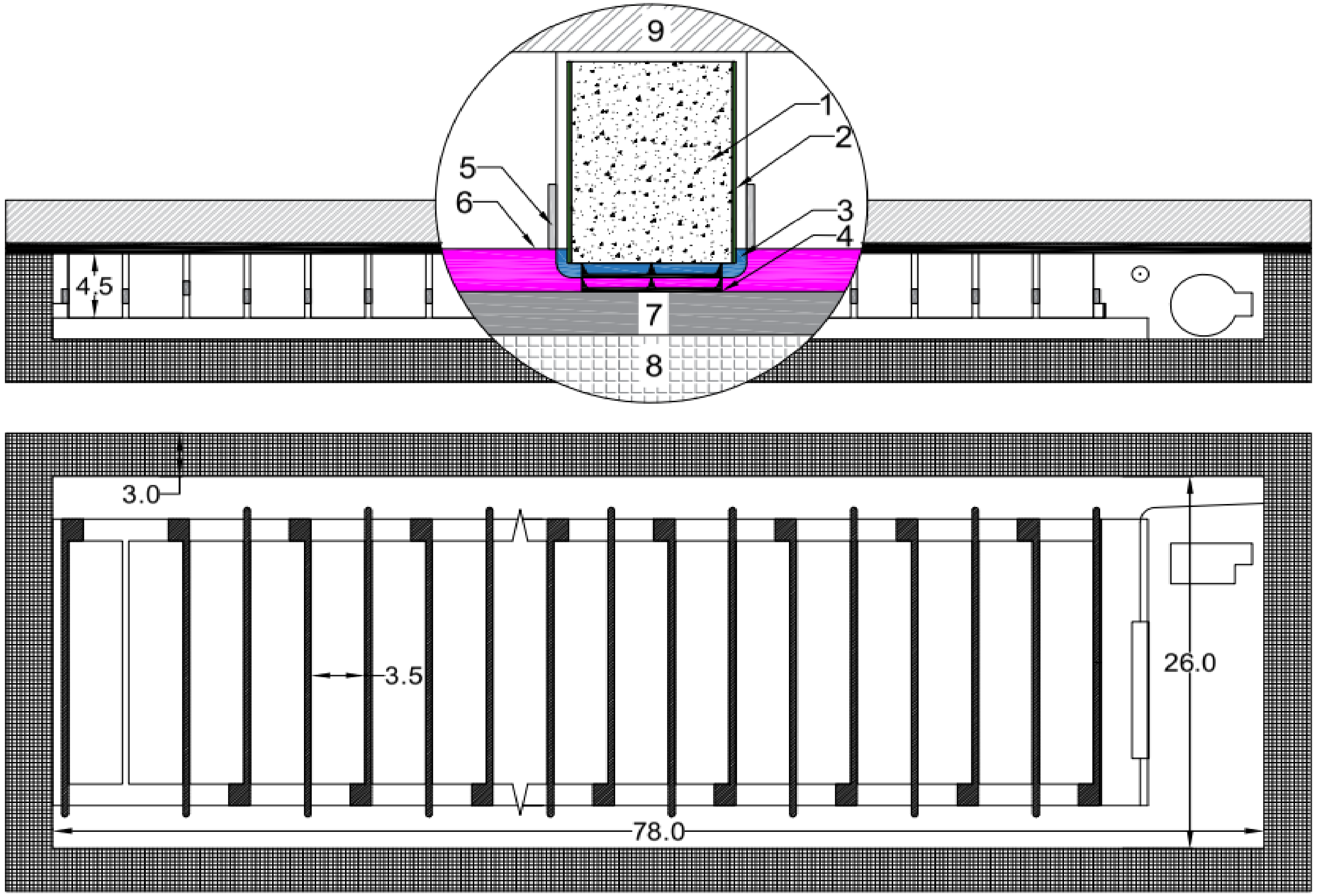
Damage Mechanisms

- Cooling Rate
- Time at Freezing Temperatures
- Number of cycles
- Age/Initial Conditioning
- Degree of Saturation
- Freezing Fluid

Figure 1: Typical FT cycle in ASTM C666(left) and RILEM (right) adopted after19,16

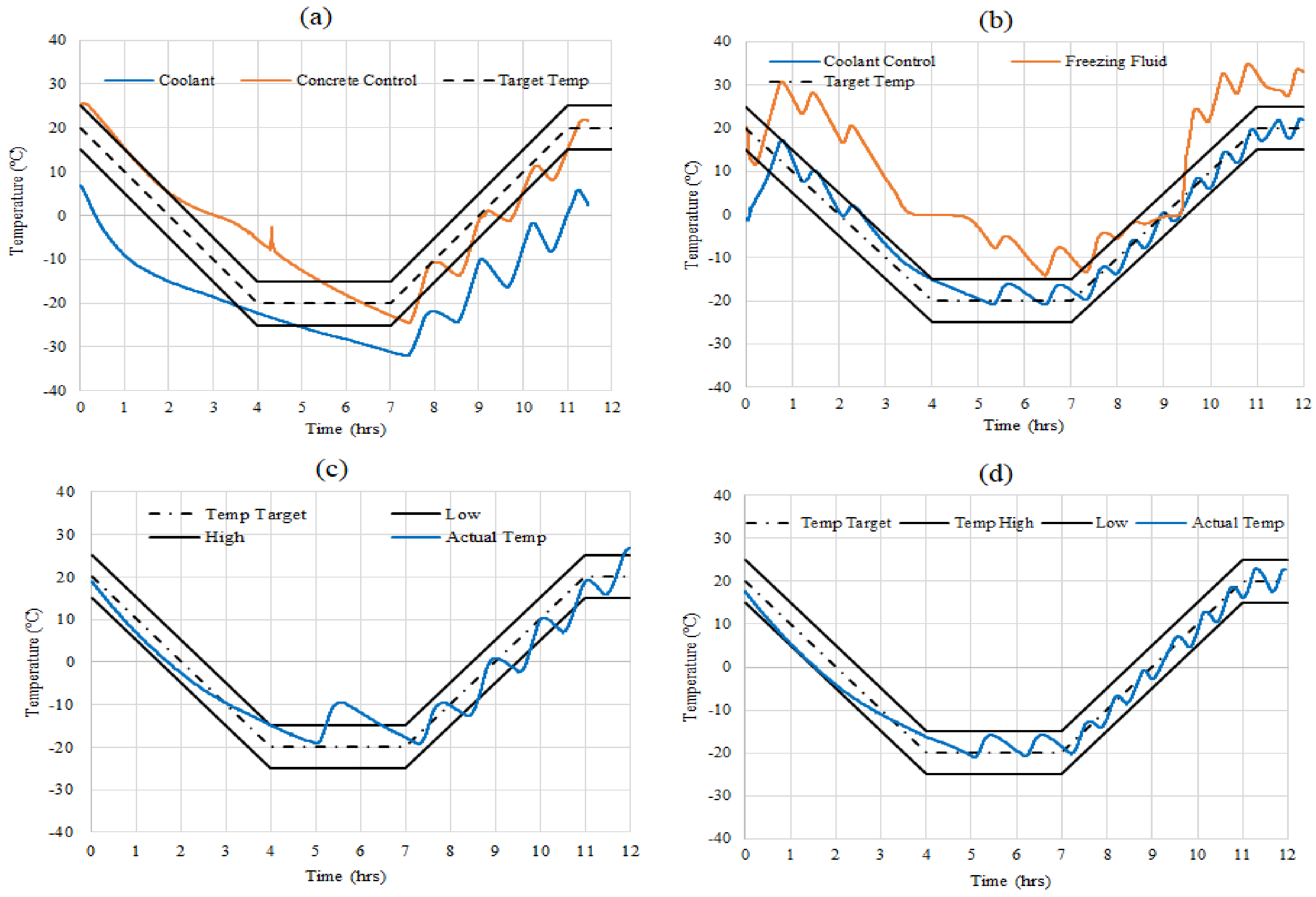


Developed Test Method - CDF



1-	Concrete specimen	4-	ABS plastic stand	7-	Cooling plate
2-	Aluminum tape	5-	Heating bar	8-	Isolated base
3-	Testing fluid	6-	Testing fluid	9-	Isolated Lid

AASHTO T161 A - Equipment Tuning



Anticipated F-T Performance

Table 25. Air system values used for rating expected freeze–thaw performance.

Characteristic Parameter	Rating		
	Good	Marginal	Poor
Fresh Air Volume (%)	> 5%	4%–5%	< 4%
SAM Number	< 0.30	0.30–0.40	> 0.40
ASTM C457 Total Air Volume (%)	> 4.5%	3.5%–4.5%	< 3.5%
ASTM C457 Spacing Factor	< 0.0114	0.0114–0.0140	> 0.0140

Note: Values of fresh air content are based on ACI 201 (2016) recommendations for mixtures made with crushed aggregates. For mixtures prepared with rounded aggregates, the air content can be lowered, typically by 1%.

Evaluated Mixtures

Table 24. Concrete mixture parameters considered for freeze–thaw testing.

Mixture Designation	Air Volume	Air System	SCM Influence	Other
2 (A, S, N)	Acceptable	Stable	None	–
14 (A, NS, N)	Acceptable	Not Stable	None	–
1 (M, S, N)	Marginal	Stable	None	–
13 (M, NS, N)	Marginal	Not Stable	None	–
17 (M, S, S)	Marginal	Stable	Significant	–
29 (M, NS, S)	Marginal	Not Stable	Significant	–
29 Retempered	Acceptable	–	–	Clustering

Note: A = acceptable air content in fresh state, S = stable AEA, N = no significant effect due to SCM use, M = marginal air content in fresh state, NS = unstable AEA.

Table 26. Air testing results and anticipated freeze–thaw performance.

Mixture Designation	Fresh		Hardened		Anticipated Performance
	Air (%)	SAM	Air (%)	S.F. (in.)	
2	7.1	0.44	5.8	0.009	Good–Marginal
14	5.8	0.39	5.0	0.007	Good
1	3.2	0.69	2.3	0.022	Poor
13	3.1	0.70	2.6	0.019	Poor
17	4.0	0.74	3.9	0.017	Marginal–Poor
29	3.8	0.80	2.5	0.022	Poor
29 Retempered	6.7	0.31	5.1	0.010	Good

Note: S.F. = spacing factor.

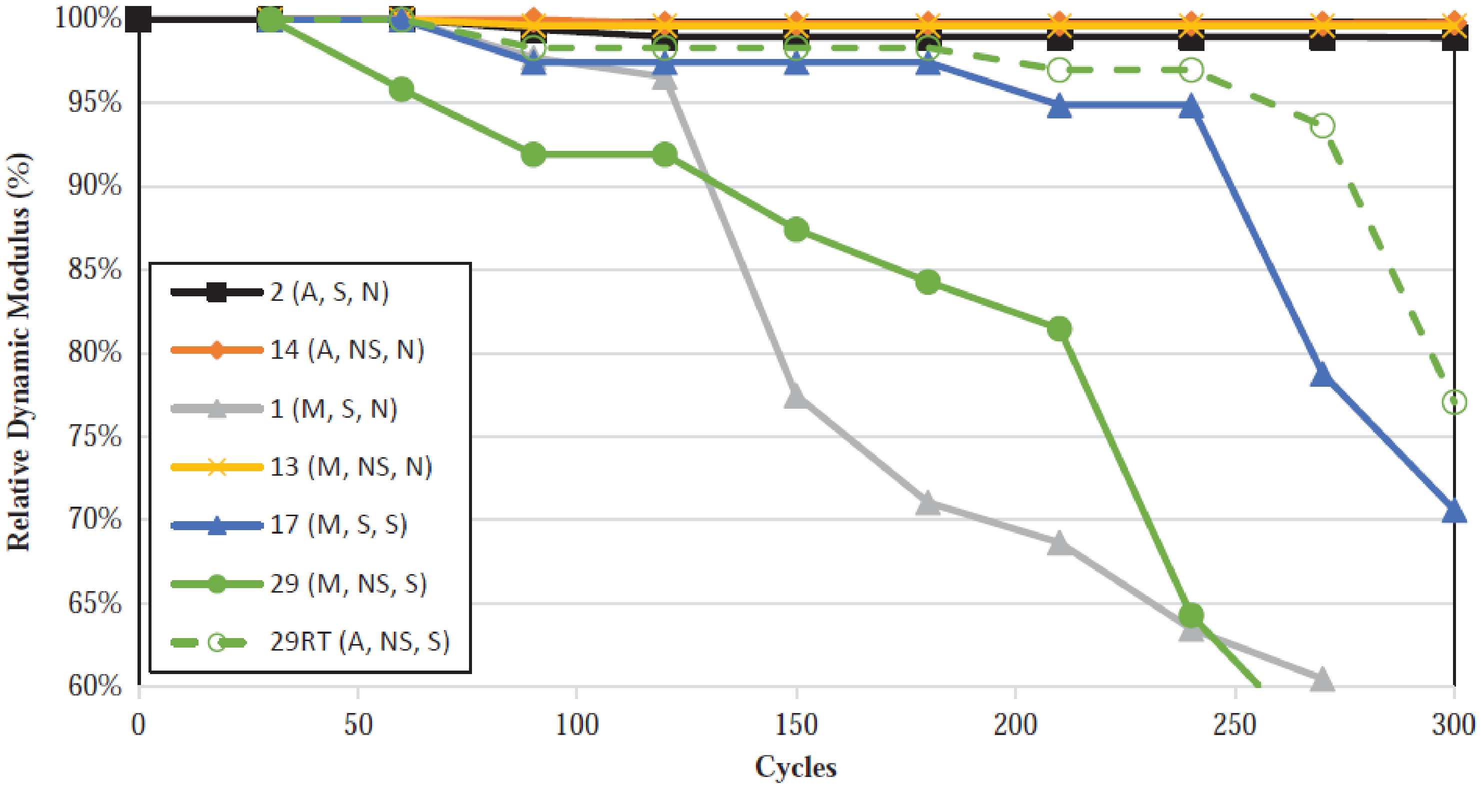
All Test Conditions

Table 7. Freeze–thaw testing evaluation parameters.

Test Variant	Test	Curing Time	Conditioning Fluid	Freezing Fluid	Number of Cycles	Total Test Duration
CDF-A	FT-1	**7 days**	Limewater	Deionized	56	63 days
	FT-2	**28 days**	Limewater	Deionized	56	84 days
	FT-3	**56 days**	Limewater	Deionized	56	112 days
CDF-B	FT-4	7 days	Limewater	**NaCl (3%)**	56	63 days
	FT-5	7 days	Limewater	**$CaCl_2$ (3%)**	56	63 days
	FT-6	7 days	Limewater	**$MgCl_2$ (3%)**	56	63 days
CDF-C	FT-7	7 days	**NaCl (35%)**	Deionized	56	84 days
	FT-8	7 days	**$CaCl_2$ (74%)**	Deionized	56	84 days
	FT-9	7 days	**$MgCl_2$ (54%)**	Deionized	56	84 days

Note: Shading indicates varied parameters.

AASHTO T161A Performance



Note: A = acceptable air content in fresh state, S = stable AEA, N = no significant effect due to SCM use, M = marginal air content in fresh state, NS = unstable AEA.

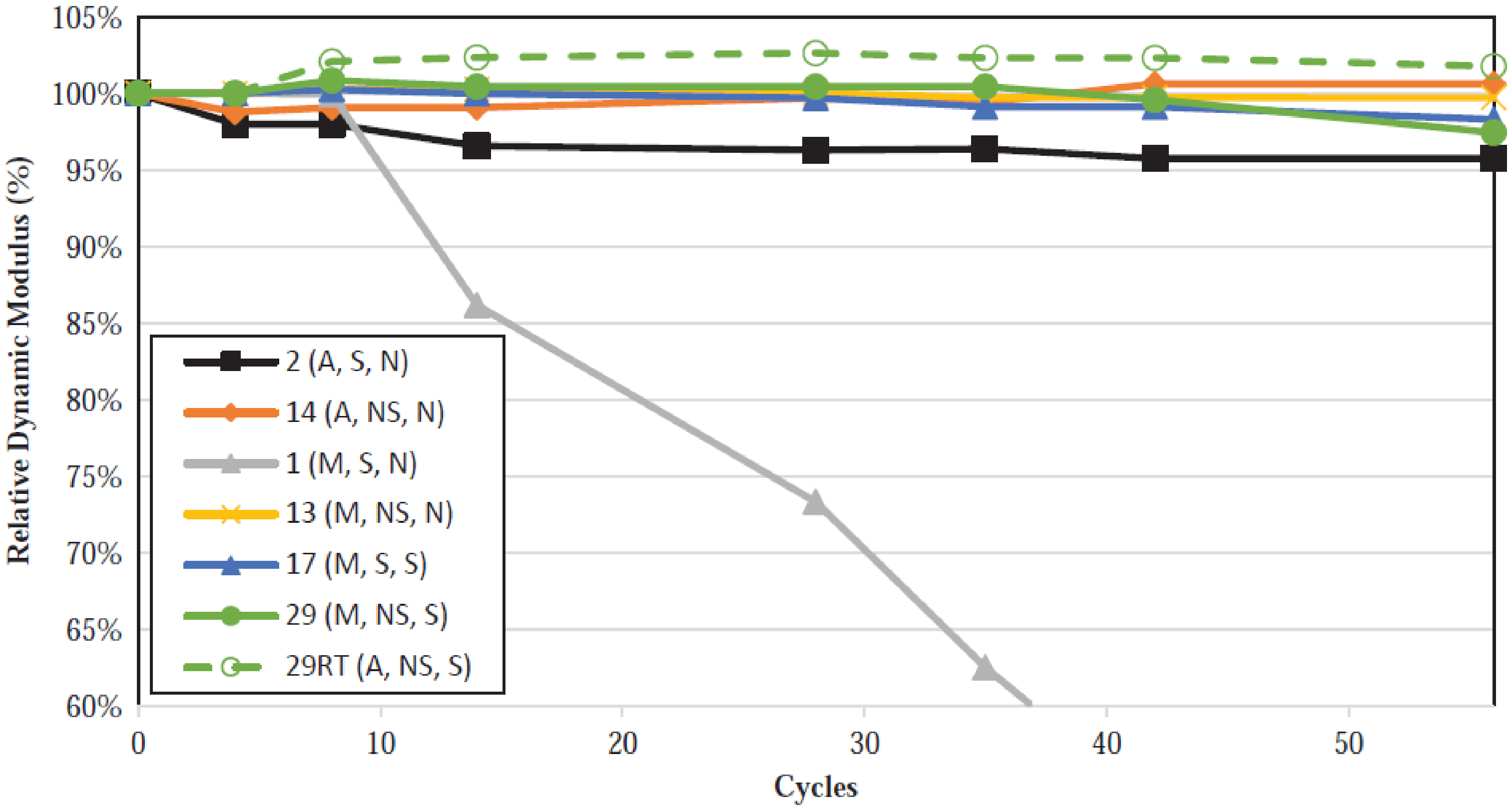
Figure 41. Relative dynamic modulus versus freeze–thaw cycles for AASHTO T 161 "A".

Table 26. Air testing results and anticipated freeze–thaw performance.

Mixture Designation	Fresh		Hardened		Anticipated Performance
	Air (%)	SAM	Air (%)	S.F. (in.)	
2	7.1	0.44	5.8	0.009	Good–Marginal
14	5.8	0.39	5.0	0.007	Good
1	3.2	0.69	2.3	0.022	Poor
13	3.1	0.70	2.6	0.019	Poor
17	4.0	0.74	3.9	0.017	Marginal–Poor
29	3.8	0.80	2.5	0.022	Poor
29 Retempered	6.7	0.31	5.1	0.010	Good

Note: S.F. = spacing factor.

CDFA – FT1 (7d cure, water) performance



Note: A = acceptable air content in fresh state, S = stable AEA, N = no significant effect due to SCM use, M = marginal air content in fresh state, NS = unstable AEA.

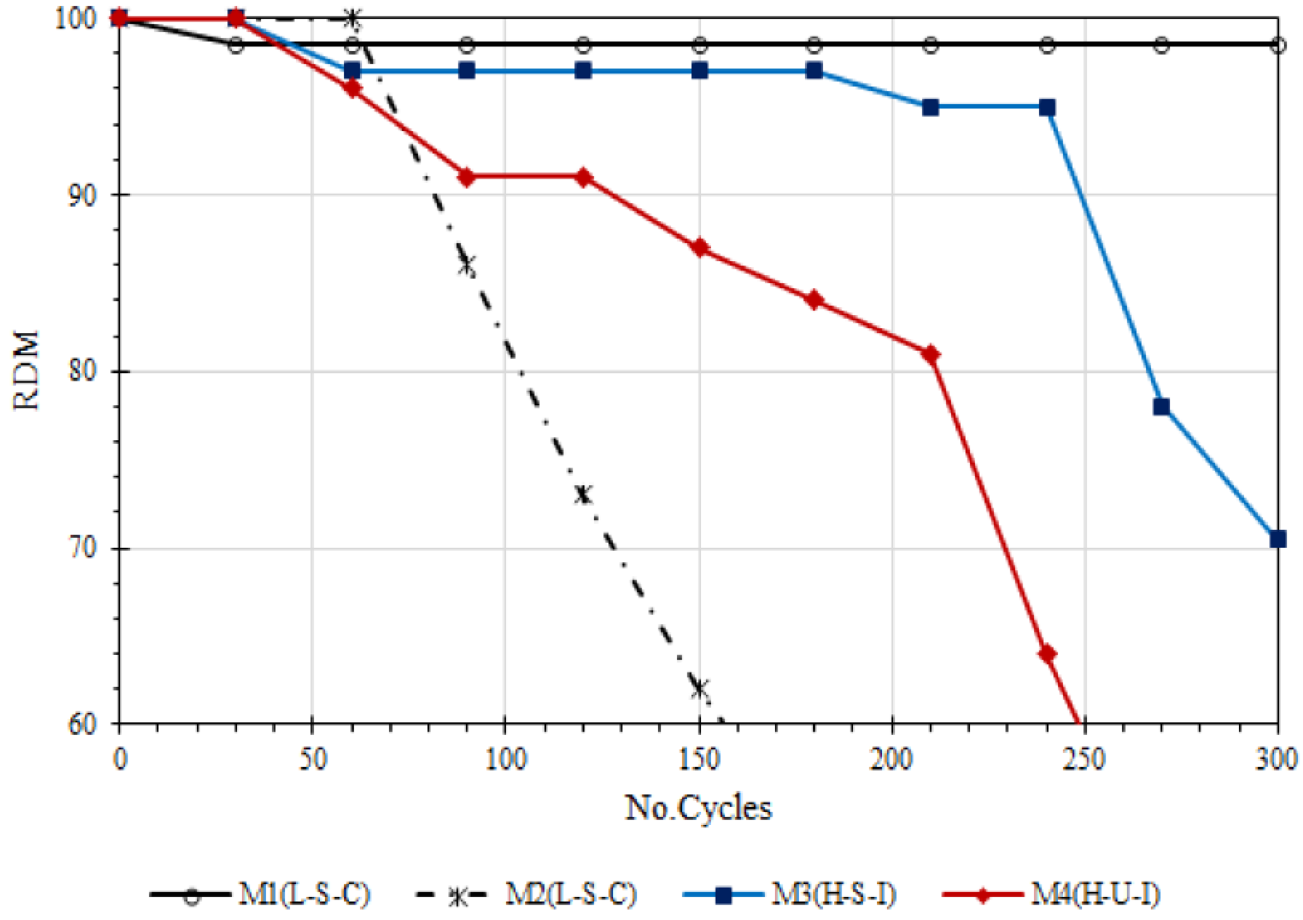
Figure 42. Relative dynamic modulus versus freeze–thaw cycles for CDF-A:FT1.

Table 26. Air testing results and anticipated freeze–thaw performance.

Mixture Designation	Fresh		Hardened		Anticipated Performance
	Air (%)	SAM	Air (%)	S.F. (in.)	
2	7.1	0.44	5.8	0.009	Good–Marginal
14	5.8	0.39	5.0	0.007	Good
1	3.2	0.69	2.3	0.022	Poor
13	3.1	0.70	2.6	0.019	Poor
17	4.0	0.74	3.9	0.017	Marginal–Poor
29	3.8	0.80	2.5	0.022	Poor
29 Retempered	6.7	0.31	5.1	0.010	Good

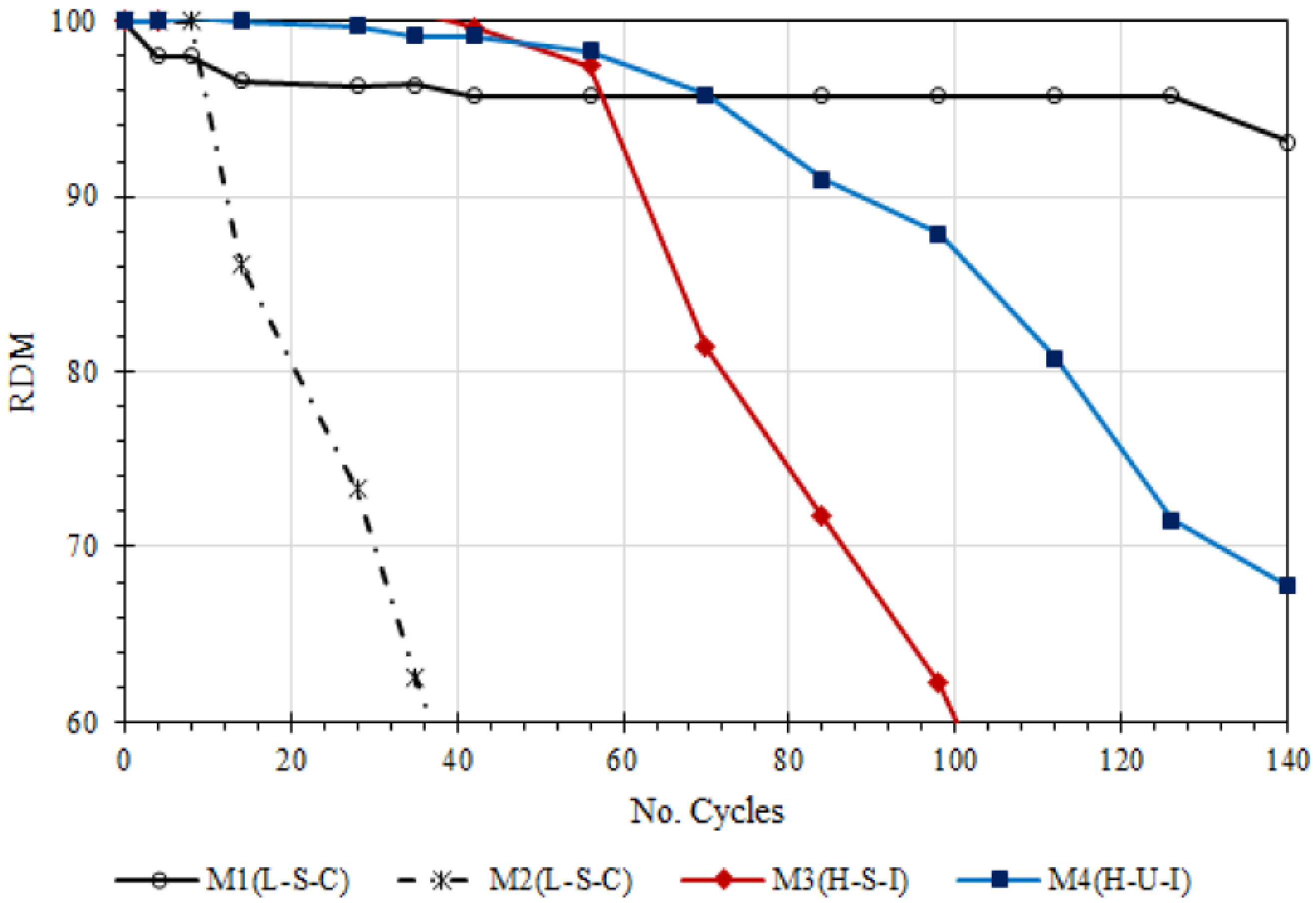
Note: S.F. = spacing factor.

AASHTO T161A performance (Select 4 mixtures)



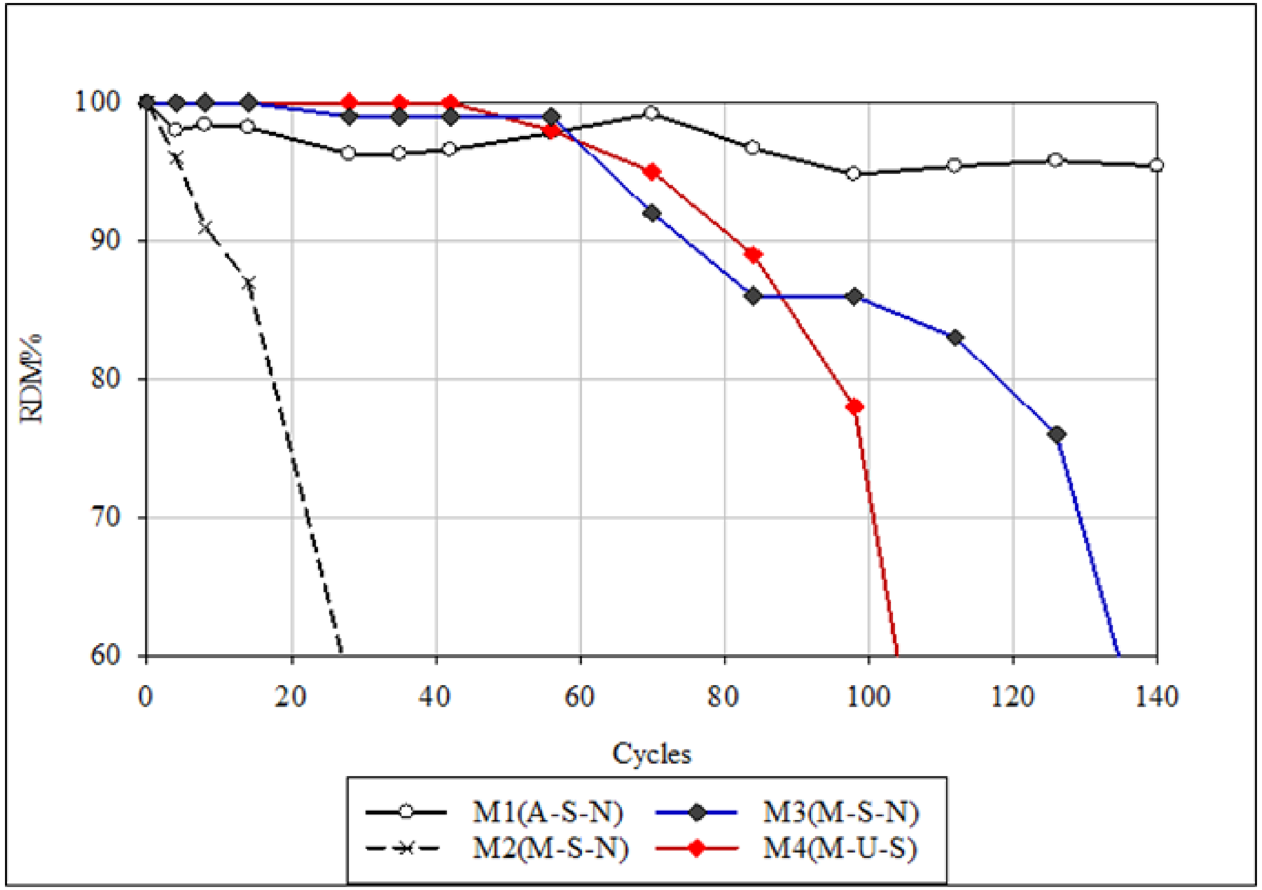
ID	Fresh	Hardened				
	Air Vol (%)	SAM	Air Vol (%)	S.F all Chords	S.F. over 30	Anticipated Performance
M1(L-S-C)	7.1	0.44	5.8	0.169	0.239	Good
M2(L-S-C)	3.2	0.69	2.3	0.350	0.553	Poor
M3(H-S-I)	4.0	0.74	3.9	0.282	0.432	Marginal
M4(H-U-I)	3.8	0.80	2.5	0.446	0.556	Poor

CDFA – FT1 (7d cure, water) performance



ID	Fresh	Hardened					
	Air Vol (%)	SAM	Air Vol (%)	S.F all Chords	S.F. over 30	Anticipated Performance
M1(L-S-C)	7.1	0.44	5.8	0.169	0.239	Good
M2(L-S-C)	3.2	0.69	2.3	0.350	0.553	Poor
M3(H-S-I)	4.0	0.74	3.9	0.282	0.432	Marginal
M4(H-U-I)	3.8	0.80	2.5	0.446	0.556	Poor

CDF B – FT4 (3% NaCl) Performance



ID	Fresh	Hardened				
	Air Vol (%)	SAM	Air Vol (%)	S.F all Chords	S.F. over 30	Anticipated Performance
M1(L-S-C)	7.1	0.44	5.8	0.169	0.239	Good
M2(L-S-C)	3.2	0.69	2.3	0.350	0.553	Poor
M3(H-S-I)	4.0	0.74	3.9	0.282	0.432	Marginal
M4(H-U-I)	3.8	0.80	2.5	0.446	0.556	Poor

Summary & Conclusions

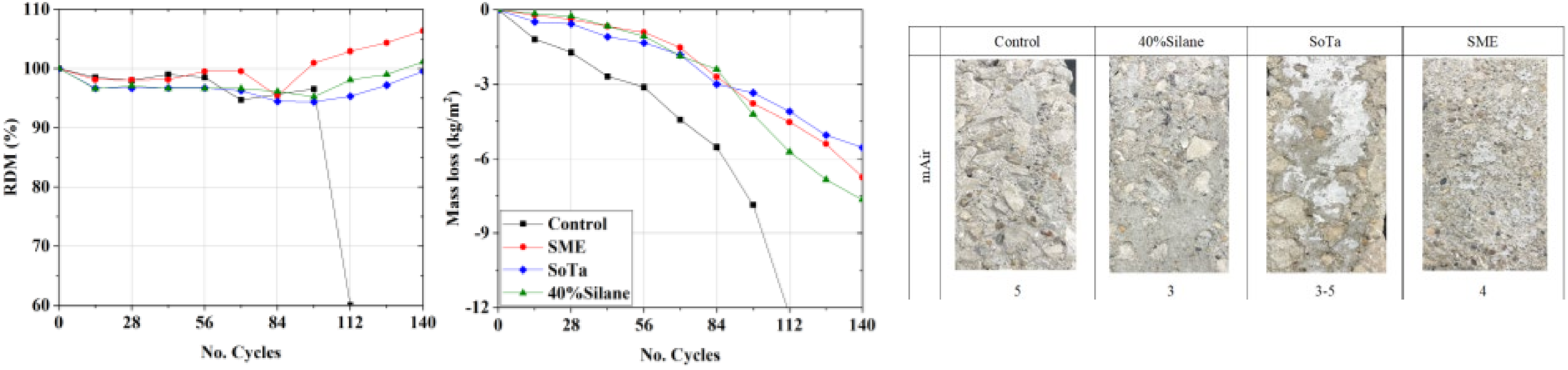
- The standard ASTM C666-A equipment was successfully modified to follow a slower freezing and thawing regime as controlled by a Linux-based microcomputer.
- The developed test method enables testing concrete at any age that represent field performance, unlike ASTM C666-A tests relatively young and saturated concrete. In proposed test method, concrete experience drying.
- Generally, field concrete does not experience cycles of FT with pure water, but a variety of salt solutions. In the present study, 3.3% NaCl utilized in current ASTM C672 deicer scaling, was considered; however a variety of different deicer solutions could be utilized in newly developed test method.

Summary & Conclusions

- Concrete in the field experiences combined effects of cycles of FT and surface scaling. In this development, a coupled effect can be studied and data showed that RDM of concrete dropped faster with the presence of the salt solution.
- Concrete with a good air void system resisted 300 cycles of ASTM C666A and 140 cycles of proposed test method when tested in pure water. Concrete with marginal to poor air system failed much earlier. The marginal air system mixtures failed at significantly different cycles between the testing arrangements indicating nuance in performance related to how solution is introduced into the samples.

Test Method Observations and Improvements

- In addition to RDM and sample mass, mass of scaled material is an important measurement in addition to visual scaling
- The developed test method can be used to evaluate sealers.



(a) mAir

CDF test results from sealed samples produced with a marginal air system

Air Void System for F-T Durability…

- Conclusions
  - Air Content using scanner or microscope
    - Hardened air minimum ~4.5%
    - Spacing factor <0.011 in.
  - SAM
    - <0.3
  - AASHTO T161 A correlated well with concrete air system parameters

Today's Panelists

Moderator:
Peter Taylor,
Iowa State University

Hamed Sadati,
California Department of Transportation

John Kevern,
University of Missouri, Kansas City

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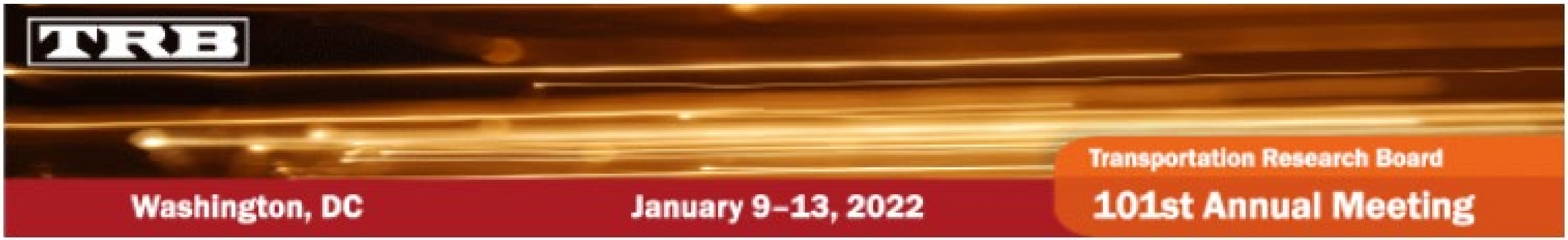

Register now for our January meeting! ***There will be no onsite registration this year.***

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