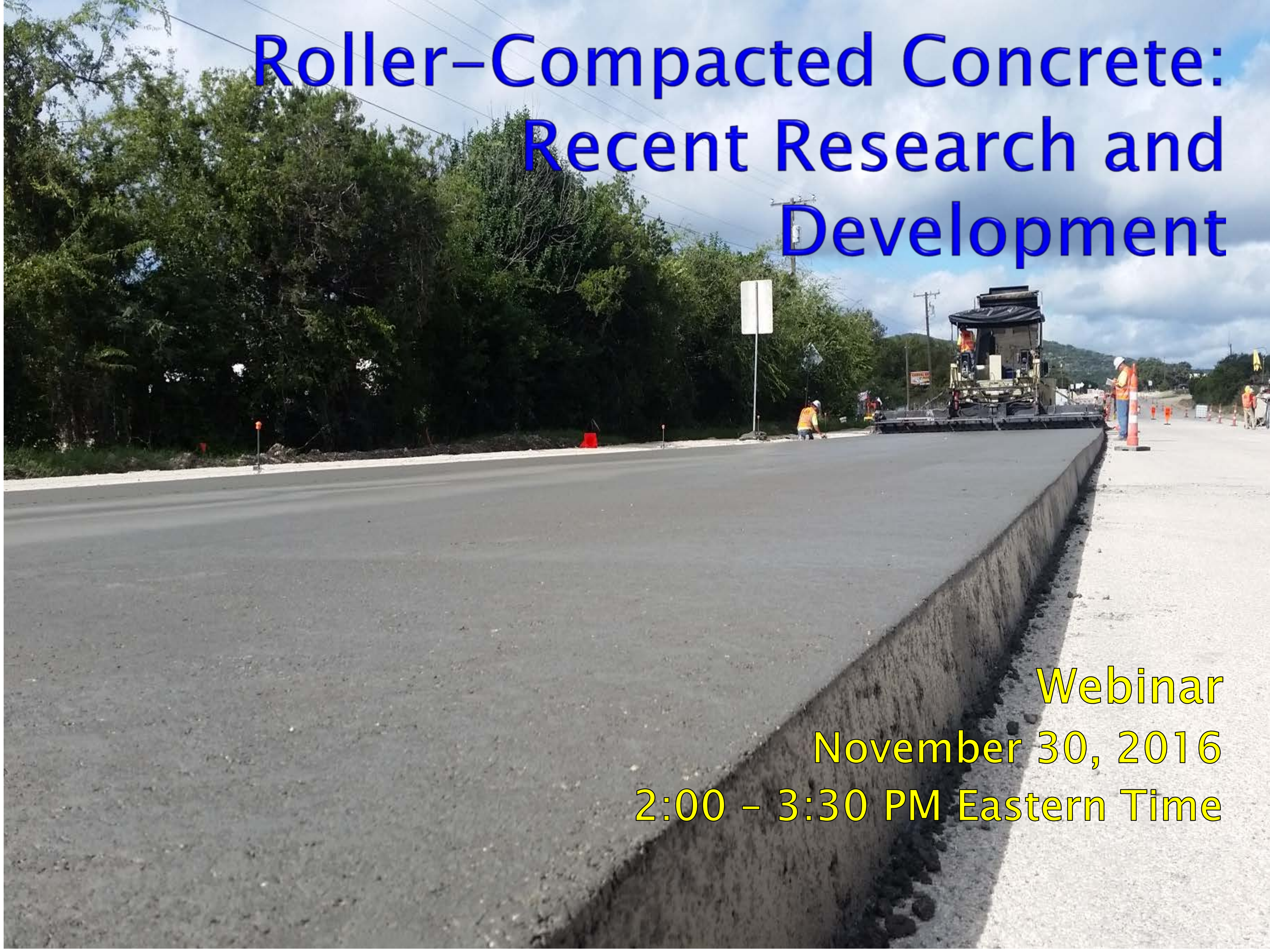
# Roller-Compacted Concrete: Recent Research and Development



Webinar

November 30, 2016

2:00 – 3:30 PM Eastern Time

# Hosting Committees

- Standing Committee on Design and Rehabilitation of Concrete Pavements (AFD50)
- Standing Committee on Concrete Pavement Construction and Rehabilitation (AFH50)
- Standing Committee on Concrete Materials and Placement Techniques (AFN40)

# TRB 96th Annual Meeting

- Subcommitee on Design and Construction of Roller Compacted Concrete Pavements (AFH50(1))
- Join Us:
  - Tuesday, January 10th, 2017
  - 7:30 – 9:30 PM

# Today's Presenters

- Andrew Johnson
  - *Southeast Cement Promotion Association*
  - **RCC Surface Performance: Natural and Diamond Ground**
- Tyson Rupnow
  - *Louisiana Department of Transportation and Development*
  - **2015 Results from the Accelerated Load Testing on RCC Pavements**

# Today's Presenters

- Jeffrey Roesler
  - *University of Illinois, Urbana-Champaign*
  - **Effect of RCC Mixture Constituents on Physical and Mechanical Properties**

Moderator:

- Matthew Singel
  - *Cement Council of Texas*

# RCC Pavement Surface Performance South Carolina Experience

Andy Johnson, Ph.D., P.E.
Pavement Design Engineer
Southeast Cement Promotion Association

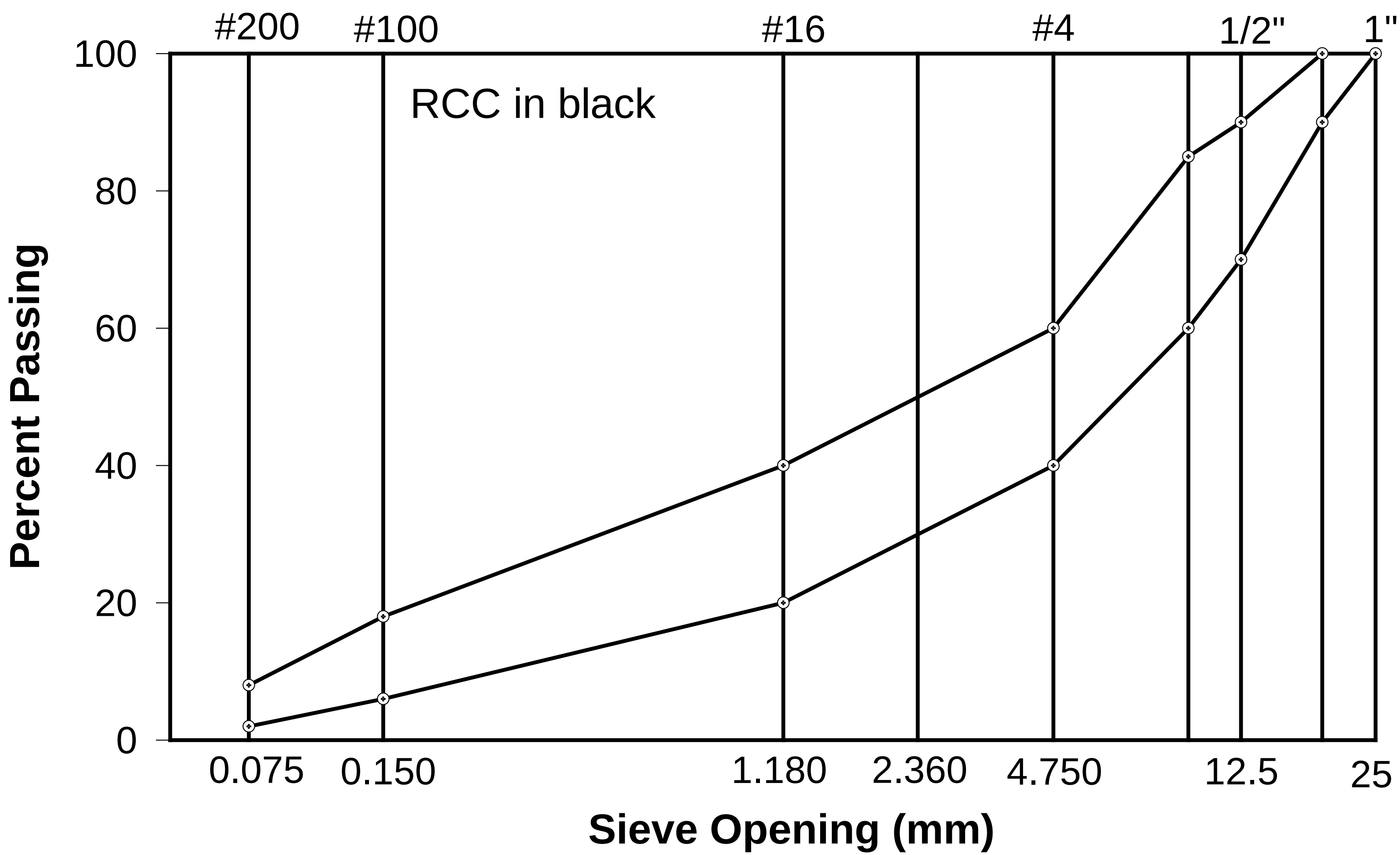
# RCC surface textures

- RCC is a “negative slump” concrete that must be placed with an high-density paver and compacted with rollers.
- Gradation is typically similar to a hot mix asphalt.
- Textures resemble hot mix asphalt.
- This is not what many people are accustomed to when they think of “concrete.”

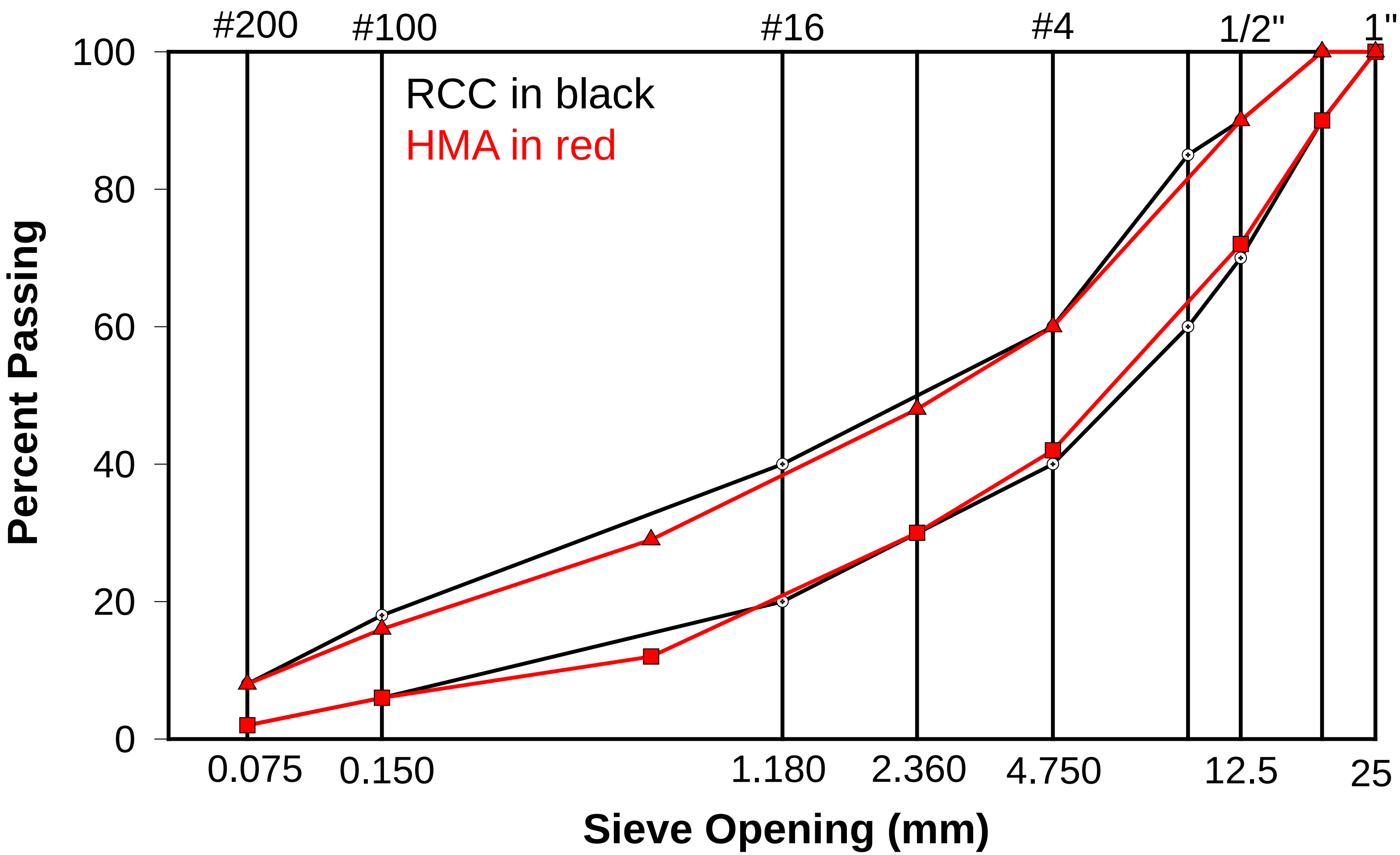
# SCDOT gradation specification to 2012

| Sieve Size | Percent Passing by Weight |
| --- | --- |
| 1 inch | 100 |
| ¾ inch | 90-100 |
| ½ inch | 70-100 |
| 3/8 inch | 60-85 |
| #4 | 40-60 |
| #16 | 20-40 |
| #100 | 6-18 |
| #200 | 2-8 |

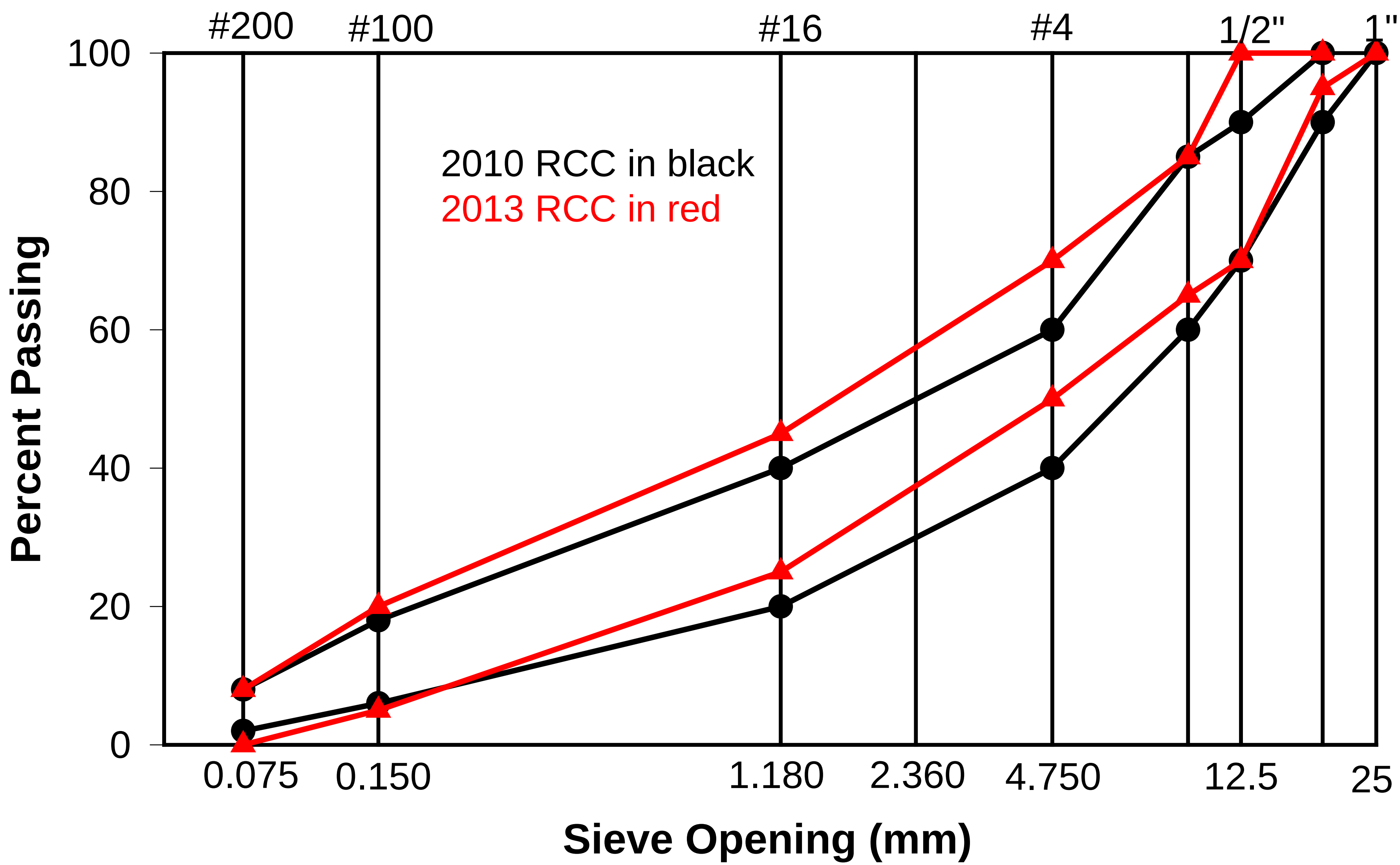
# RCC vs. HMA intermediate course



# RCC vs. HMA intermediate course



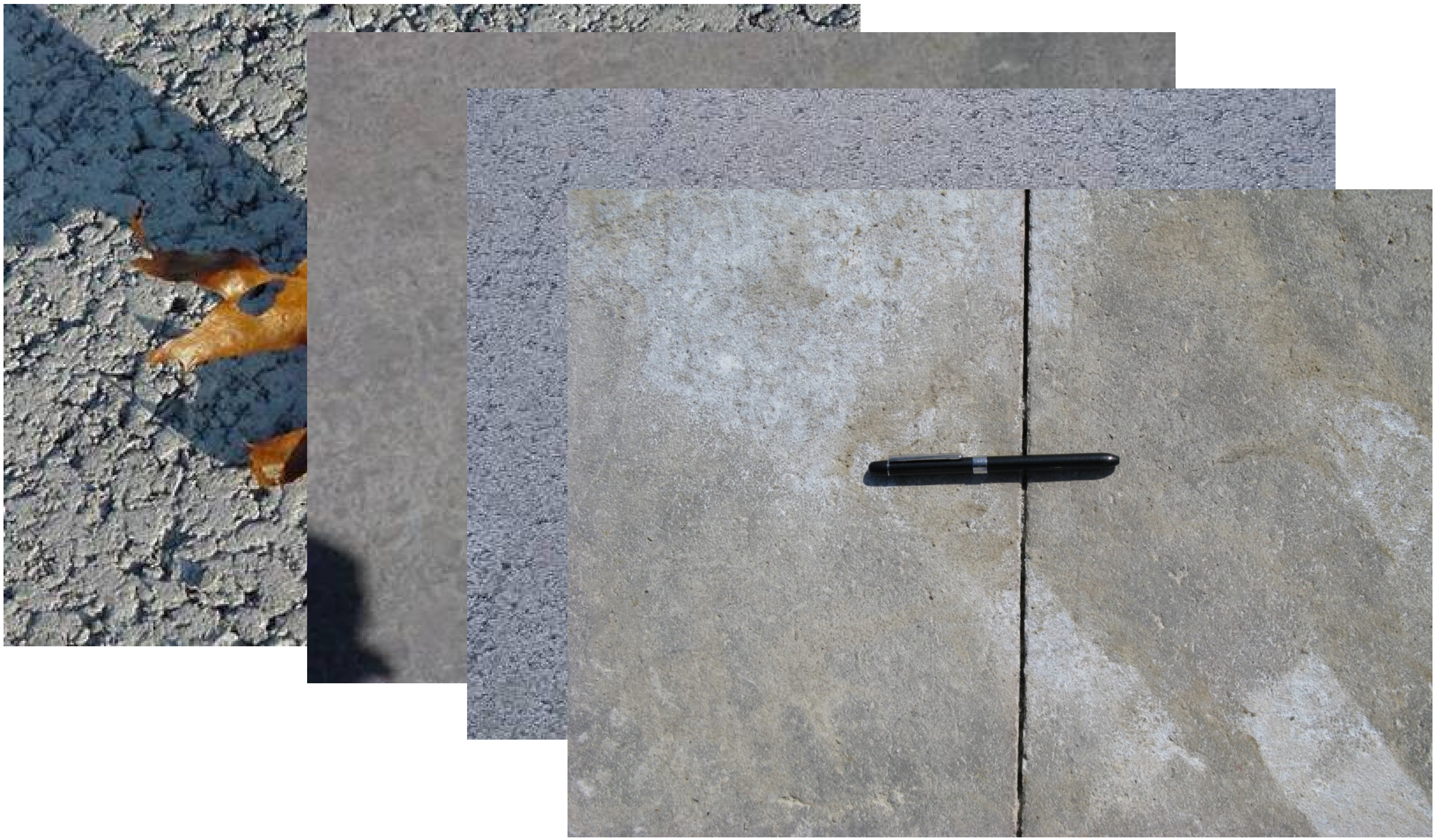
# Evolving gradation specs



## Surface appearance

- Not as smooth as conventional concrete
- Important to recognize difference
- Similar appearance to asphalt only light grey instead of black

# Surface Texture



# SCDOT RCC history

- First test section in 2002
  - Natural texture
- First contract in Charleston, 2008
  - Hot-mix asphalt surface
- Two contracts, 2009
  - Two sites with HMA surface
  - Two sites with diamond ground texture

# SCDOT RCC history

- Currently, SCDOT has let over 25 RCC mainline projects totalling about 600,000 sy.
- All projects since 2009 have had asphalt surface.

# Powell Pond Rd., Aiken, SC - 2002

- First project had natural RCC texture.
- Was a very “tender” mix prone to shallow tension cracks at surface.  Also had some coarse areas.
- Based on asphalt experience, there were concerns that the surface would not be durable.


Powell Pond Road
Aiken, SC
February 2003


August 2013


January 2016


Powell Pond Road
March 2002


August 2013


January 2016

# US-78, Ladson, SC – 2008

- Based on Powell Pond experience, decided to construct next project with asphalt surface.


BRICE
TAKEUCHI


2015


2015

# US-25, Aiken - 2009

- Decided to try diamond grinding surface of RCC.


Richland Avenue (US 25) Aiken, SC

www.morgan-corp.com
morgan corp.
7820
ABG
GOMACO


Explor
South Carolina!
Discovery Cente
24 Miles Ahea
Museum • Gift Shop
Travel Services
CLEAN FILTER DAILY
FIREWORKS


2009
SPEED LIMIT
45


2015
BEACON HOMES
AUTO CARE
EXHAUST


2016

# S. Beltline Boulevard, Columbia – 2009

- SCDOT's second diamond ground project, done same year as US-25.
- Did not go well…
- Numerous problems encountered with QC, unfortunate decisions made regarding construction.


S. Beltline Blvd.
2010


S. Beltline Blvd.
2013


S. Beltline Blvd.
2016

S. Beltline Blvd. - 2009

S. Beltline Blvd. - 2009

# S. Beltline Blvd. - 2010


S. Beltline Blvd. - 2013


S. Beltline Blvd. - 2016

# S. Beltline Blvd. - 2010


S. Beltline Blvd. - 2013

S. Beltline Blvd. - 2016


S. Beltline Blvd. - 2016

# Greystone Boulevard, Columbia - 2009

- Done on same contract as S. Beltline.
- Asphalt surface.
- Reflection cracking typical of other projects.

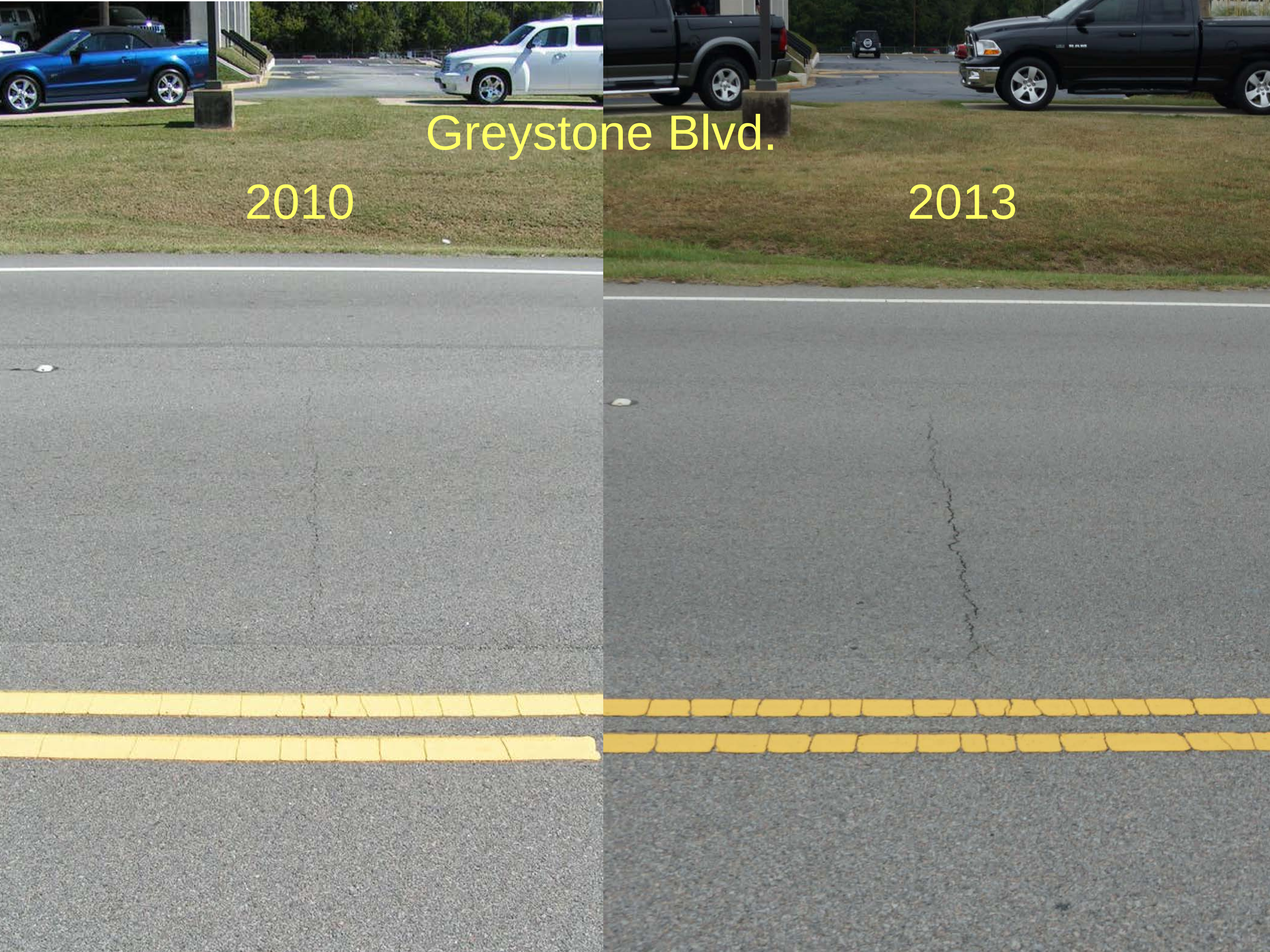
# Greystone Blvd. - 2009

Greystone Blvd. - 2009

# Greystone Blvd - 2009


Greystone Blvd - 2016.
KIA
KIA GALEANA


Greystone Blvd - 2016.


Greystone Blvd.
2010
2013

Greystone Blvd.
2010
2016

# Conclusions

- In a wet, non-freeze climate like SC, natural RCC surfaces are generally unaffected by environmental factors in the 8 to 10 year timeframe.
- RCC <u>can</u> be successfully diamond ground, but the surface needs to be sound prior to grinding.
- Ground surface also appears durable if no other problems with RCC exist.

# Conclusions

- When overlaid with a single lift of asphalt, RCC can cause reflective cracking promptly within the first year.
- Cracking can continue to appear for several years after completion.
- Surface cracking does not appear to cause deterioration in underlying RCC or subgrade. (YMMV in harsher climates.)

# Future developments

- Improvements in mix design and finer gradations have yielded better textures.
- New admixtures allow limited finishing of RCC, giving appearance of conventional concrete.

# Roller compacted Concrete
# Results from LTRC's Accelerated Loading Facility

**TRB Webinar**
**November 30, 2016**

Tyson D. Rupnow, Ph.D., P.E.
Zhong Wu, Ph.D., P.E.
Moinul Mahdi – Ph.D. student

# Outline

- Background
- Objectives
- Field construction results
- Load test results
- Conclusions
- Implementation efforts
- Questions

# Why interested in RCC?

# Background

- Successful RCC projects include:
  - U.S. 78 near Aiken, SC
    - 10" RCC – 1 mile 4 lane section completed in 2009
  - 2012 Arkansas completed a section in the Fayetteville Shale Play Area
    - 7" RCC over a reconstructed base course
    - 8" RCC placed as an overlay

# Objectives

- Determine the structural performance with failure mechanism and load carrying capacity of thin RCC surfaced pavements
- Determine the applicability of using a thin RCC surfaced pavement structure (with cement treated or stabilized base) as a design option for low- and high- volume pavement design in Louisiana

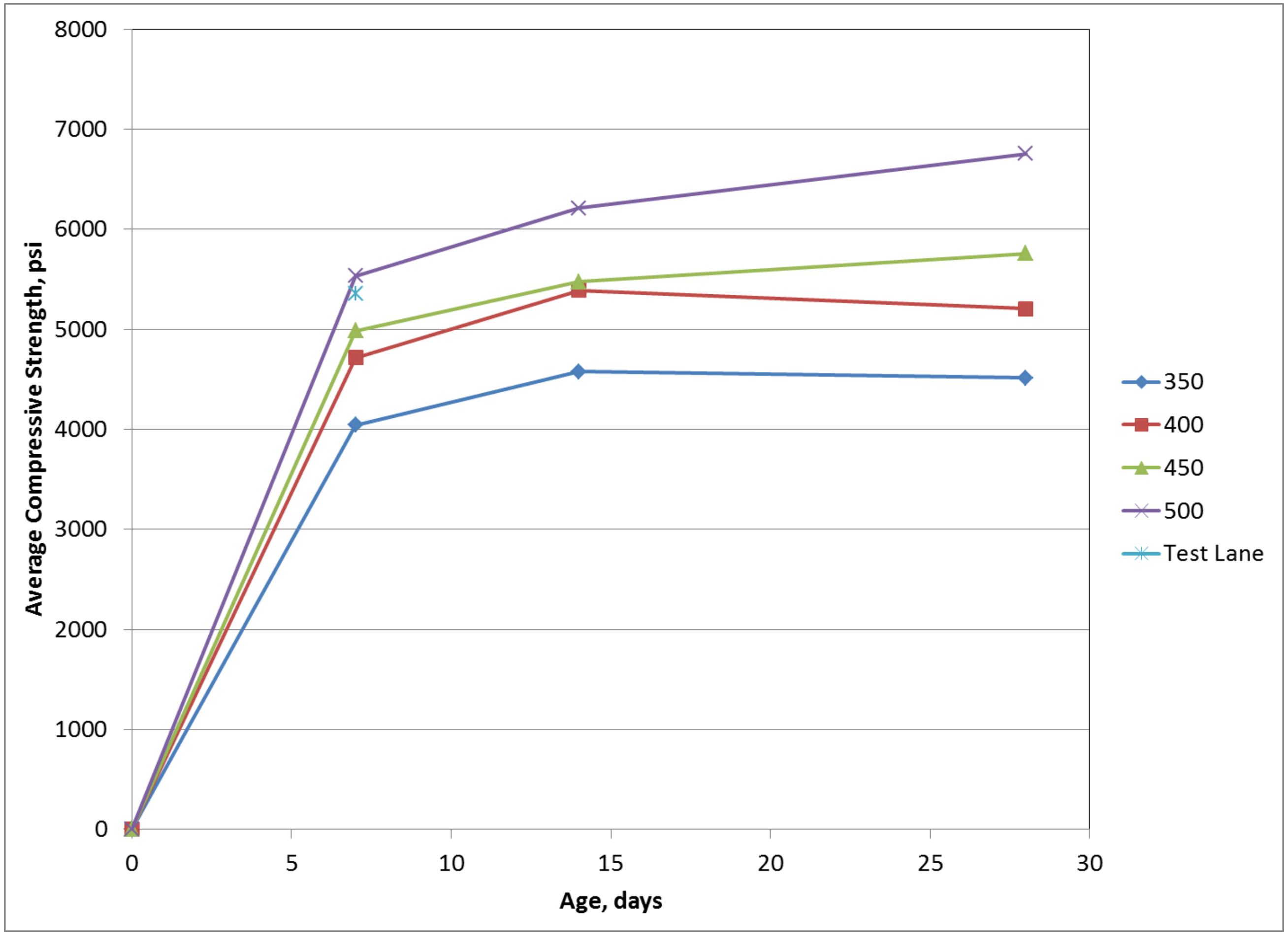
# Lab Materials and Test Methods

- Materials
  - No. 67 crushed limestone
  - Manufactured sand
  - Type I portland cement
- Test methods
  - ASTM C1557 Modified Proctor
  - ASTM C1435 for cylinders
  - ASTM C39
  - ASTM C6938 and ASTM C1040

# Laboratory Mixtures

- 350, 400, 450, and 500 PCY mixtures
- Tested for density first (Modified Proctor)
- Then tested for strength

# Mixture Results - Strength



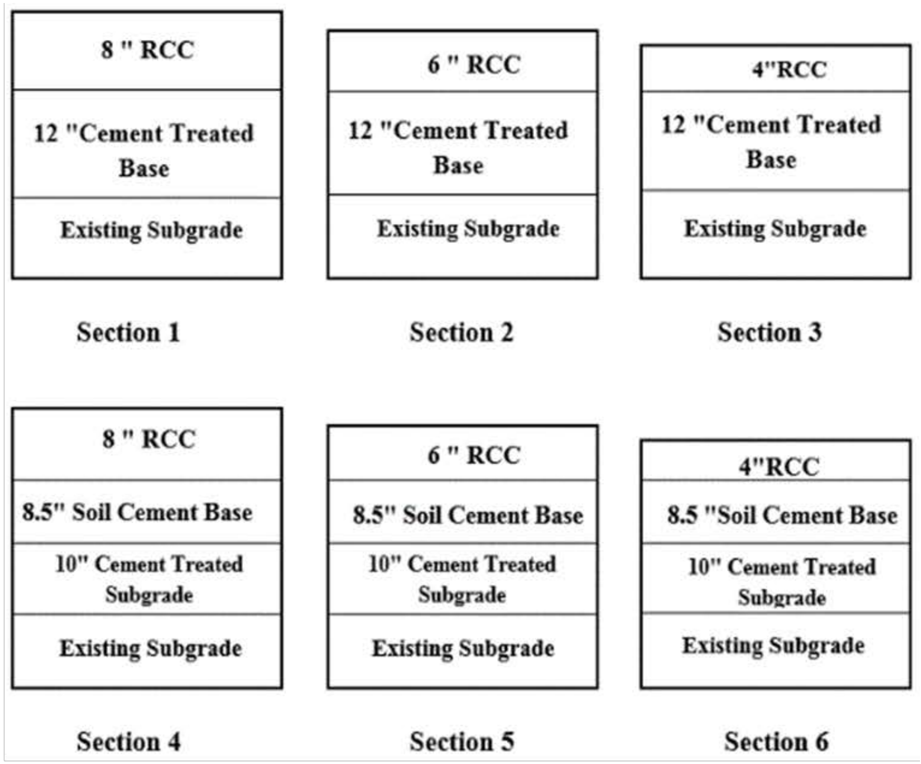
# Mixture Proportion

| Material | Quantity (pcy) |
|---|---:|
| Cement | 450 |
| Coarse Aggregate | 1521 |
| Fine Aggregate | 2017 |
| Water | 154 |

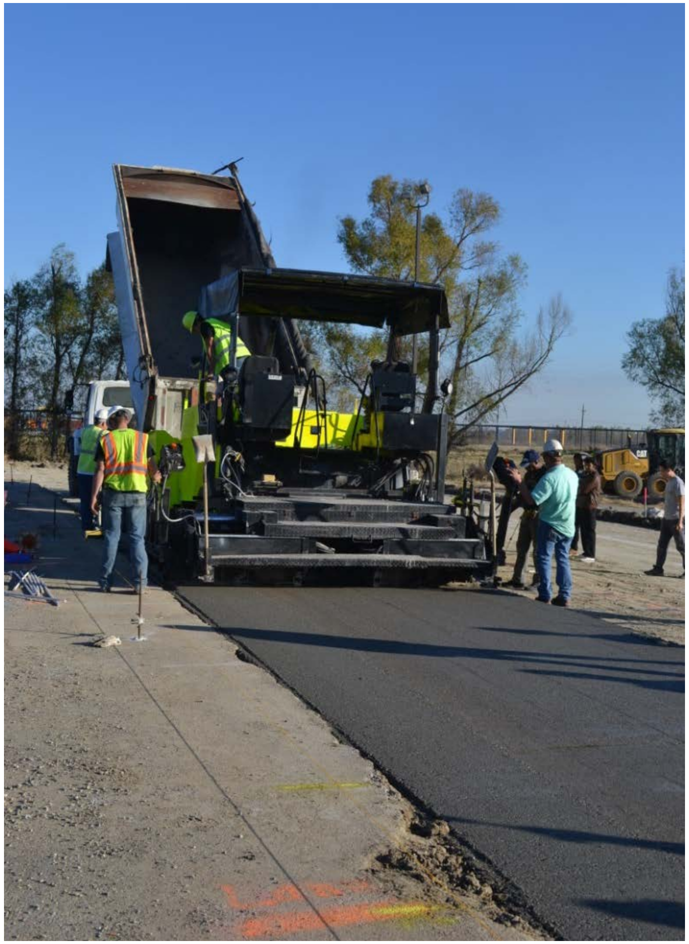
# Constructed Sections

- Six full-scale RCC pavement test sections were constructed at Pavement Facility of Louisiana Transportation Research Center (LTRC)
  - Each section: 71.7-ft long and 13-ft wide

# Constructed Sections

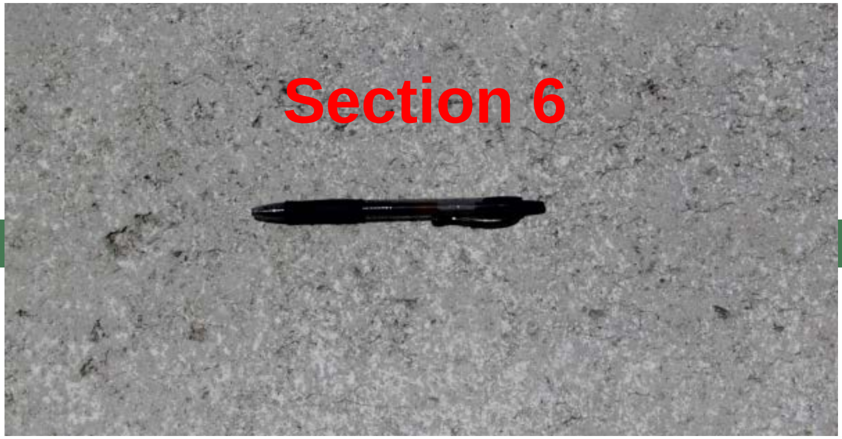
# Pictures

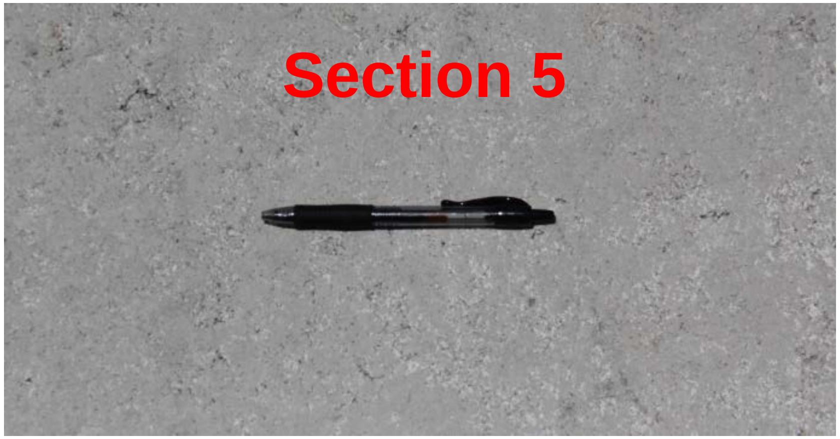



Section 3


Section 2


Section 1


Section 6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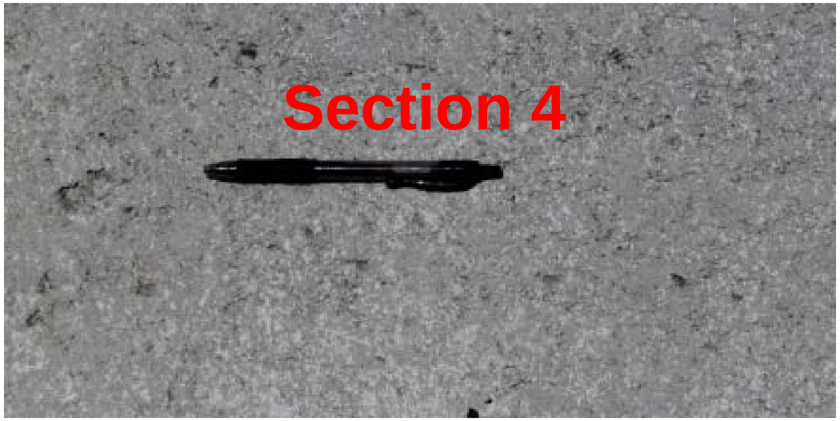

Section 4

# FWD Back Calculated Moduli


**8"RCC+12CT**
$E_{RCC}$=3587ksi
$E_{base}$=258ksi
$E_{sub}$ = 27ksi

**Section 1**

**6"RCC+12CT**
$E_{RCC}$=2361ksi
$E_{base}$=181ksi
$E_{sub}$ = 24ksi

**Section 2**

**4"RCC+12CT**
$E_{RCC}$=2904ksi
$E_{base}$=139ksi
$E_{sub}$ = 22ksi

**Section 3**

**8"RCC+8.5SC**
$E_{RCC}$=3767ksi
$E_{base}$=418ksi
$E_{sub}$ = 31ksi

**Section 4**

**6"RCC+8.5SC**
$E_{RCC}$=3763ksi
$E_{base}$=352ksi
$E_{sub}$ = 28ksi

**Section 5**

**4"RCC+8.5SC**
$E_{RCC}$=4384ksi
$E_{base}$=305ksi
$E_{sub}$ = 26ksi

**Section 6**

**Those backcalculated results consistent with FWD deflections obtained from individual layers**

# Field Results

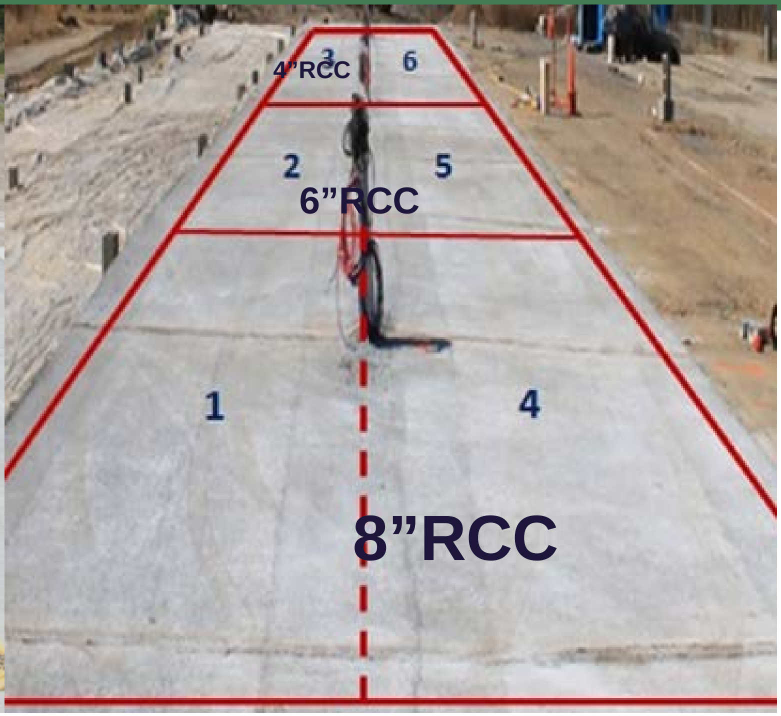
- Density slightly lower in the bottom depth
- Strengths at 55 days of age
  - Lane 1 – 5192 psi
  - Lane 2 – 4422 psi
    - Due to lower densities

| Section Number | Thickness (in) |
|---|---|
| 1 | 9.65 |
| 2 | 6.05 |
| 3 | 4.90 |
| 4 | 8.01 |
| 5 | 6.36 |
| 6 | 4.10 |

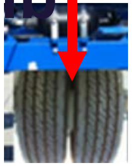
# ATLaS30


- Dual-tire load, 130psi
- Load: up to 30 kips
- Speed: 4~6 mph
- Bi-directional loading
- Effective length: 42-ft
- About 10,000 passes/day

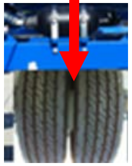
# Accelerated Loading Testing



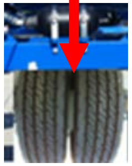

9,000 lb



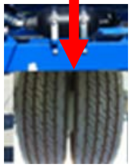
16,000 lb



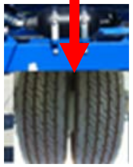
20,000 lb



22,000 lb



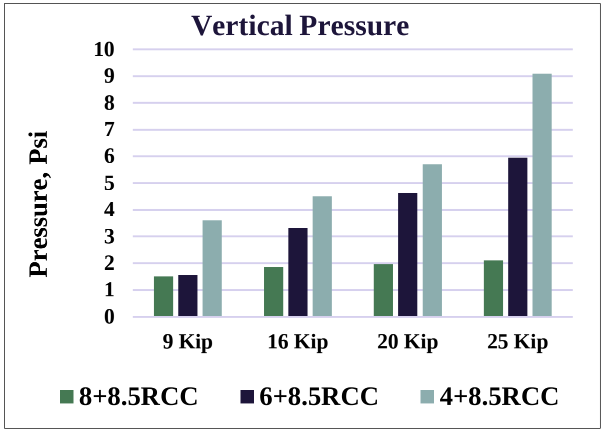
25,000 lb

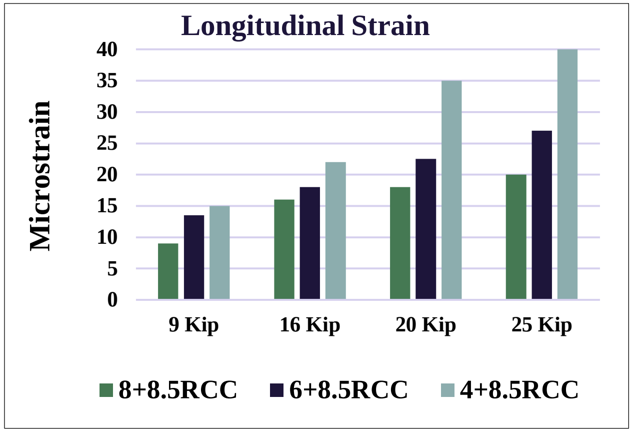


- Roughly 78,000 reps. for each load level

# Instrumentation Response

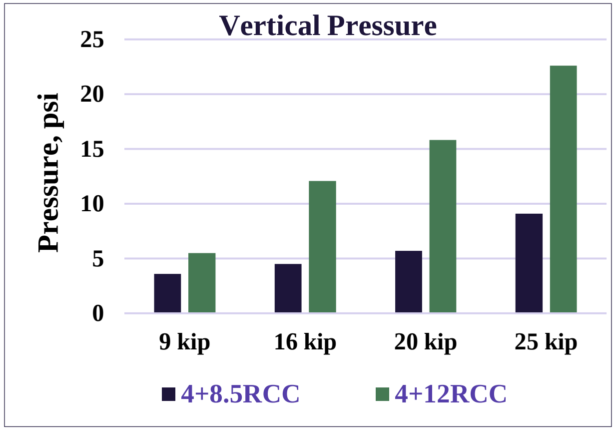
- Typical stress and strain measured at the bottom of RCC slabs with different thickness under APT loading

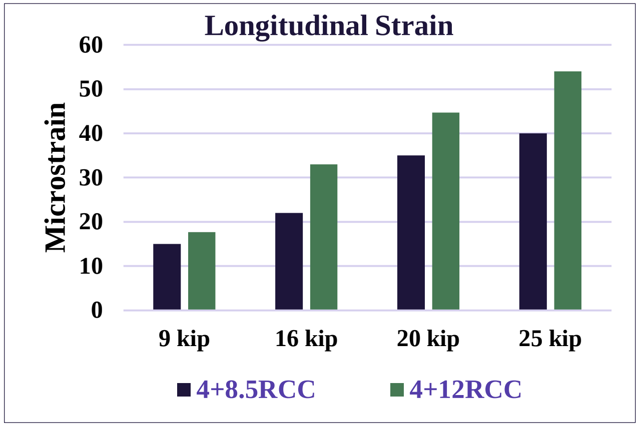


# Instrumentation Response

- Typical stress and strain measured at the bottom of RCC slabs over different base support under APT loading



# Distress Observed (8+8.5RCC) – Section 4

- Approximately after 392,500 load repetition (11.28 million equivalent ESALs), no significant damage was observed
- Due to the high load repetitions received on section 6+8.5RCC to fatigue failure, the test was discontinued

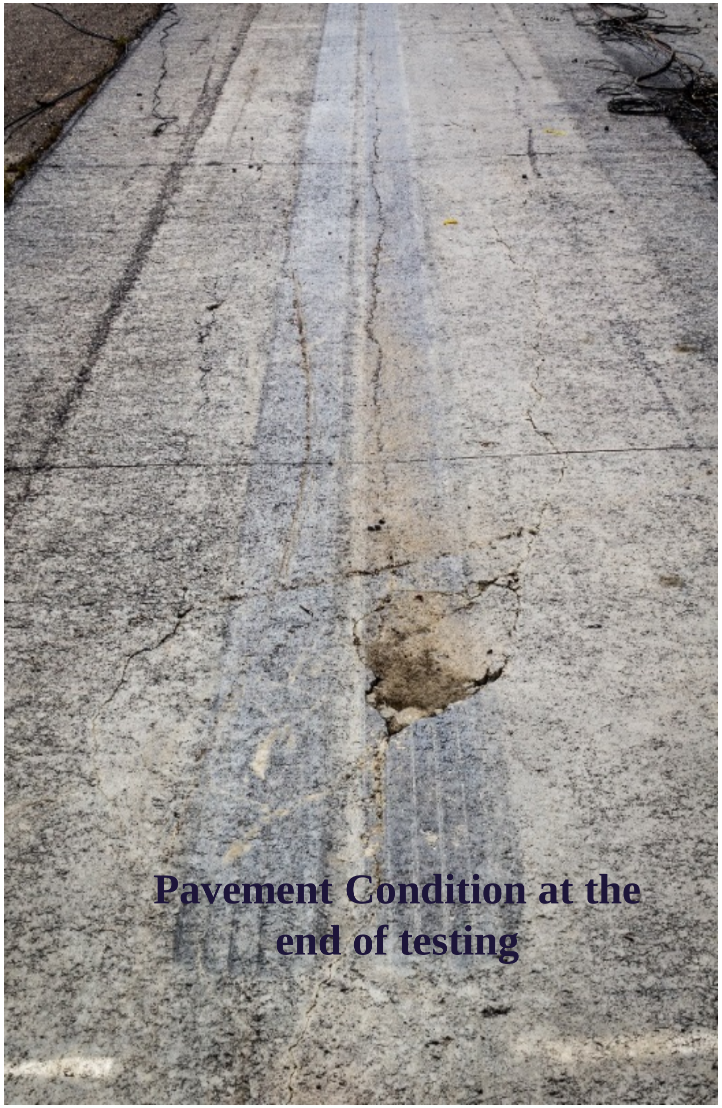
**392,500 Passes**

**Current Pavement Condition**

# Distress Observed (6+8.5RCC) – Section 5

- Visual Distresses
- Longitudinal cracks were observed along the wheel path and at the edge of the tire print
- Pumping action was observed through cracks and joints
- 87.4 million ESALs to failure
- ***1.9 million ESALs predicted***

**1.75 million Passes**



**Pavement Condition at the end of testing**

# Distress Observed (4+8.5RCC) – Section 6

- Visual Distresses
- Longitudinal cracks were observed along the wheel path and at the middle of the tire print
- Pumping action was observed through the cracks and joints
- 19.2 million ESALs to failure
- ***0.7 million ESALs predicted***

**706,500 Passes**

**Pavement Condition at the end of testing**

# Distress Observed (4+12RCC) – Section 3

- Due to relatively weaker support, an early longitudinal crack was observed after 55,000 passes under 9 loading
- About 3 million ESALs to failure
- ***Predicted 0.7 million ESALs to failure***

**196,000 Passes**

**Longitudinal crack along the wheel path**

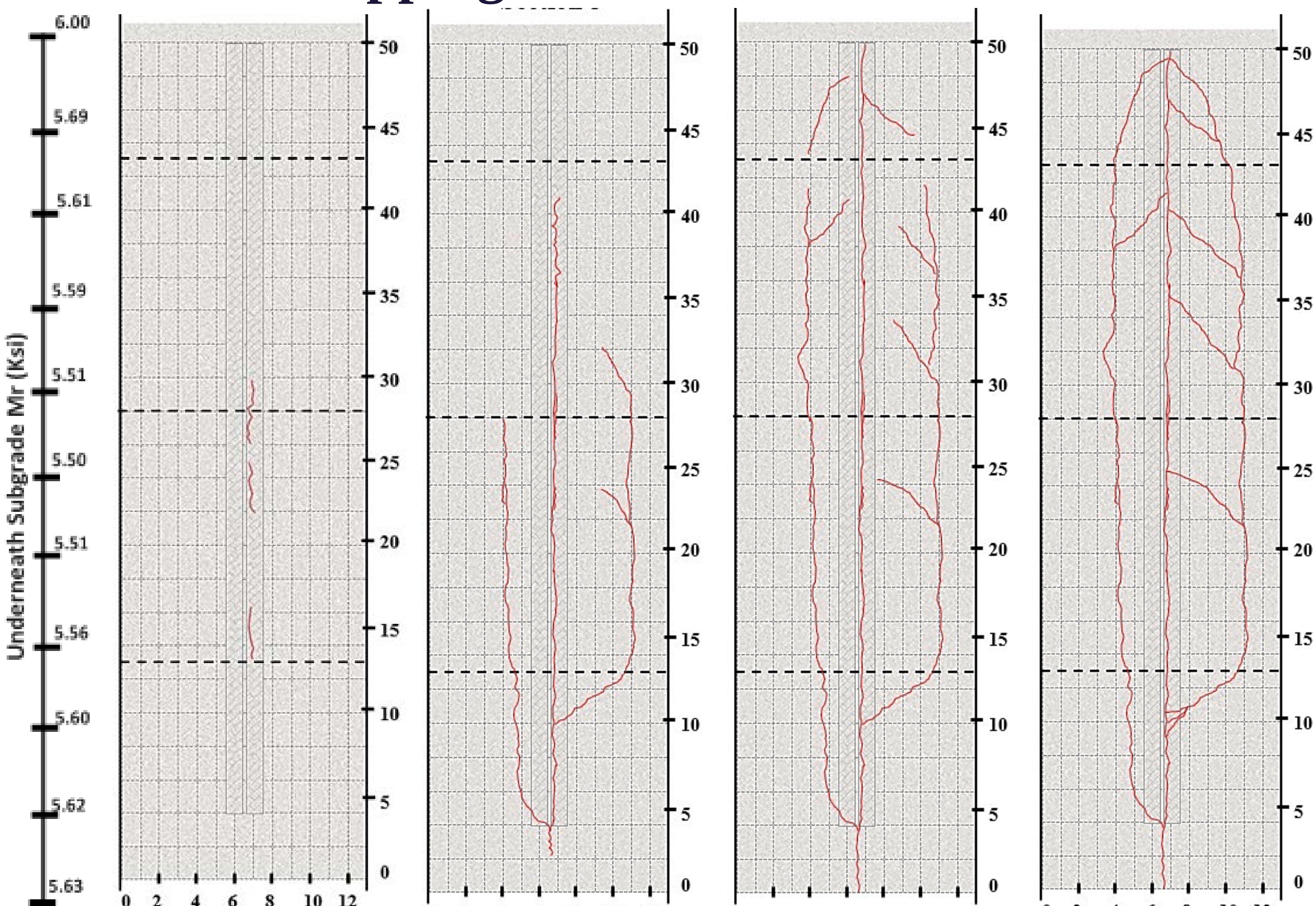
# Distress Observed (6+12RCC) – Section 2

- Longitudinal cracks
- Pumping and Local failure
- About 19 million ESALs to failure
- ***Predicted 1.9 million***

**637,000 Passes**

# Crack Mapping on (6+8.5RCC) – Section 5

- **Crack Mapping**




After 1,050,000 Load Repetition

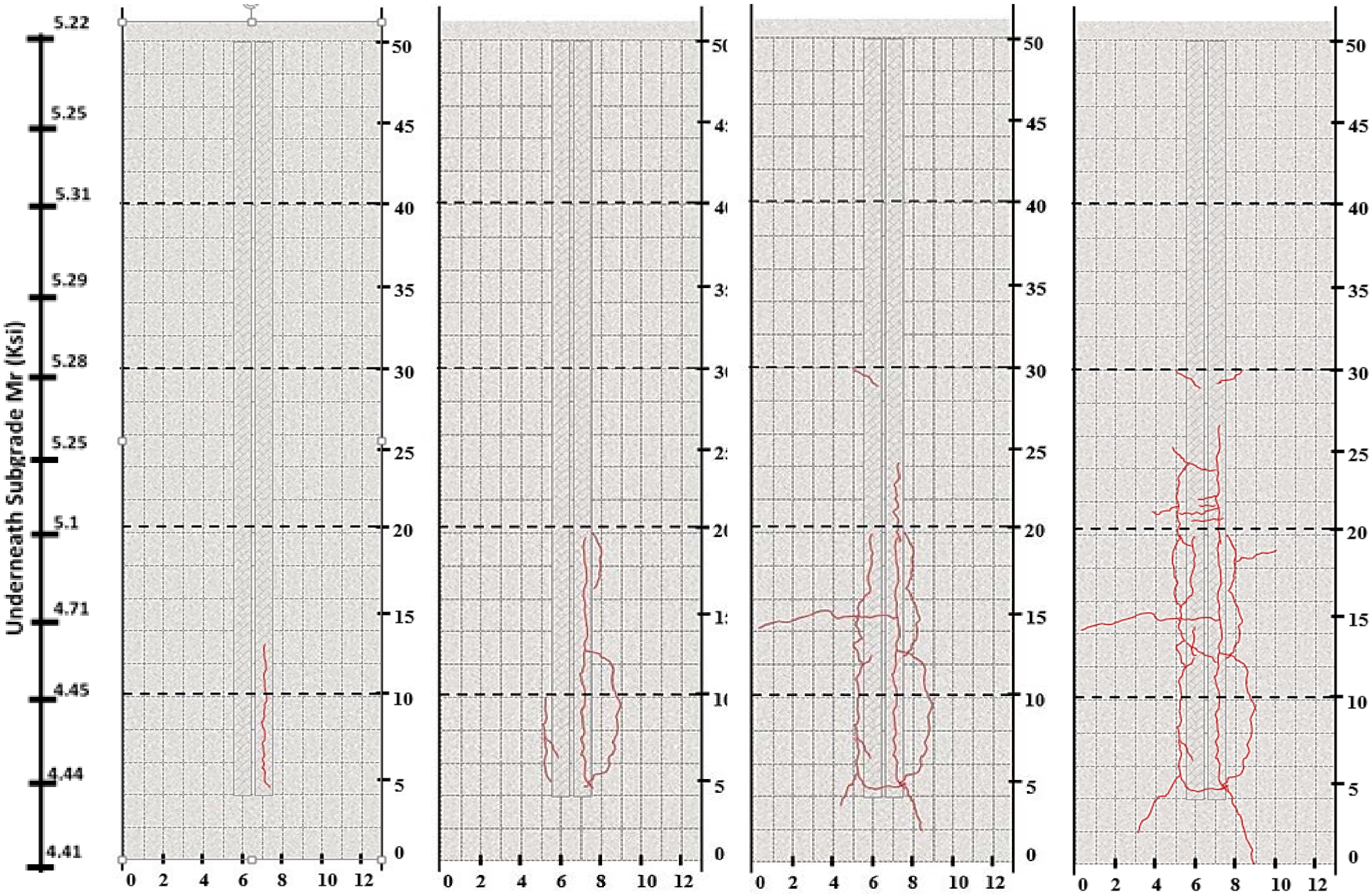
After 1,230,000 Load Repetition

After 1,500,000 Load Repetition

After 1,750,850 Load Repetition

# Crack Mapping on (4+8.5RCC) – Section 6

- **Crack Mapping**



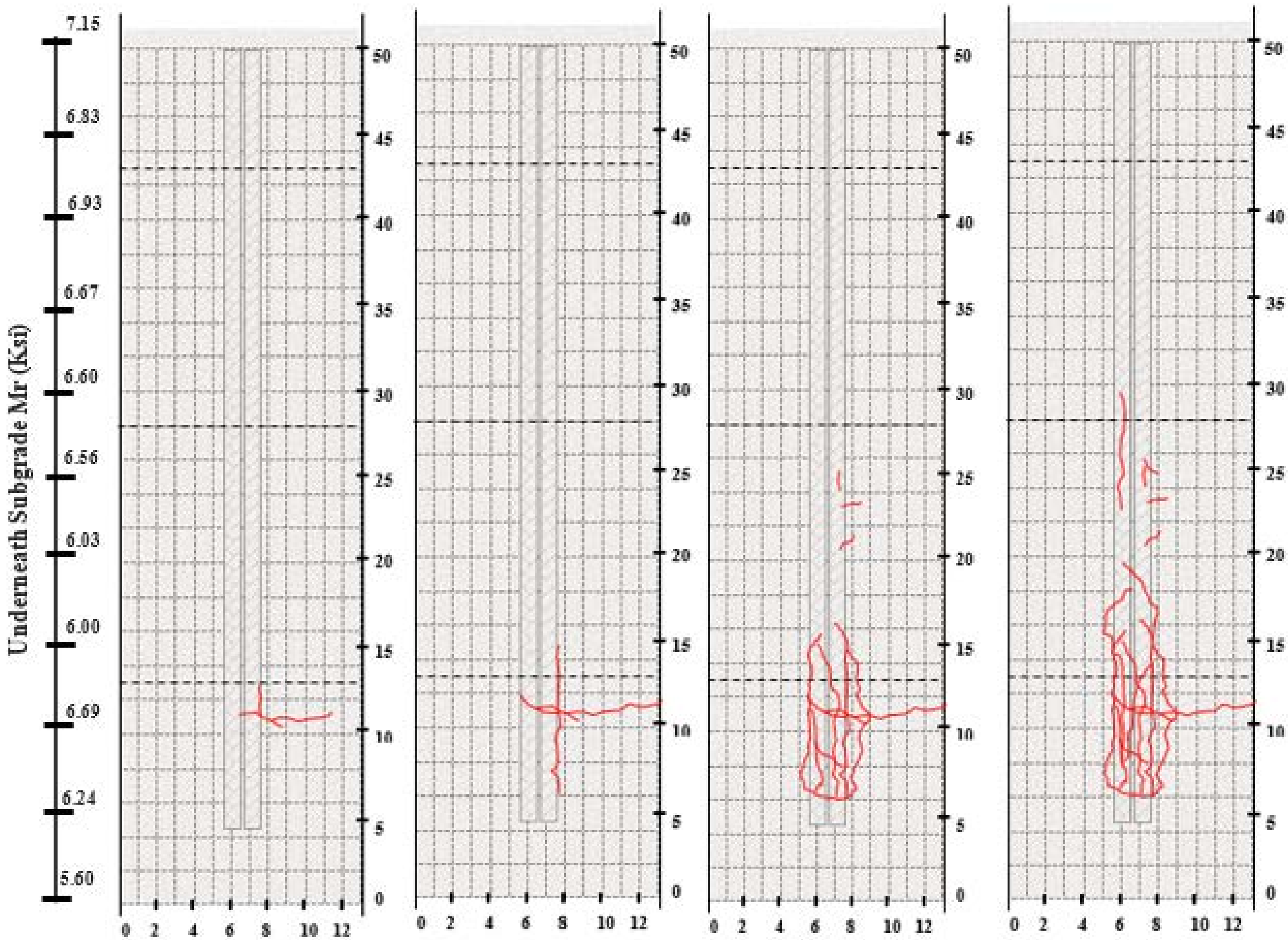

After 390,000 Load Repetition

After 480,000 Load Repetition

After 560,000 Load Repetition

After 706,500 Load Repetition

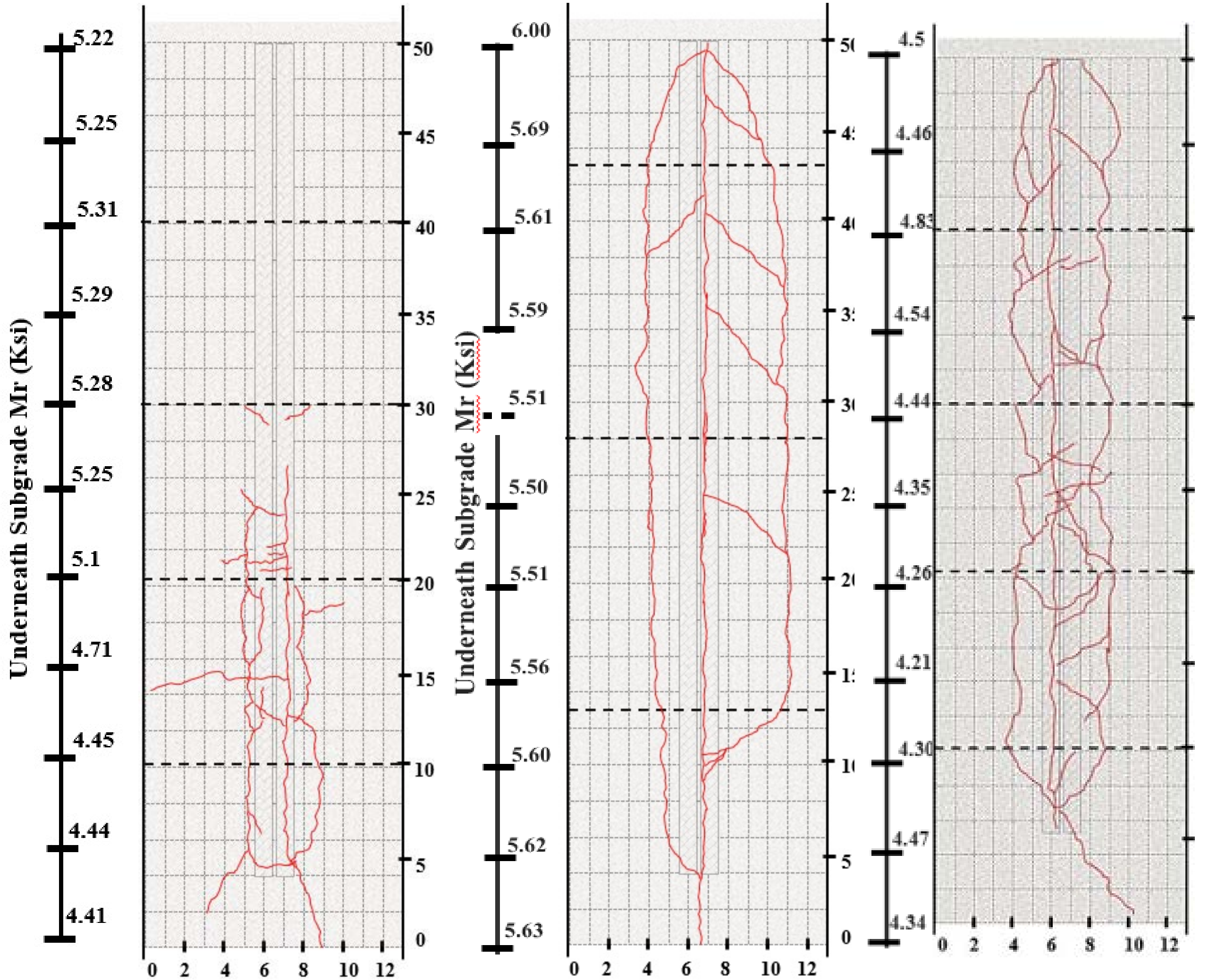
# Crack Mapping on (6+12RCC) – Section 2




After 455,000 Load Repetition | After 525,000 Load Repetition | After 550,000 Load Repetition | After 610,000 Load Repetition

# Comparison of Cracking Pattern of Failed RCC Sections

- Crack initiated at the weakest subgrade location
- Cracking pattern for thicker section was much wider than the thinner section
- Uniform subgrade resulted in a final cracking failure covering the entire loading area for <u>6+8.5RCC</u> & <u>4+12RCC</u>




4+8.5RCC 6+8.5RCC 4+12RCC

# Summary

- Except two 8” RCC test sections, the best performer is (6”RCC + 8.5” soil cement) section, with
  - Outstanding load carrying capacity, est. ESALs = 87.4 M;
  - Potential to be used for heavy-loaded, medium speed pavements;
- Sections (4”RCC+8.5” soil cement) and (6”RCC+12” cement treated) also performed very well
  - Both can carry large amounts of heavy traffic (half axle >20kips); Est. ESALs > 15 M
  - Surface IRI to be controlled during the construction
  - Potential to be used for low-volume roads with heavy truck traffic.

# Summary

- RCC sections failed under fatigue cracking. The observed fatigue cracks were initiated first either in the middle or at the edge of the tire print along a longitudinal direction;
- The width of fatigue cracking pattern was found much wider for 6-in RCC sections (e.g. 6+8.5RCC) than that for 4-in. RCC sections
- RCC-Pave fatigue models were found not suitable for the fatigue life prediction of thin RCC sections evaluated.
- Two preliminary fatigue models for thin RCC pavement fatigue analysis have been developed
  - Will finalize the developed fatigue model
  - Will perform cost-benefit analysis
  - Will build a Finite element model to simulate thin-RCC pavement

# Conclusions

- 450 pcy mixture chosen for desired surface characteristics and density
- 4000 psi strengths were easily achieved
- Speed of construction affected density, IRI, and surface characteristics
- 100-130 IRI values and 5000 psi+ strengths may be expected in full scale construction efforts
- Thin RCC can hold a significant amount of load

# RCC Implementation

- The ATLaS30 loading results generally indicate that
  - a thin-RCC over soil cement pavement structure has a superior load carrying performance
  - Recommendation to select and build several field RCC test sections on those Louisiana highways where the pavements are often encountered by heavy truck loading
    - To validate the APT performance and provide further implementation guidelines
  - ***Will not test the 8-inch sections to failure!***

# Acknowledgements

- FHWA, LADOTD, and LTRC
- Greg Tullier, Craig Johnson, and Norris Rosser
- George Crosby, Keith Gillespie, Alphonse Vallery
- Holcim, LaFarge, Buzzi Unicem, Vulcan Materials
- Cemex, Rollcon, and Gilchrist

# Effect of RCC Mixture Constituents on Physical and Mechanical Properties

**Prof. Jeffery Roesler, Ph.D., P.E**
Department of Civil and Environmental Engineering
University of Illinois Urbana-Champaign

RCC: Recent Research and Development

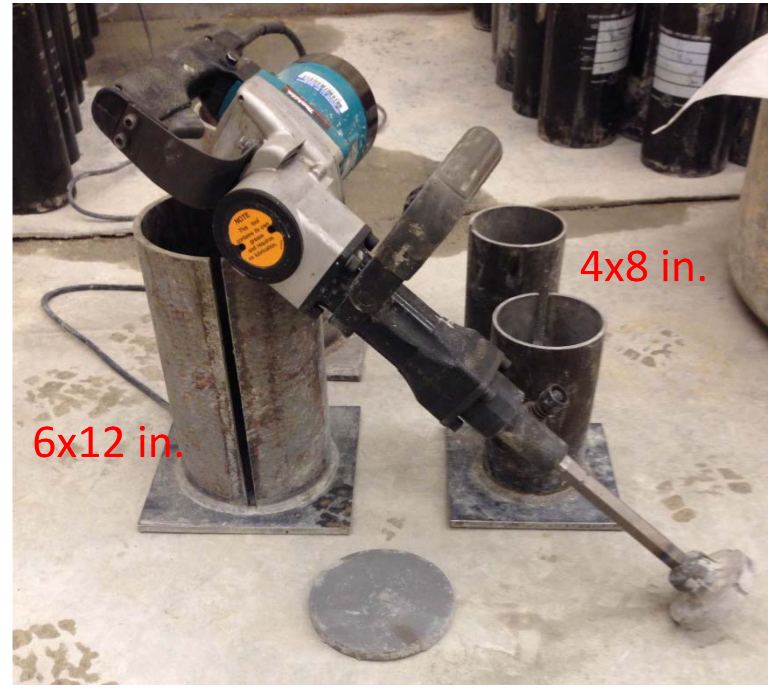
*November 30, 2016*

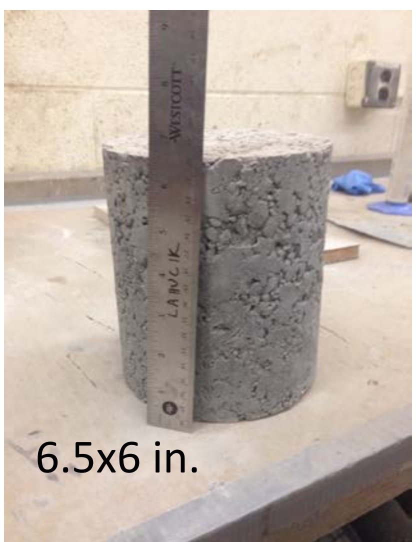
# ACKNOWLEDGMENTS


- **Jeff LaHucik**, MS thesis in CEE (2016)

  *Selecting Material Constituents and Proportions for Specific Roller-Compacted Concrete Mechanical Properties*
- UIUC students: Josh Cheung, Douglas de Andrade, Juan Pablo Mendez-Ruiz
- Illinois Department of Transportation (IDOT)
  - Illinois Center for Transportation (ICT)
    - ICT-R27-149
    - Chuck Wienrank, TRP chair

# Specimen Fabrication & Geometry


3x6 in.

6x12 in.

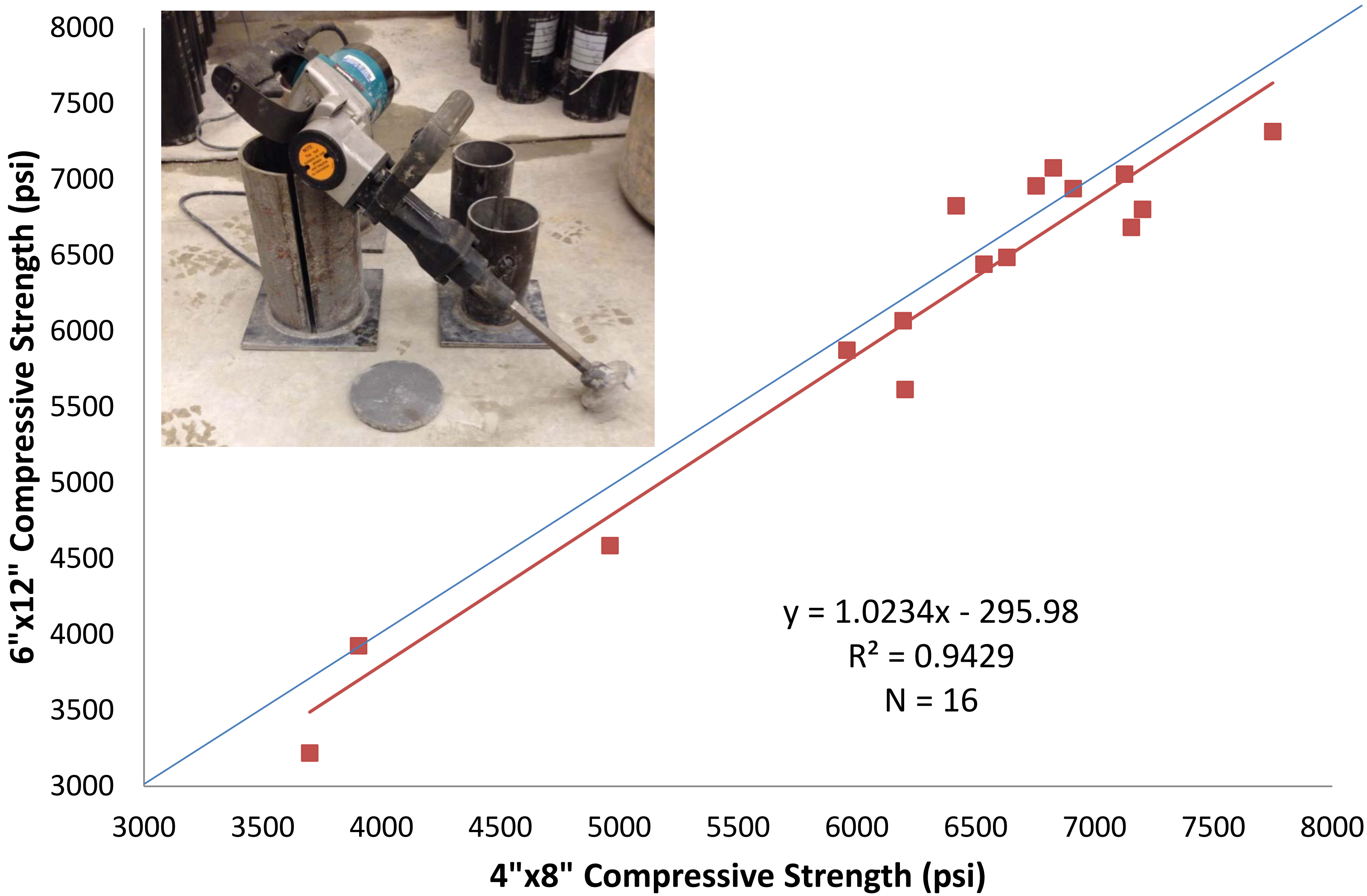
# Specimen Fabrication

- 6x12" Cylinders: strength and DCT fracture testing
  - ASTM C1435: Molding RCC in cylinder molds using a vibratin
  - 5.5" diameter compaction plate
  - RCC placed in 5 lifts, each lift vibrated until visible mortar ri (i.e. about 3-5 seconds)

- 4x8" Cylinders: strength testing
  - 3.5" diameter compaction plate
  - RCC placed in 3 lifts, each lift vibrated until visible (i.e. about 3 seconds)

- 6x6x21" MOR Beams: flexural strength ar
  - Draft ASTM standard, placed in 2 lifts with vibrati
- 4x4x16" MOR Beams: flexural strength
  - RCC placed in 2 lifts with vibrating hammer
- 3x3x11.25" Shrinkage Beams: drying shrinkage
  - RCC placed in 2 lifts with each lift vibrated with the vibr and a rectangular plate for 5 seconds.

# Potential for 4x8" Cylinders for QC/QA

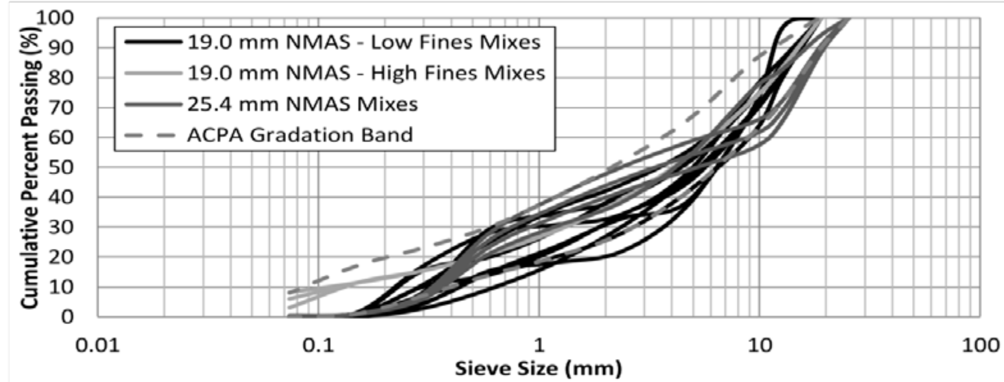


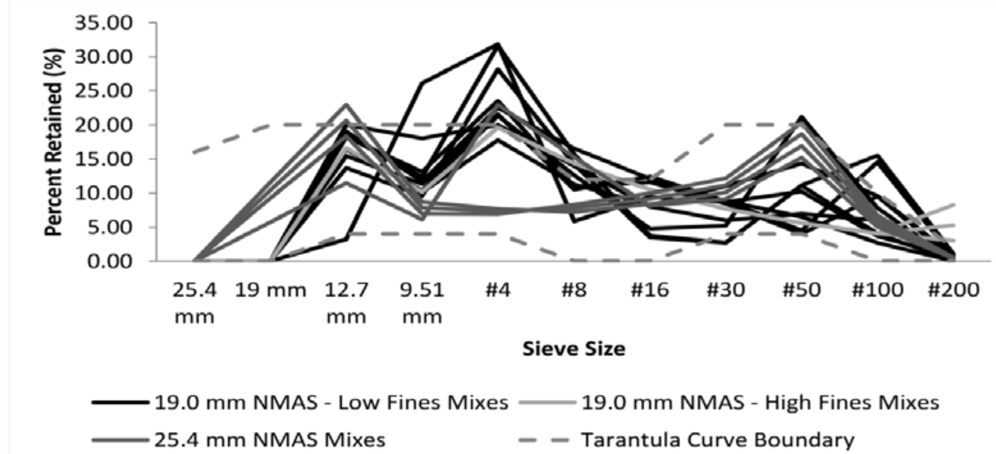
# Effect of Aggregate Gradation

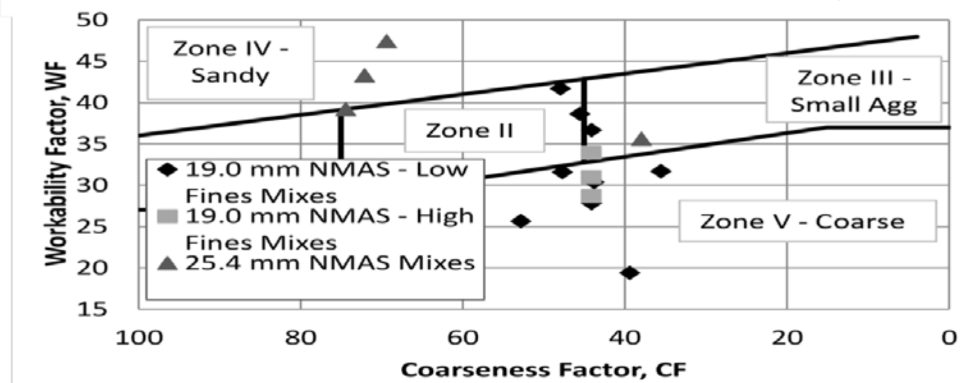
- 16 gradations tested
- Fixed cement content (282 kg/m$^3$)
- Same aggregate sources

- Gradations cover wide range
  - Within and outside recommended RCC gradations
- General agreement with Tarantula curve
  - Developed for lean concrete pavements

- Non-agreement with Coarseness Factor chart (Zone II)
  - Developed for slip-formed concrete pavements



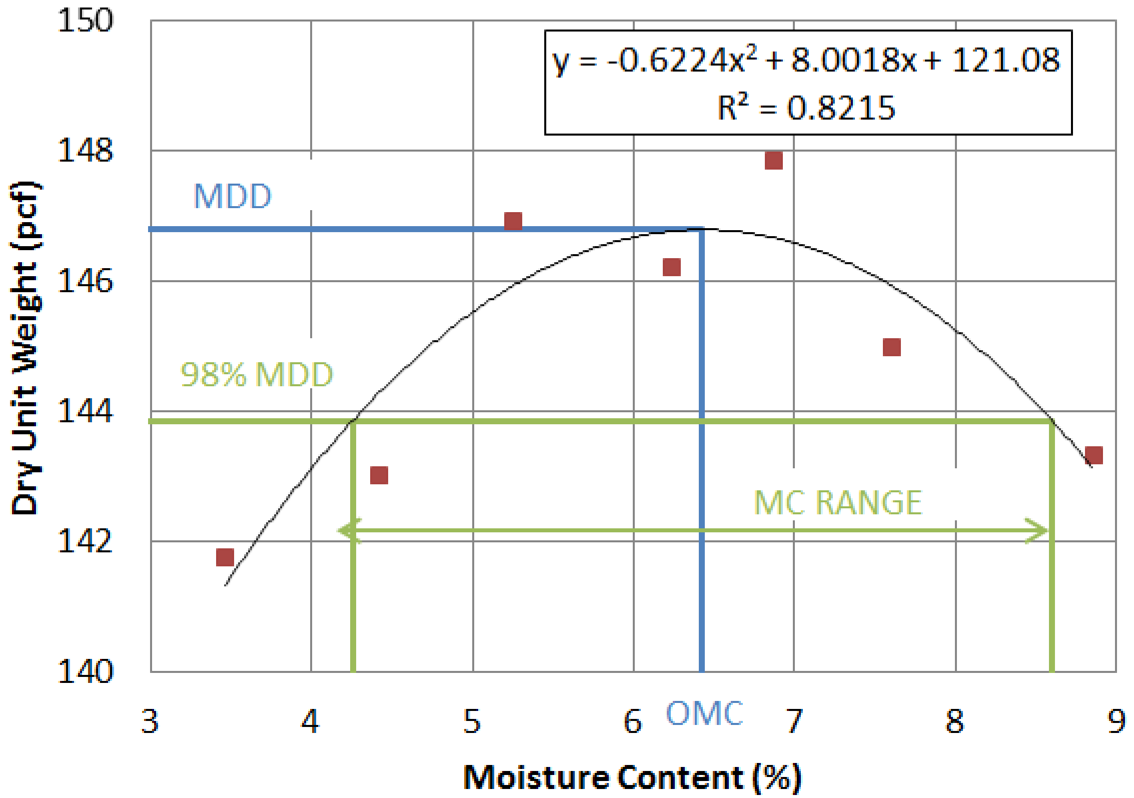



# Mix Design: Moisture Density Relationship

- Modified Proctor tests were conducted to determine maximum dry density (MDD) and optimum moisture content (OMC) for each mix

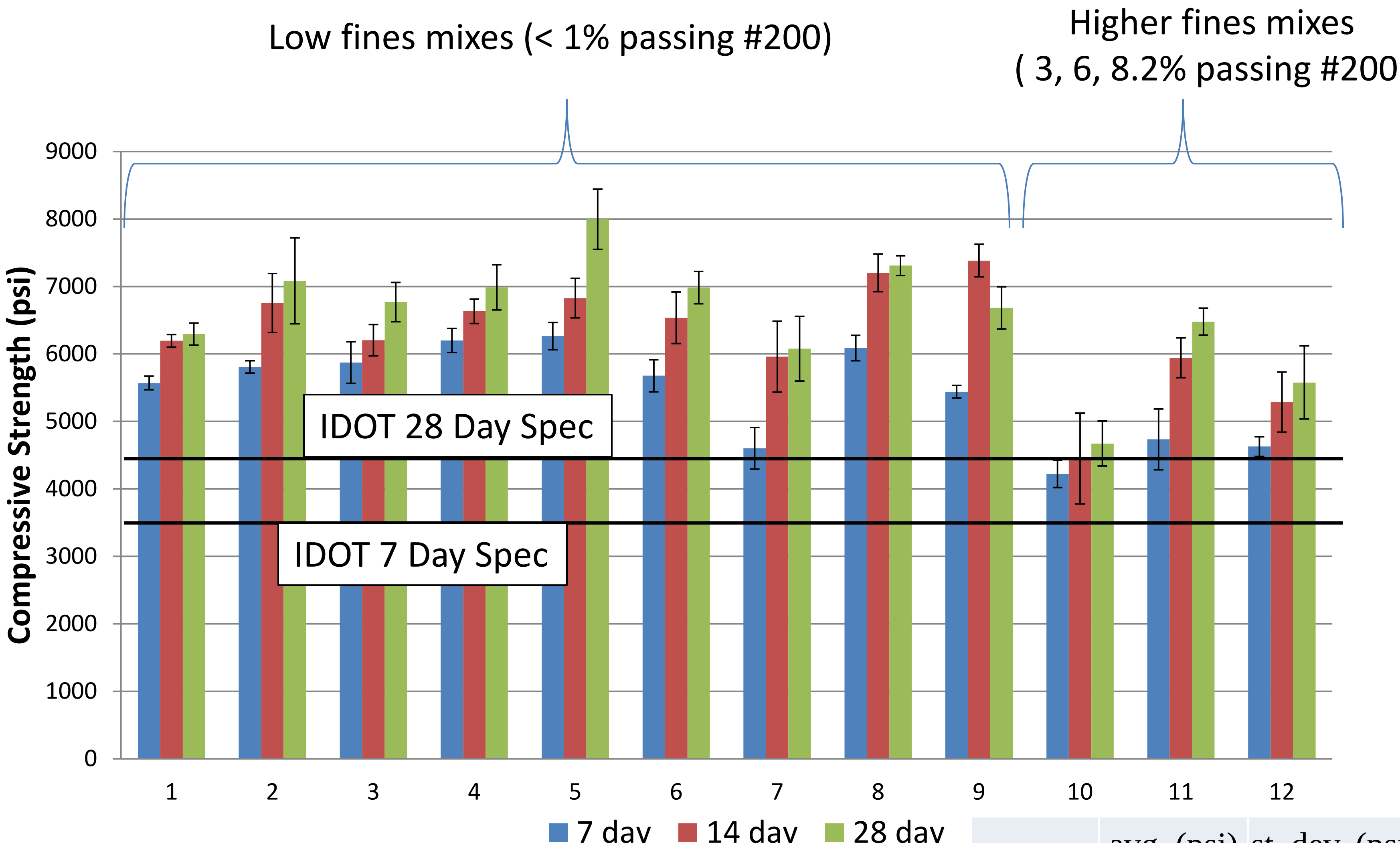
- OMC: 6.1 – 7.2%
- MDD: 145.4 – 152.1 pcf
- MC range of ***2.9 – 5.1%*** to achieve 98% MDD



# Effect of Aggregate Gradation – Fresh Properties

- Modified Proctor Testing:
  - Similar MDD for all 16 gradations
    - 2,330 to 2,440 kg/m$^3$
  - Similar OMC for all 16 gradations
    - 6.1 to 7.1% with most being 6.4 to 6.8%
- Vebe Testing (right):
  - Measure time to form mortar ring
    - Typically under 25 seconds for low fines gradations
    - Higher aggregate fines mixes had 30-40 seconds
    - ACI recommends 30-40 seconds for RCC pavements

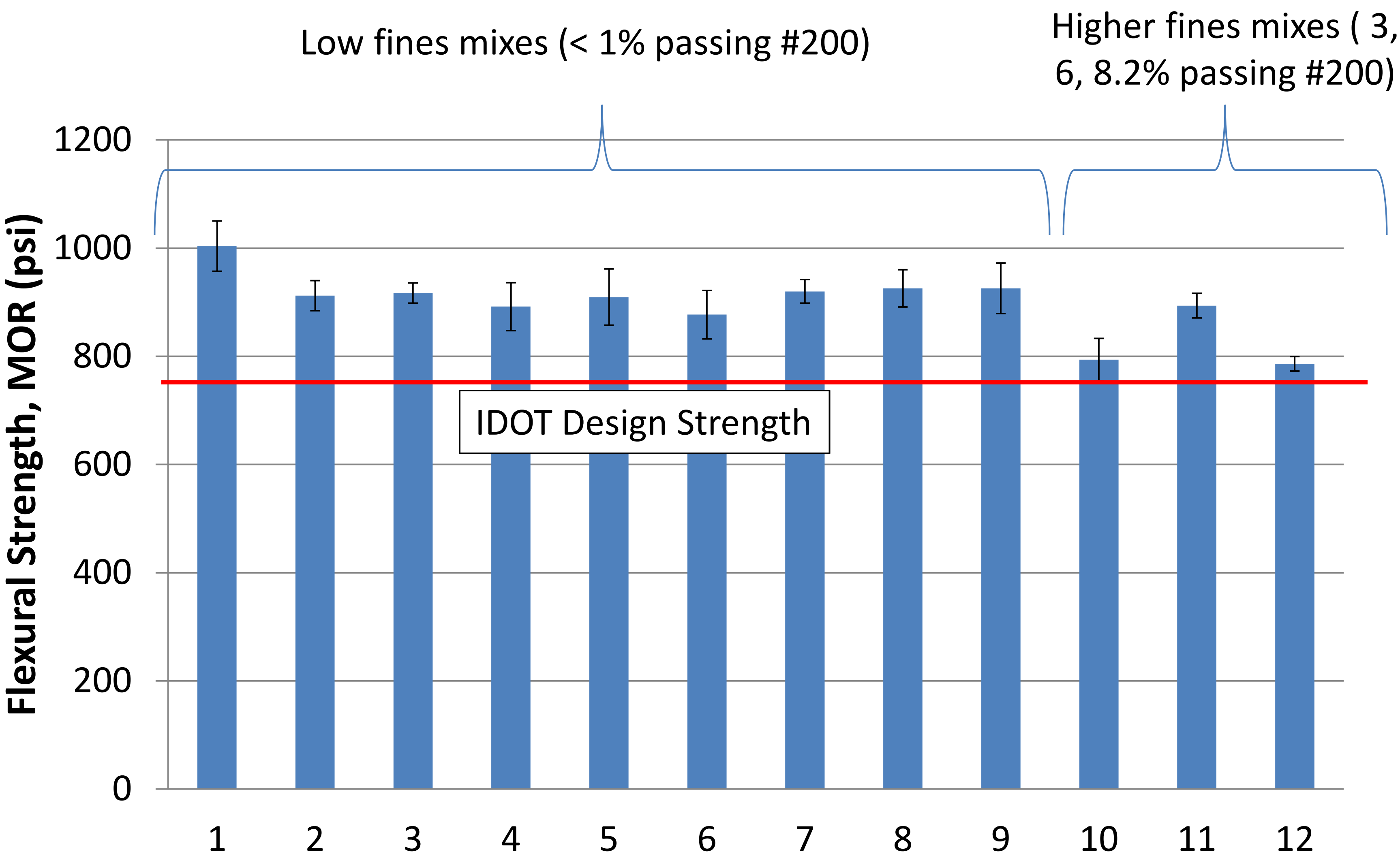
# ¾" NMAS Compressive Strengths




| | avg. (psi) | st. dev. (psi) |
|---|---|---|
| 7 day | 5425 | 702 |
| 14 day | 6281 | 817 |
| 28 day | 6576 | 861 |

*error bars indicate one standard deviation

# 28-Day Flexural Strengths (4x4x16”)



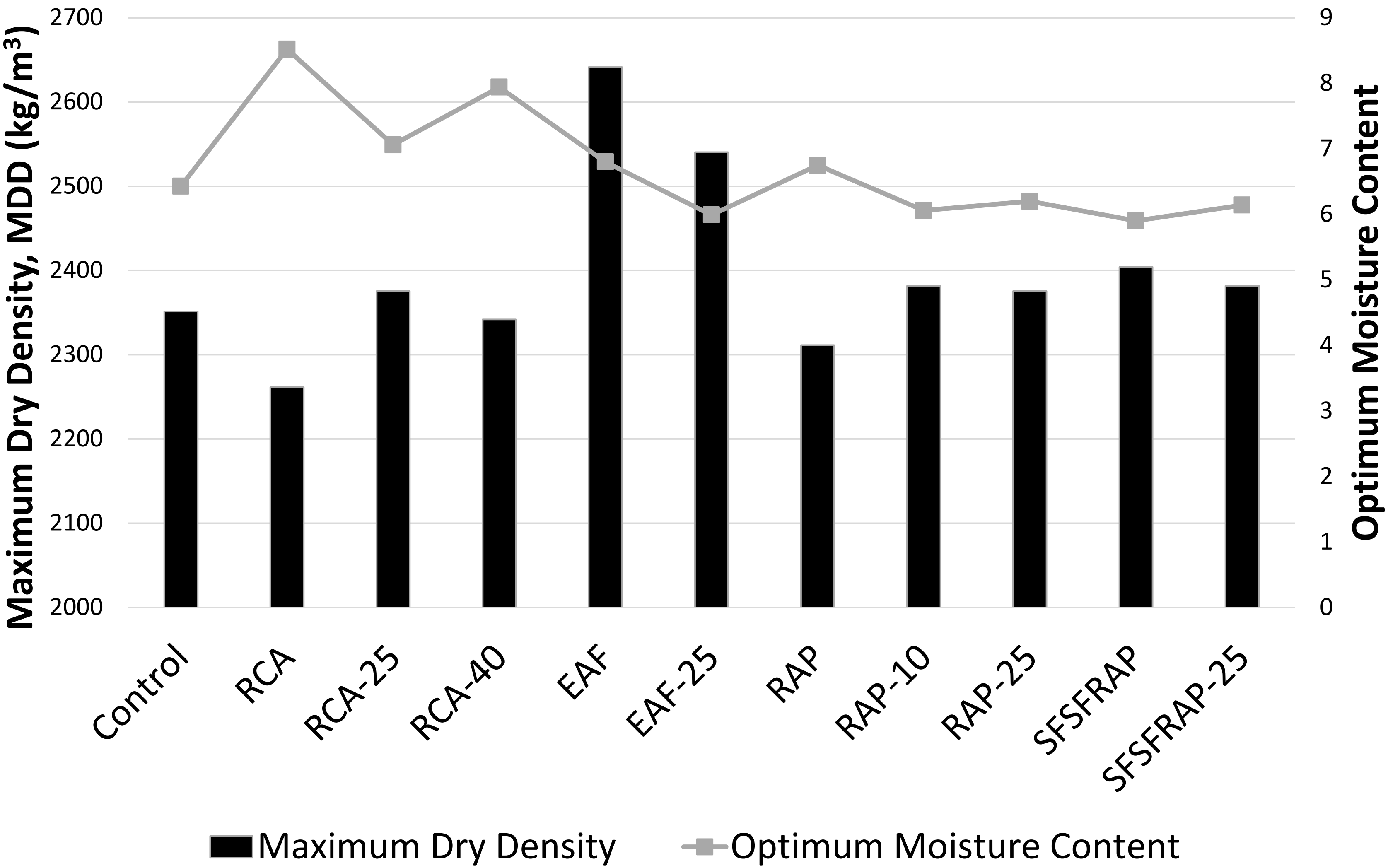
# Recycled Aggregates & RCC

- Tested 4 recycled aggregates:
  - Recycled concrete aggregate (RCA)
  - Electric Arc Furnace steel furnace slag aggregates (EAF - SFS)
  - Reclaimed asphalt pavement (RAP)
  - RAP with SFS (SFSFRAP)
- Fixed cement content (282 kg/m$^3$)

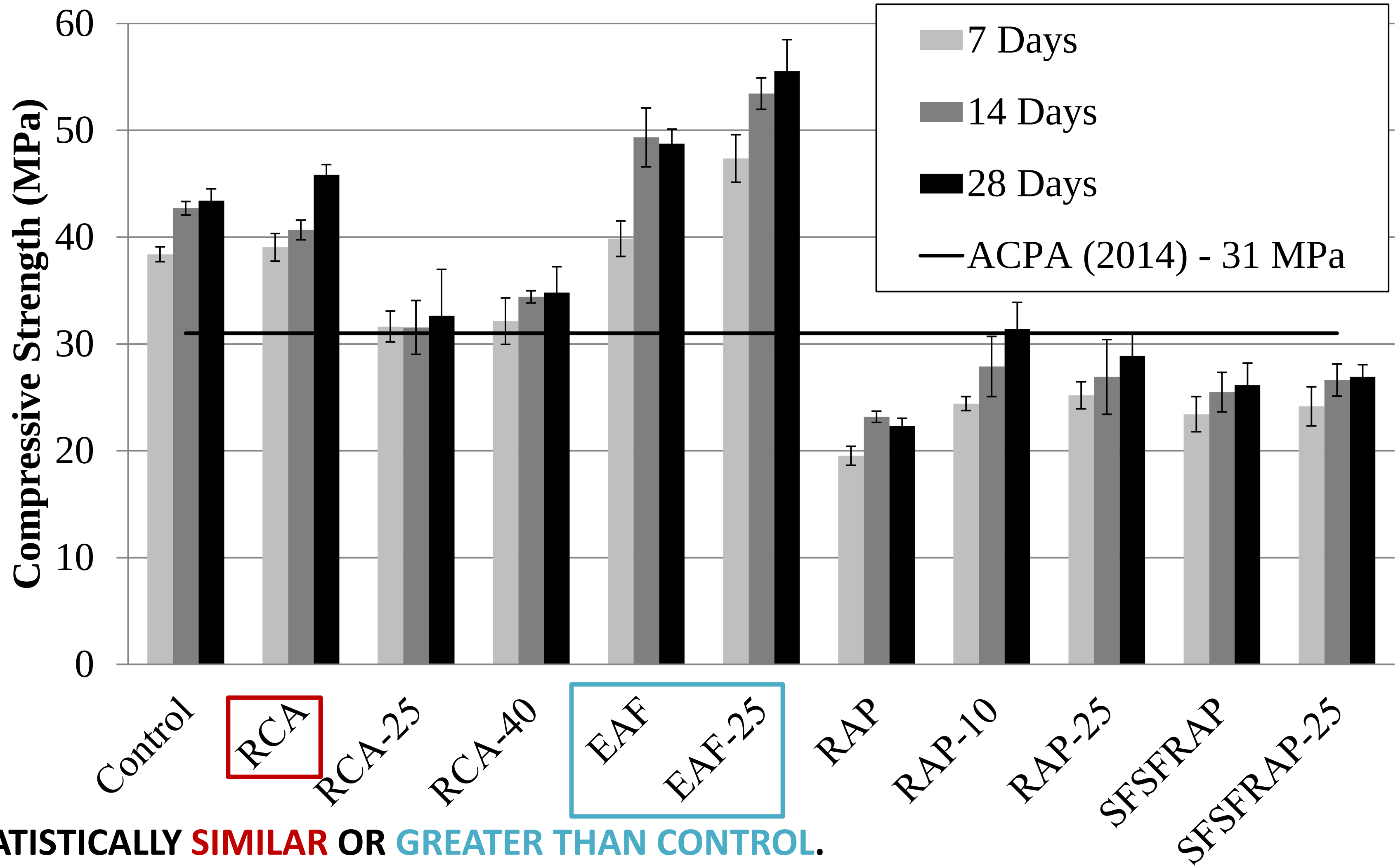
- Mix Nomenclature:
  - Control: Virgin aggregate RCC
  - EAF, RAP, RCA, SFSFRAP: 40% replacement of total aggregate and same gradation as control
  - EAF-X: X% replacement of total aggregate (not necessarily same gradation as control)



# Moisture - Density



# Compressive Strength – 100x200 mm

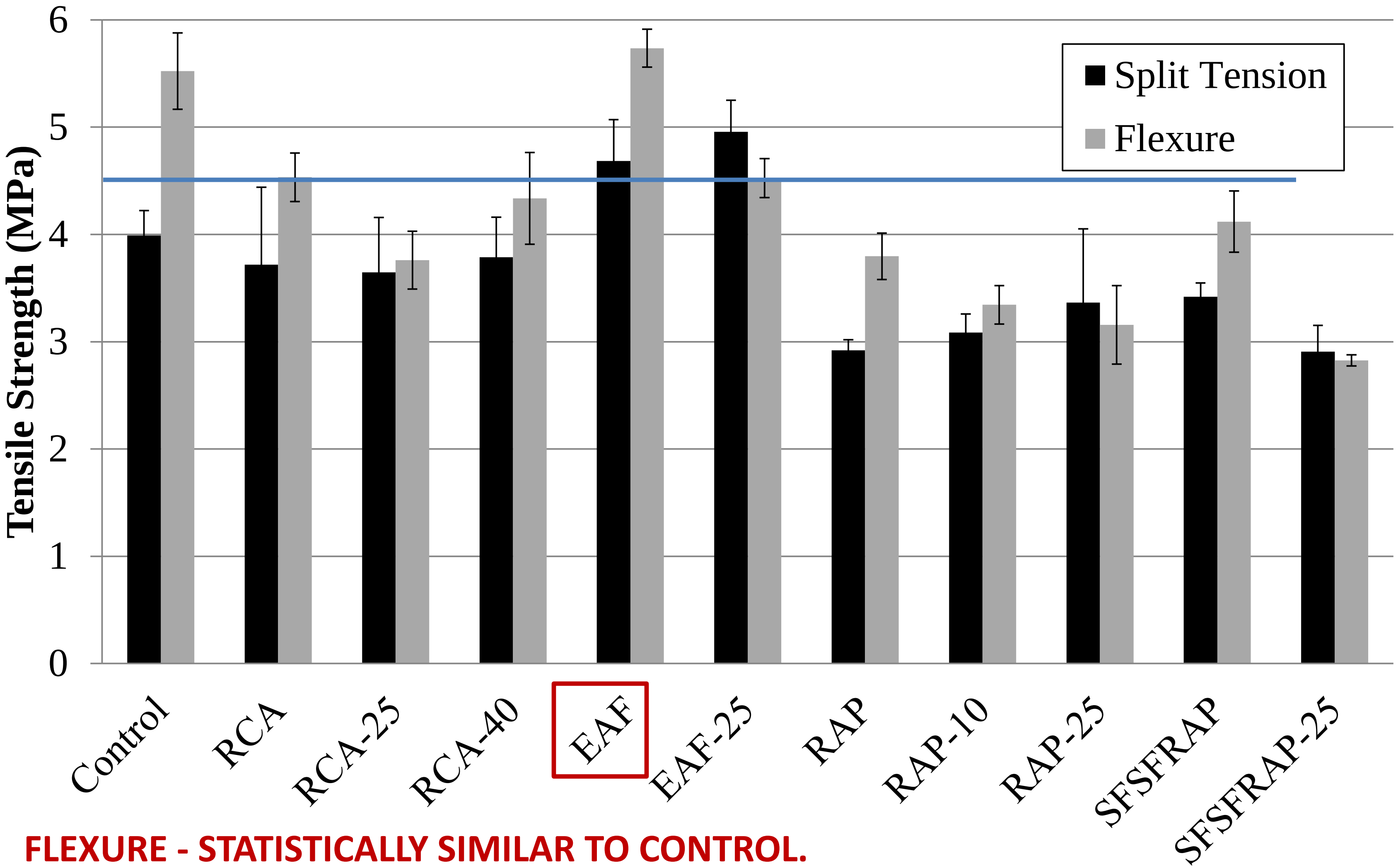



**-STATISTICALLY SIMILAR OR GREATER THAN CONTROL.**

**-ALL OTHERS STATISTICALLY LESS THAN CONTROL.**

**-RAP & SFSFRAP don’t meet min. strength**

# 28-Day Tensile Strength – Split and Flexure

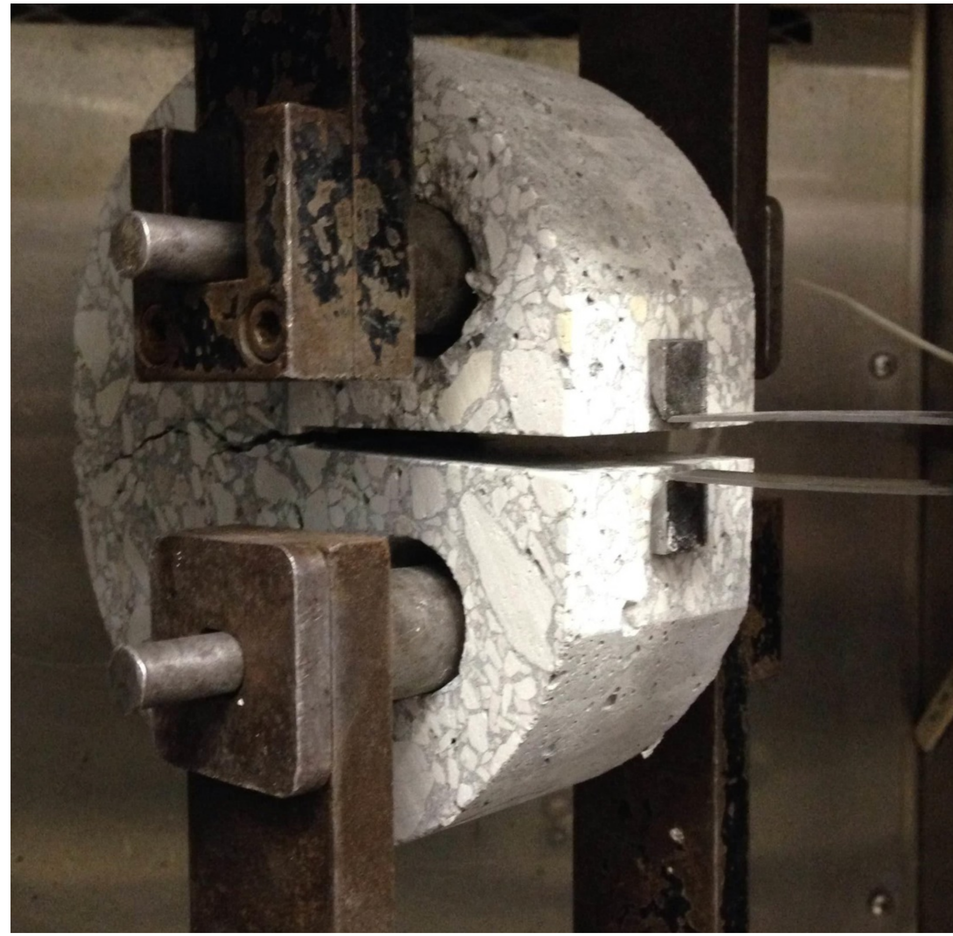



**FLEXURE - STATISTICALLY SIMILAR TO CONTROL.**

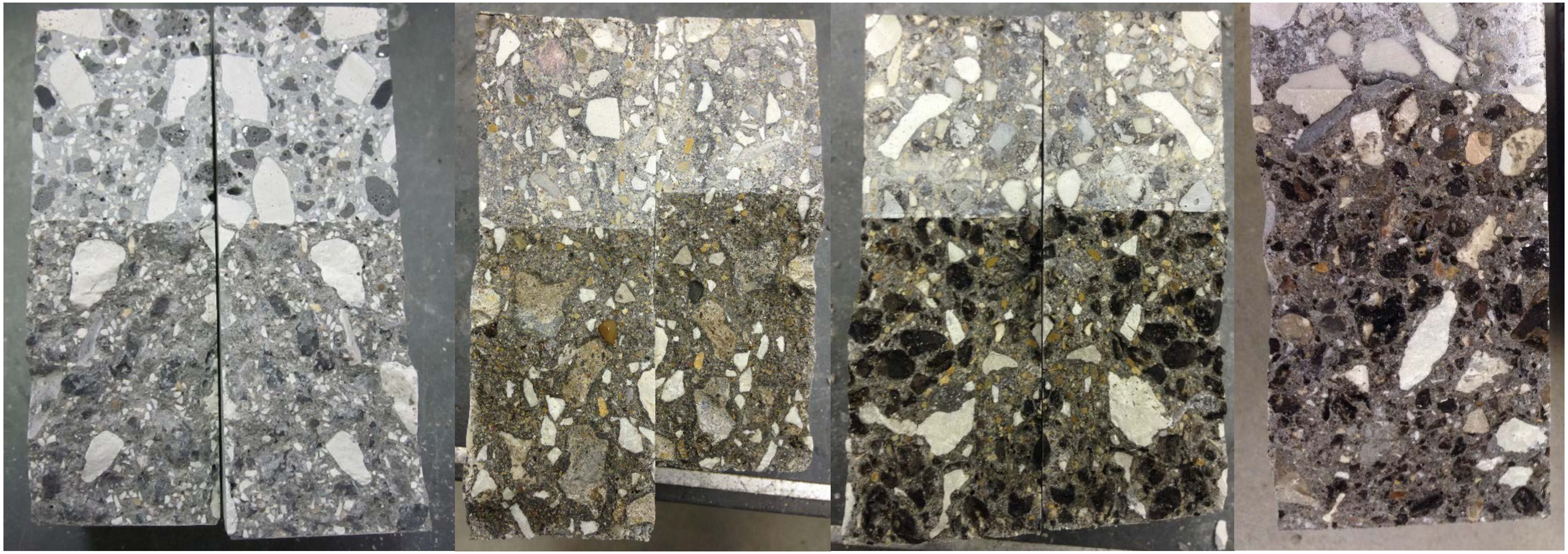
**FLEXURE - ALL OTHERS STATISTICALLY LESS THAN CONTROL.**

# Fracture Properties - Procedure

- Disk-shaped compact tension (DCT) geometry
  – Cut specimens into “pucks”
  – Notch specimen to create stress concentration
  – Load in tension
  – Measure Load-Crack Opening Response
- Fracture Mechanics
  – Good indicator of flexural slab capacity



# DCT Specimens



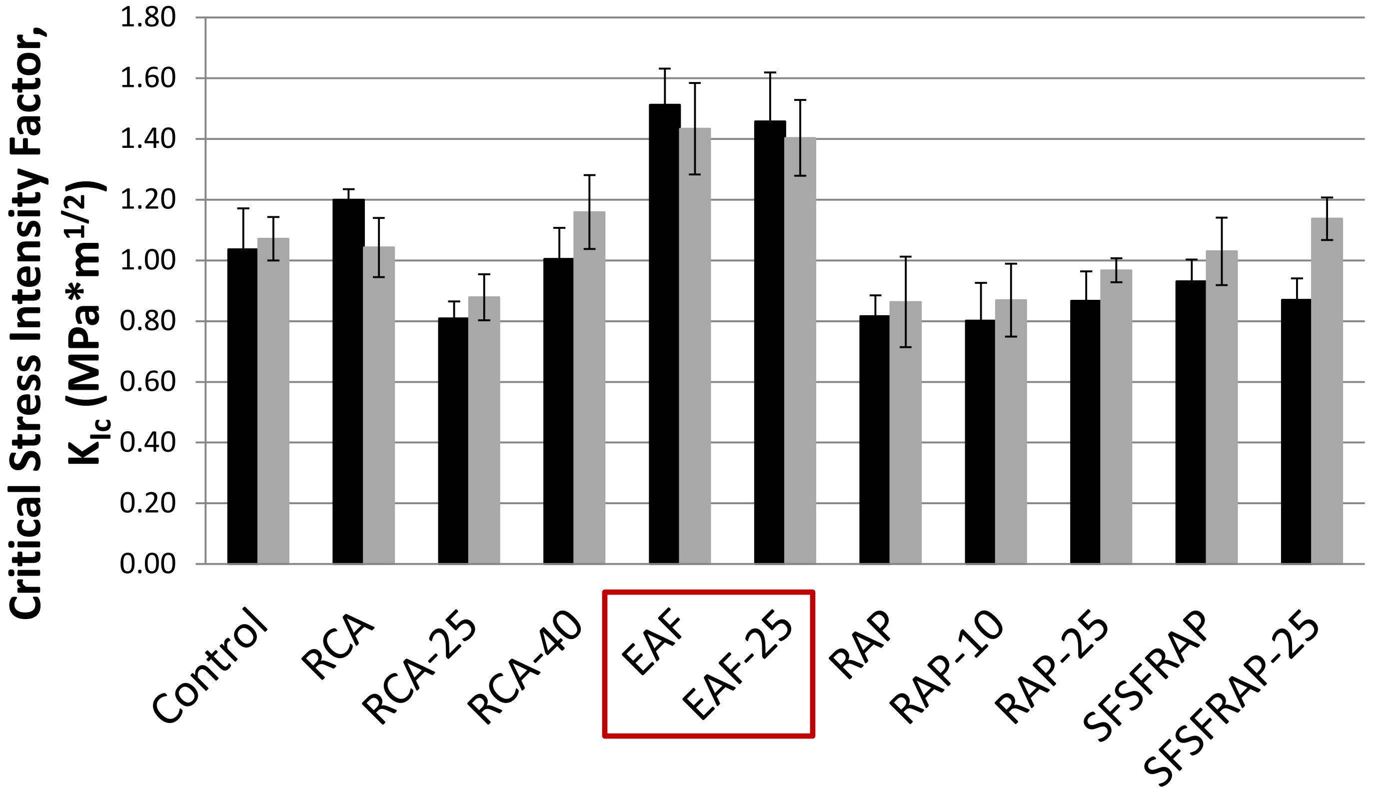
**EAF** **RCA** **SFS - FRAP** **RAP**

Fracture Surfaces:

- EAF and RCA fracture through aggregate
- SFS-FRAP and RAP fracture around aggregate

# Critical Stress Intensity Factor

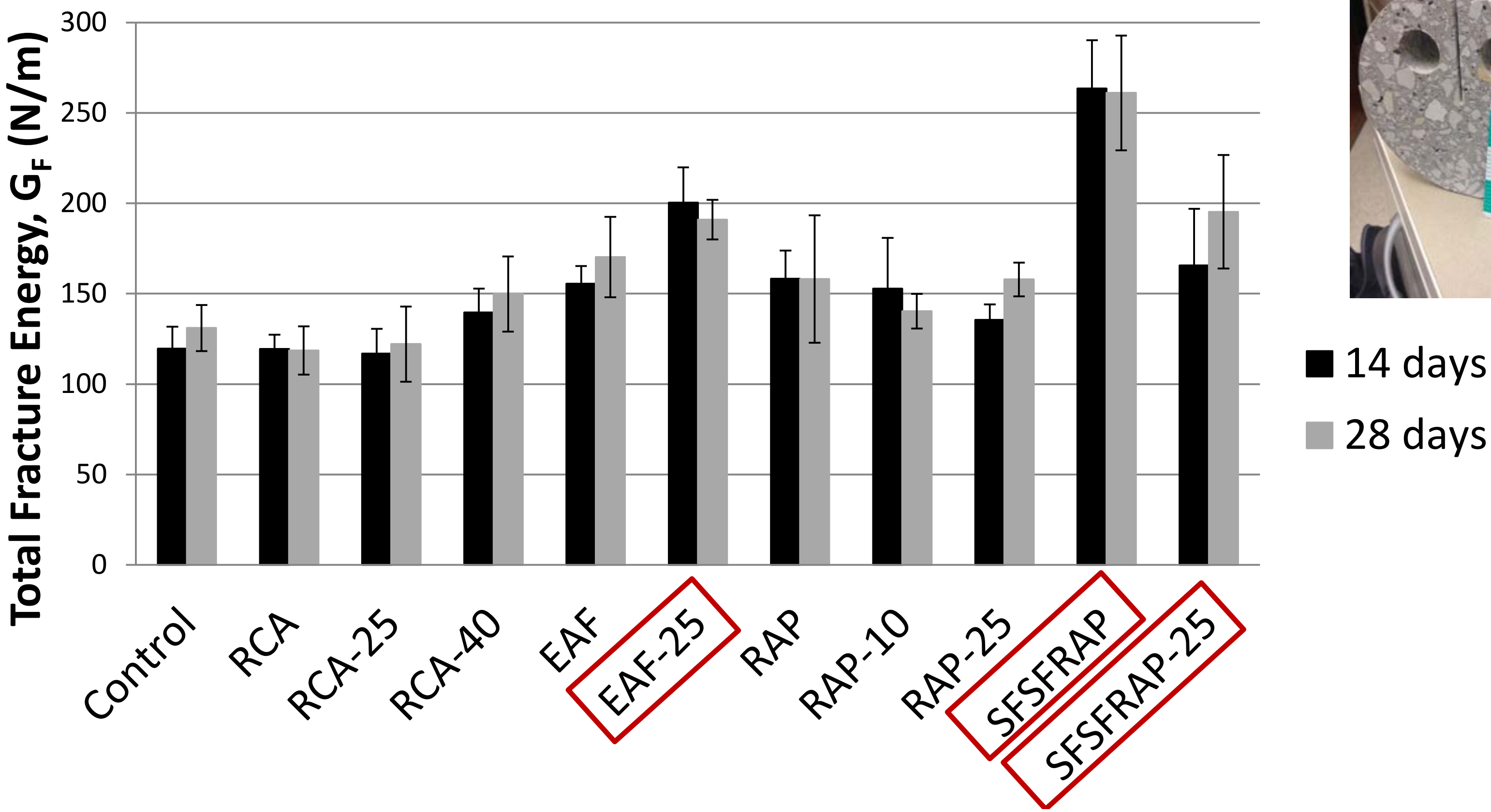
- Material property indicating resistance to crack initiation




**- ALL MIXTURES STATISTICALLY SIMILAR OR GREATER THAN CONTROL.**

# Total Fracture Energy

- Material property indicating resistance to crack propagation



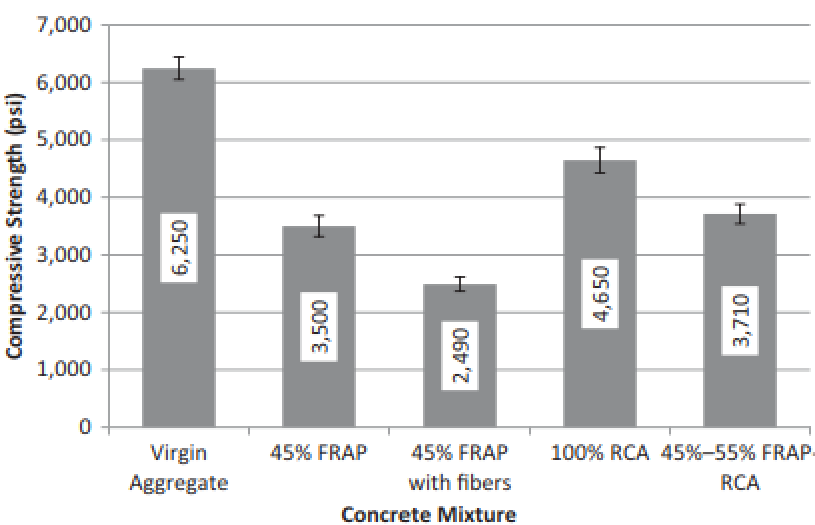

**ALL MIXTURES STATISTICALLY SIMILAR OR GREATER THAN CONTROL.**

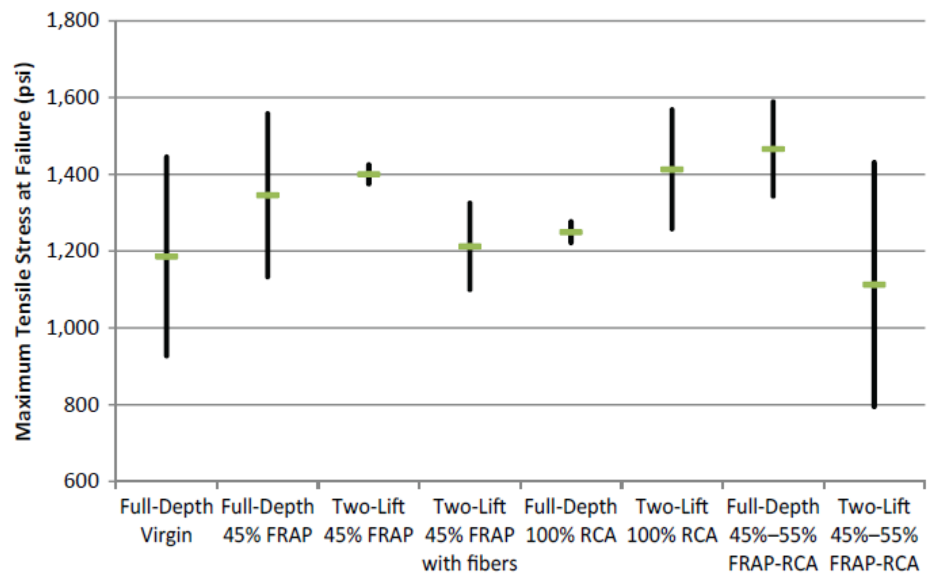
# Flexural Slab Capacity – PCC

**TABLE 4 Concrete Fracture Parameters** (Brand et al. 2014)

| Concrete Mixture | Peak Load, P (kN)[a] | Critical Stress Intensity Factor, $K_{Ic}$ (MPa m$^{1/2}$)[a] | Critical Crack Tip Opening Displacement, CTOD$_c$ (mm)[a] | Initial Fracture Energy, $G_{Ic}$ (N/m)[a] | Total Fracture Energy, $G_F$ (N/m)[a] |
|---|---|---|---|---|---|
| Virgin aggregate | 3.57 (9.8) | 1.146 (15) | 0.0191 (24) | 44.3 (22) | 73.8 (7.3) |
| 45% FRAP | 2.83 (8.3) | 0.898 (10) | 0.0205 (40) | 36.6 (25) | 75.7 (6.8) |
| 45% FRAP with fibers | 2.39 (5.0) | 0.760 (8.0) | 0.0205 (13) | 29.7 (10) | 3,193 (29) |
| 100% RCA | 3.18 (13) | 0.953 (11) | 0.0160 (27) | 35.0 (22) | 84.5 (0.1) |
| 45%–55% FRAP-RCA | 3.15 (8.9) | 0.920 (14) | 0.0177 (10) | 38.5 (19) | 84.3 (14) |

Recycled Aggregates ➡ Lower Strength ➡ Similar Fracture Properties ➡ Similar Slab Capacity



# Motivation of RCC with Macro-Fibers

- No steel across joints
  - Load transfer has been reported to be as low as 20% (Nanni and Johari, 1989)
    - Fibers have been shown to maintain load transfer (Roesler et al. 2012)
- Delay onset of HMA reflective cracking for composite pavements
  - Keep crack widths tight
- Thickness reduction
  - Account for residual strength (ASTM C1609)
- Lower crack deterioration rates

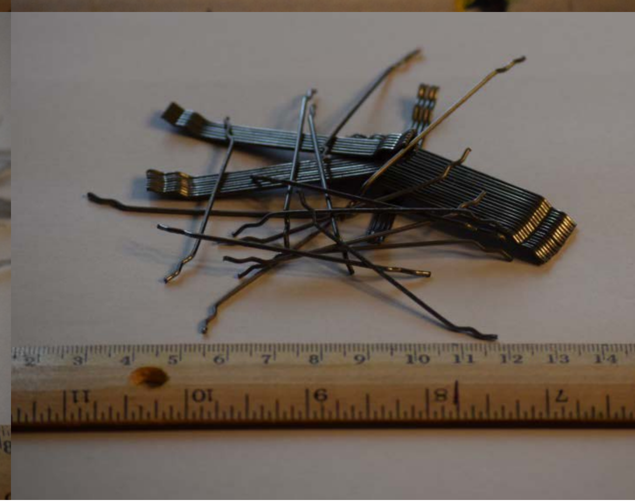
# RCC with Macro-Fibers (FR$^2$C$^2$)

Emboss-48

Smooth-40

Emboss-50

Smooth-58

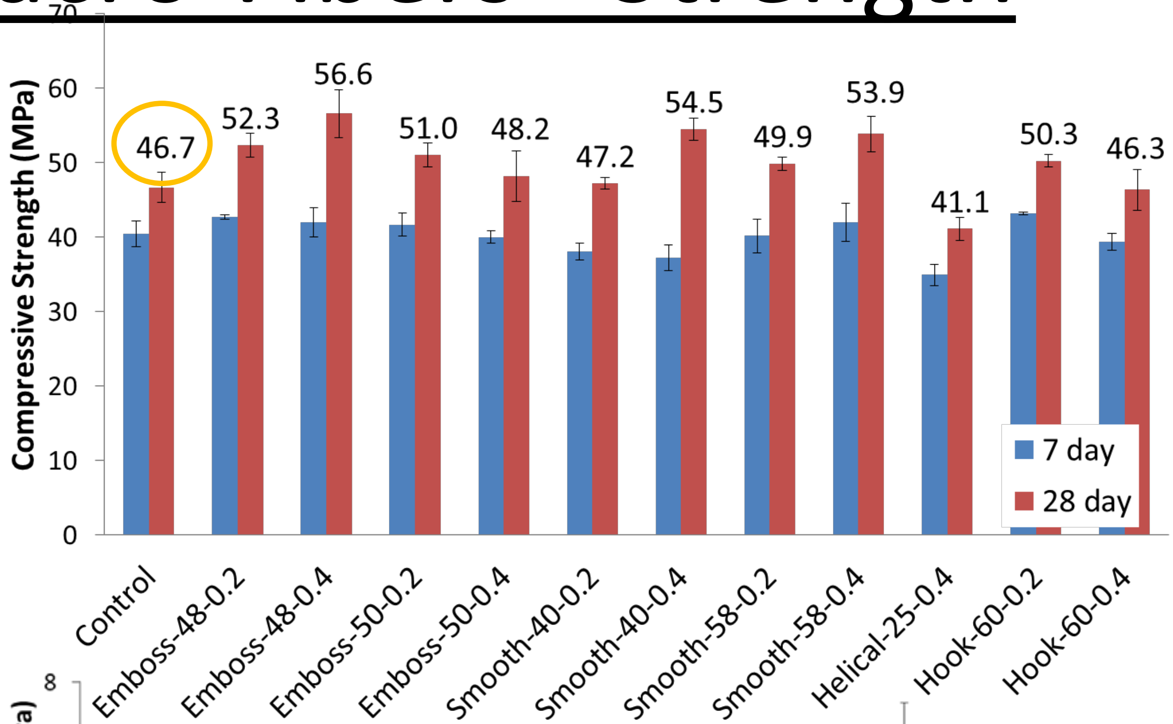


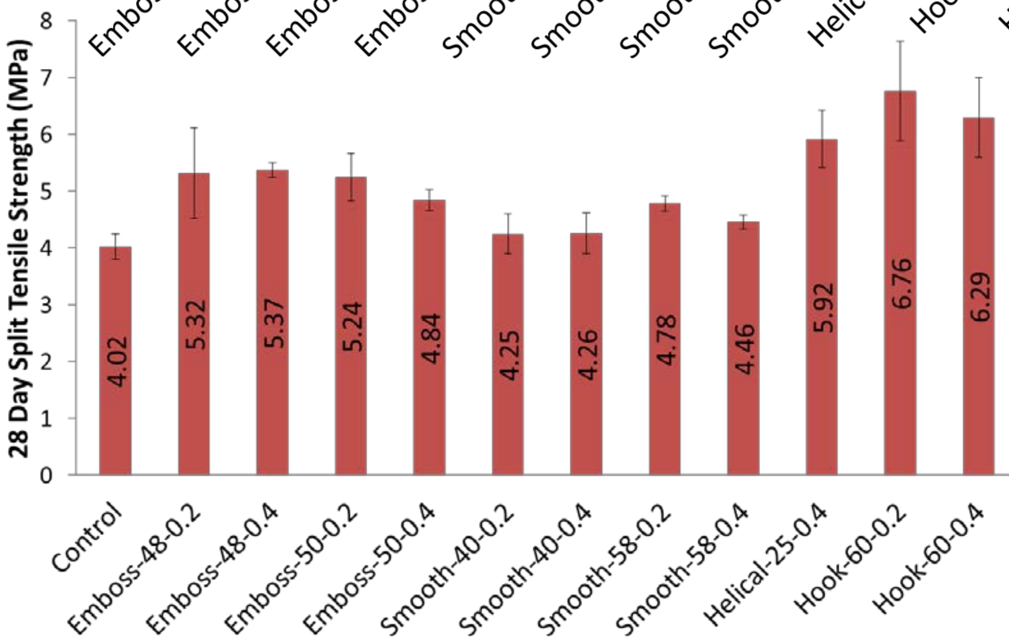
Hook-60

Helical-25

# RCC with Macro-Fibers - Strength

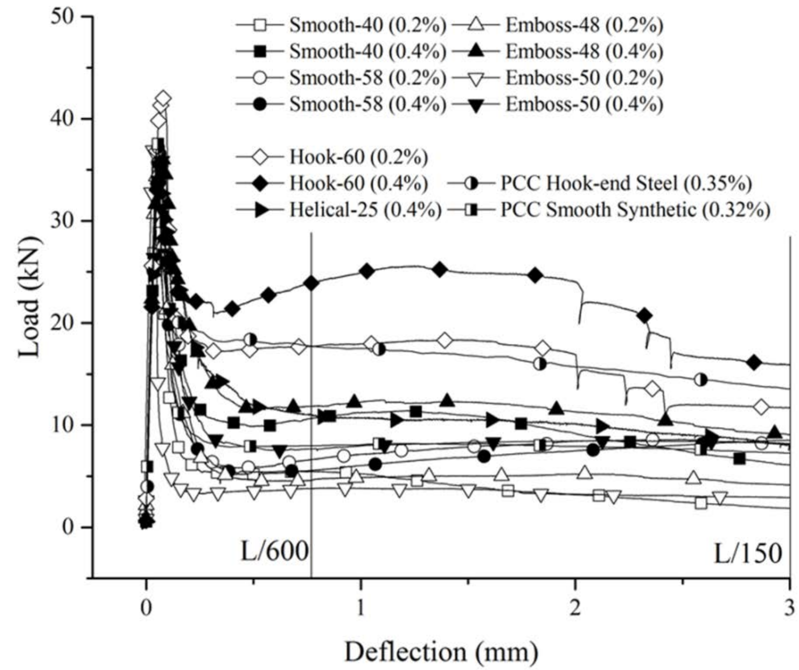
- Compressive strength unaffected
- Split tensile strength improved
  - Significantly for steel fibers
- Elastic modulus not affected
- Increased strengths with polymer fibers lead to increased RCC density

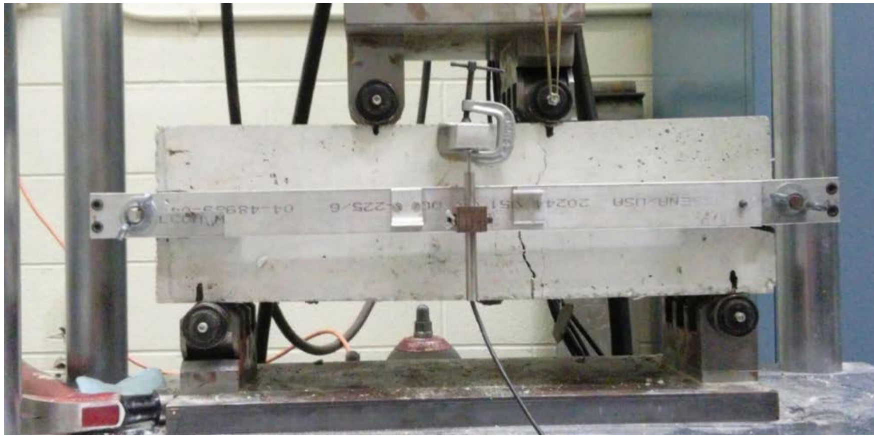


# $FR^2C^2$ – Flexural Toughness Testing

- Residual strengths from fiber-reinforced RCC ($FR^2C^2$) similar to fiber-reinforced PCC (FRC)
  - Some synthetic fibers showed lower residual strengths in RCC than PCC
- Equivalent flexural strength ratio of $FR^2C^2$ similar or lower than conventional FRC



# Summary: RCC with Macro-Fibers

- Macro-Fiber reinforcement of RCC feasible
  - Need more field trial
  - *Andale* built many $FR^2C^2$ roads past 4 yrs
- Polymer fibers may increase RCC density
  - Lead to increase in strength properties
- Flexural toughness properties similar to FRC paving mixes
- Fracture properties of RCC and $FR^2C^2$ equal to greater than PCC and FRC

# *Field vs. Lab RCC – Compressive Strength

| | | Specimen Size | | |
|---|---|---|---|---|
| | | 75x150 mm | 100x100 mm | 100x200 mm |
| Site A | Lab | | | 49.2 (3.5) |
| | Field | | | 39.3 (14.2) |
| Site B | Lab | 57.0 (4.3) | | 52.6 (2.8) |
| | Field | 32.2 (27.2) | | |
| Site C | Lab* | | 54.3 (4.0) | 49.2 (3.6) |
| | Field** | | 75.0 (3.1) | |
| Site D | Lab | 61.9 (4.0) | | 54.0 (5.2) |
| | Field | 34.1 (8.4) | | 30.5 (12.4) |

- Field core strengths significantly lower than lab specimens
  - Site D shows acceptable lab cylinder strength but failing strength from field core (< 31 MPa)
    - Same expected of Site B if 100x200 mm cores were obtained

**Illinois locations*

# RCC Compaction Methods

- Modified Proctor is most common method for mix design
  - Vibratory hammer most common for specimen fabrication
  - Both methods have limitations
- Gyratory Compactor:
  - Compaction method more similar to field conditions
    - SuperPave switched from Marshall hammer to gyratory
  - Reduce potential for operator error
  - More constant compaction energy
  - Measure of workability/compactibility

# Gyratory Compaction of RCC


Gyratory  Compactor #1

Gyratory Compactor #2


Resulting Gyratory Cylinder

Vibratory Hammer

*Previous work by Delatte et al. (2003-05); Williams (2013-14)*

# RCC Compaction Methods

- 17 (*paired but different)* mix designs w/ same gradation and cementitious contents cast w/ gyratory and modified Proctor or vibratory hammer
  - Density: gyratory vs. modified Proctor
  - Strength/Fracture: gyratory vs. vibratory hammer

# RCC Compaction Methods - Specimens

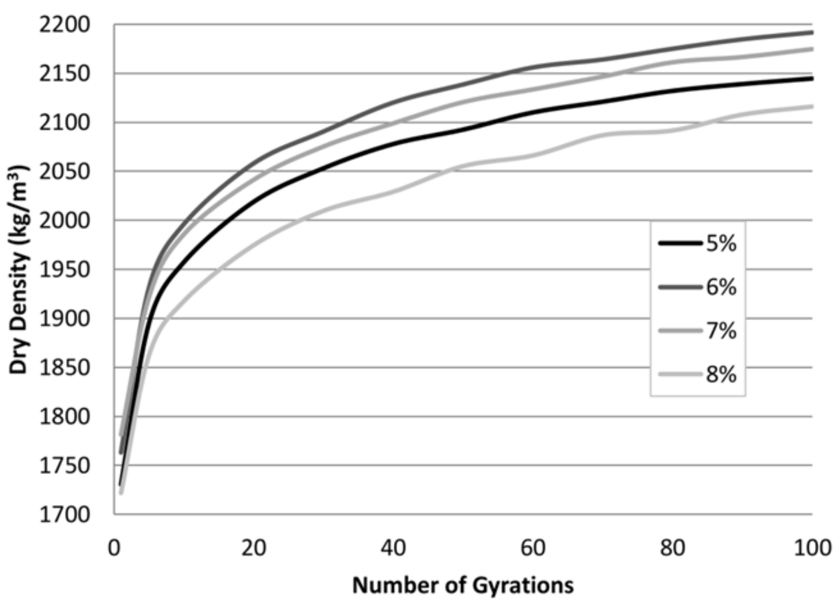
(a)

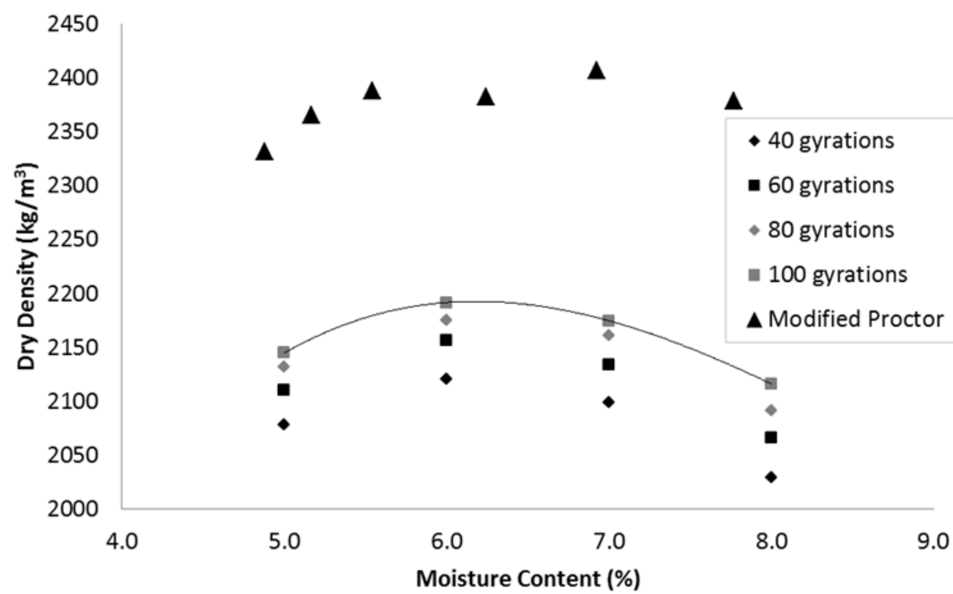
(b)

(c)

# RCC Compaction Methods – Gyratory Compactor Operation

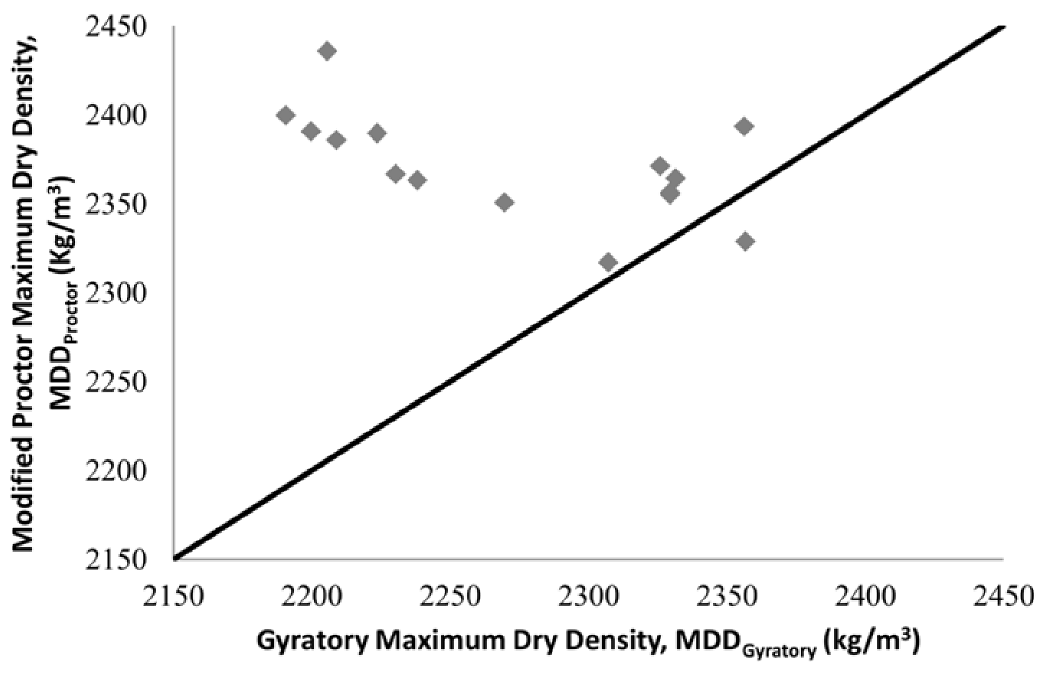
- 100 gyrations, 600 kPa pressure, 1.25 degree internal angle of gyration
- Compact at various moisture contents
- Determine MDD and OMC



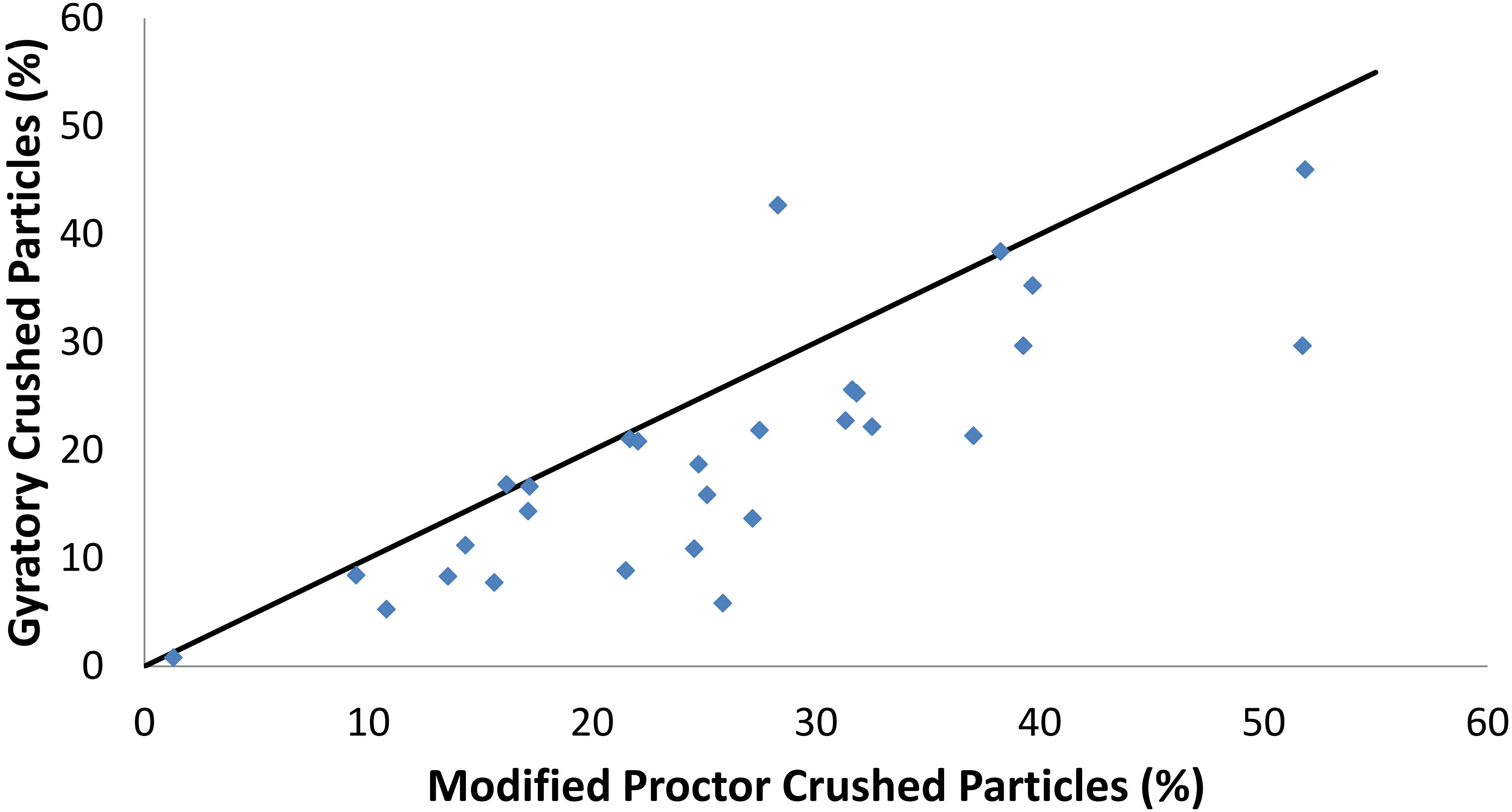



# RCC Compaction Methods - Density

- Few gyratory mixes had > 98% modified Proctor density (field compaction requirement)
  - Suggests that only some of the 17 mix designs would be suitable for field construction
    - Those that achieve 98% of modified Proctor density



# Comparing Crushed Particles from Gyratory and Modified Proctor



# RCC Compaction Methods – Strength (MPa)

| Mix Design[a] | Vibratory Hammer | Gyratory[b] |
|---|---|---|
| 1 | 45.7 | **54.9** |
| 3 | 57.9 | **45.3** |
| *4* | 51.4 | 41.0 |
| *5* | 64.8 | **49.7** |
| 6 | 44.9 | 44.9 |
| *7* | 58.2 | 50.4 |
| *8* | 57.7 | 63.7 |
| *Site B* | 57.0 | 64.5 |
| *Site C* | 54.3 | **84.0** |
| *Site D* | 61.9 | **76.8** |

[a] Italicized values indicate that the density of the gyratory specimens were at least 98% of the modified Proctor density.

[b] Bold values indicate statistical difference (t-test, 95% confidence) from vibratory hammer core compressive strength.

# Summary: RCC Compaction Methods

- Preliminary findings:
  - Gyratory compactor does not always produce similar densities as modified Proctor
    - Gyratory more sensitive to aggregate gradation and/or cementitious content/type than modified Proctor/vibratory hammer
    - Ideally can be used for determining optimal gradations
  - Strengths and fracture properties from gyratory specimens are more than sufficient
  - Uniform compaction throughout depth of specimen
- Need to validate # of gyrations against field projects to match density and strength properties

# RCC Delayed Compaction

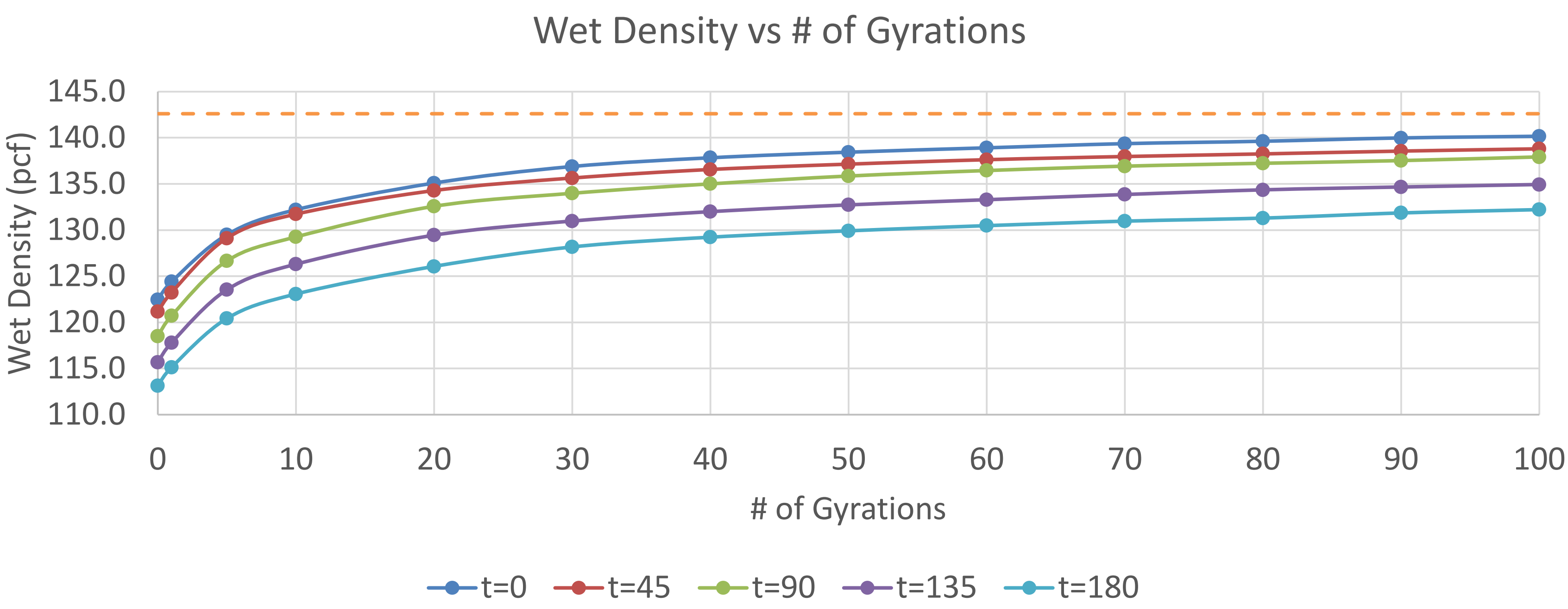
- Study effects of delayed compaction on RCC density and mechanical properties
  - Delay times: 0, 45, 90, 135, and 180 minutes
  - Four mixes: control (CT), control at 95F (HT), lightweight aggregate at 95°F (LW), and control with retarder at 95°F (RT)
  - Measure density (via gyratory compactor), compressive strength (gyratory and vibratory hammer specimens), and fracture properties at each delay time

# RCC Mix Designs

## *Delay Compaction Study*

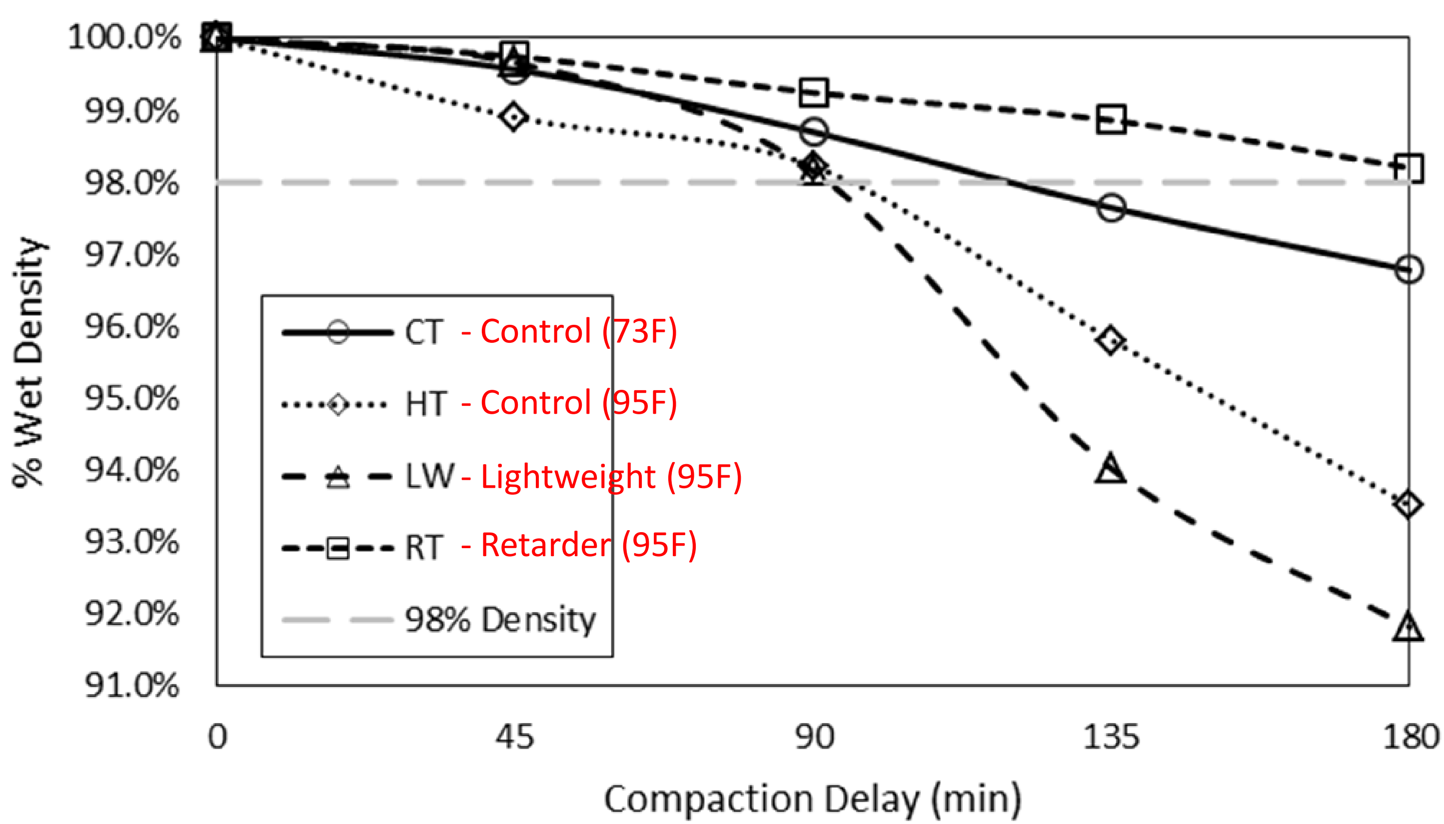
- 13% cement – approx. 450-475 pcy (depending on MDD)
- 25% coarse agg, 30% intermediate agg, 45% fine agg
- Four mixes:
  - RCC Control w/ virgin aggregates (70°F)
  - RCC Control w/ virgin aggregate (95°F)
  - Control/Virgin aggregate with retarder (V-MAR VSC-500) – 296 ml/100 lb cement (95°F)
  - Fine lightweight aggregate (25% replacement of sand by volume) at 95°F
- All mixes were kept in 90-95F tent throughout the delay time
- Measure density (gyratory compactor), compressive strength (gyratory and vibratory hammer specimens), and fracture properties at each delay time

# RCC Control Mix – 95°F Gyratory compaction



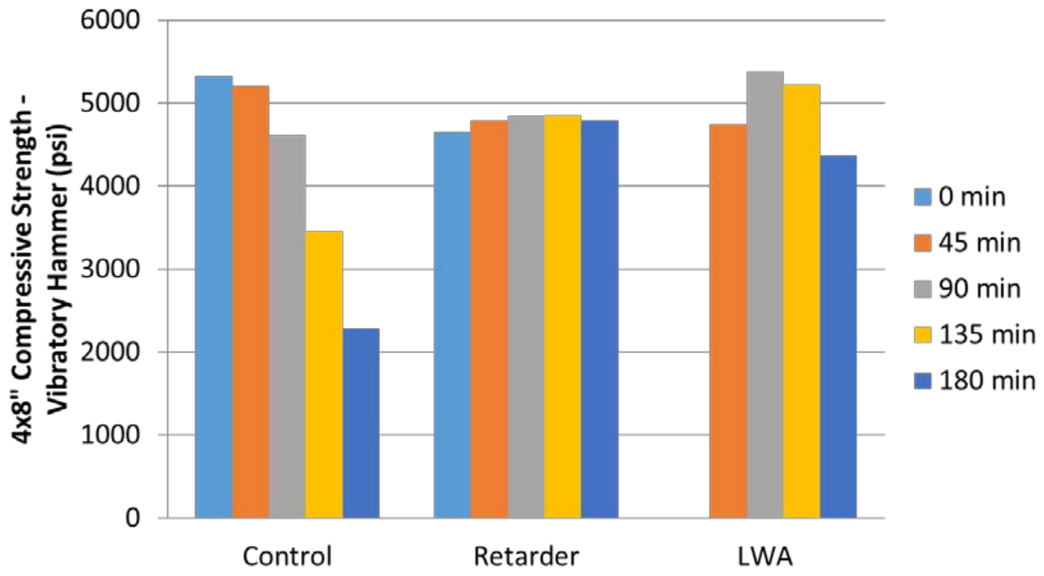
# Delayed Compaction - Density

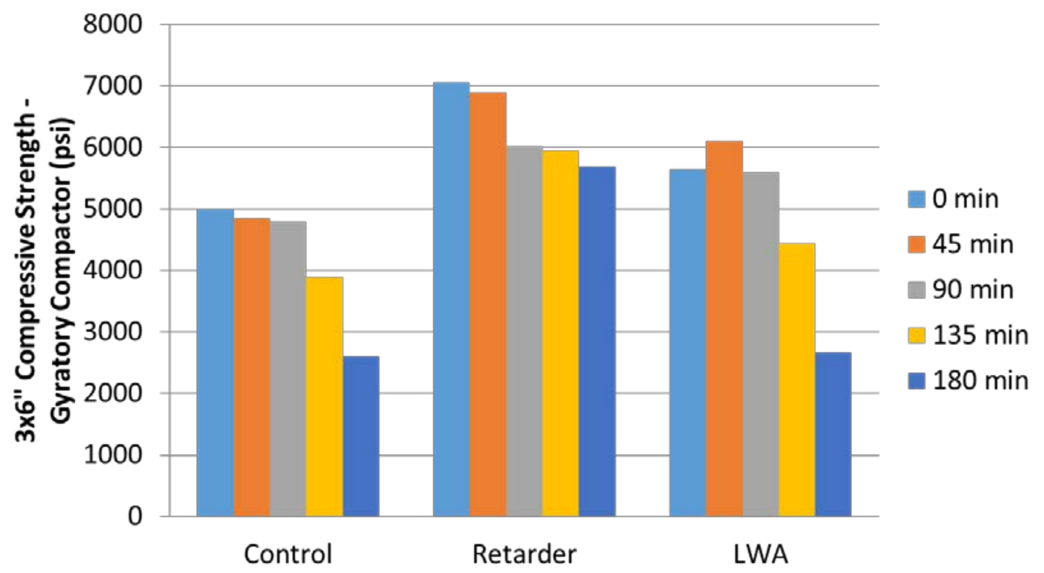
- All mixes maintained at least 98% density until 90 minutes
  - Mixes HT, LW, and RT were kept heated at 95F for the entire delay time (Mix CT was at room temp, i.e., 73F)
- Retarder mix (RT) maintained 98% of maximum gyratory density through 180 minutes



# Delayed Compaction – Compressive Strength

- Gyratory more sensitive to reductions in strength than vibratory hammer
  - Gyratory provides constant compactive energy
- Retarder mix maintains sufficient strength (> 4500 psi) even at 180 min. compaction delay
  - Other mixes have significantly reduced strengths



# Delayed Compaction - Summary

- Gyratory compactor useful for monitoring density and fabricating consistent and reproducible specimens
- All mixes maintained 98% density for at least 90 minutes under 95F
  - Retarder mix lasted 180 minutes
- Significant strength reductions beyond 90 minutes for all mixes besides retarder