RAP Workshop

Buda-TxAPA, Texas

August 27, 2009

Sponsored by

Texas Department of Transportation

Texas Asphalt Pavement Association

Texas Transportation Institute

TxDOT Reserch Project 0-6092

Performance Evaluation and Mix Design for High RAP Mixtures

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Presentation Outline

- RAP overview
- RAP stockpile survey: state of practice
- RAP processing and RAP variability
- RAP characterization
- RAP mix design
- Field performance of Texas high RAP test sections

RAP Overview (I)

- RAP:
  - Reclaimed Asphalt Pavement
- Why we use RAP?
  - Economics–***save money***
    - Aggregate, Asphalt
    - No/Low hauling costs
  - Environment
    - Reduces demands of non-renewable resources
    - Reduces landfill space demands

RAP Overview (II)

- TxDOT: SS341-022 for surface mixes
  - 10% unfractionated RAP
  - 20% fractionated RAP

- Why upper limit on RAP use?
  - One main reason is variability
    - Different sources, layers, aging……

RAP Overview (III)

- Ways to better use RAP
  - Control RAP variability
    - Stockpile management
    - RAP processing/fractionation
  - RAP characterization
  - RAP mix design

RAP Stockpile Management

- Isolate RAP source
- Blend multiple source
- Paved/sloped surface
- Store RAP under roof

Isolate RAP Source

It is critical to isolate RAP source in order to reduce RAP variability.


Blended multiple sources


RAP Storage

- Paved: minimize contamination
- Sloped: drain water
- Under roof: minimize moisture

RAP Processing

RAP Processing

Screening

Crushing

RAP Processing

- In most cases, simply ***<u>crush</u>*** RAP to a single size: either ½" or 3/8". No further fractionation.

- One size RAP and one RAP bin

RAP fractionation

RAP fractionation

RAP Fractionation

- RAP Fractionation:
  - Fine RAP
  - Coarse RAP

- RAP Fractionation: Special Cases
  - ½"-No.4
  - Passing No. 4

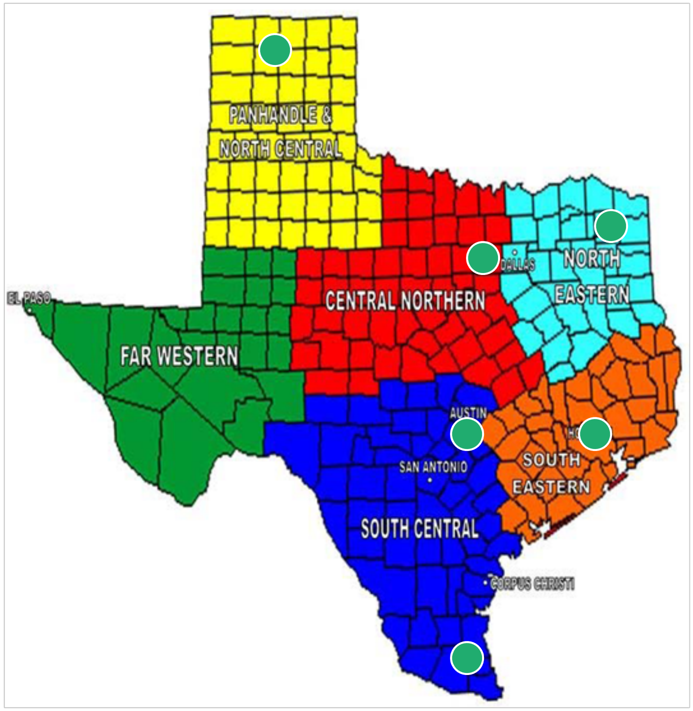
RAP-HMA plant

Astec double barrel system

RAP Variability

RAP Variability

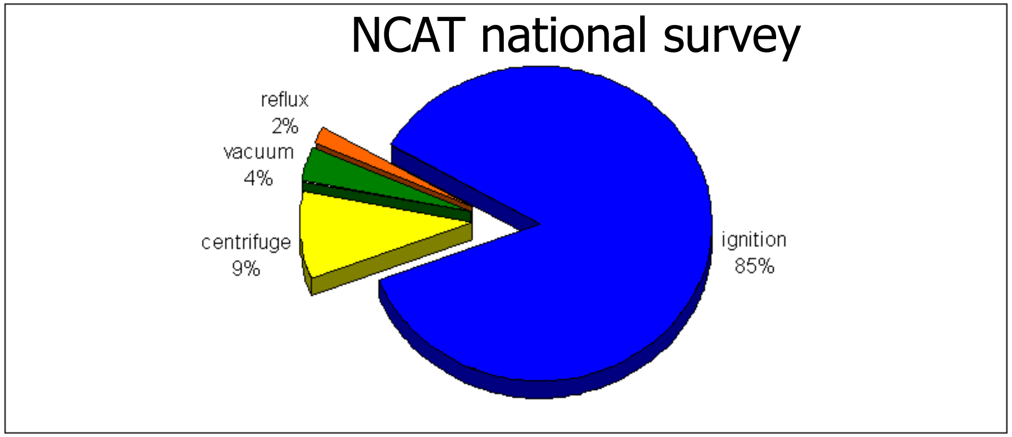
- Regions visited
  - TxDOT's RAP
    - Amarillo-single RAP source
  - Contractors' RAP
    - C1
    - C2
    - C3
    - C4
    - C5



RAP Sampling

RAP Variability

- Lab testing
  - Ignition oven test
    - Aggregate gradation
    - Asphalt content



TxDOT-Amarillo-Armstrong-unfractionated RAP

Sieve Sizes	#1	#2	#3	#4	#5	#6	#7	AVE	STDEV
3/4	100.0	100.0	100.0	100.0	100.0	100.00	100.0	100.0	0.0
1/2	97.9	99.6	99.8	98.4	99.4	99.1	100.0	99.2	0.8
3/8	88.7	90.2	94.2	89.7	91.4	94.2	95.3	92.0	2.6
#4	59.4	63.2	69.8	61.6	62.6	69.1	69.8	65.1	4.4
#8	40.6	43.7	49.2	41.7	40.6	48.4	50.6	45.0	4.3
#16	31.8	33.8	38.2	32.7	31.3	37.1	40.4	35.0	3.5
#30	26.0	26.6	30.5	26.3	25.5	29.7	32.4	28.1	2.7
#50	17.9	19.0	21.0	17.7	17.8	21.0	21.8	19.4	1.8
#100	11.0	11.1	13.1	10.5	11.2	13.5	13.7	12.0	1.4
#200	6.9	7.0	8.2	6.3	7.1	8.6	9.1	7.6	1.1
AC (%)	5.3	5.4	5.6	5.4	5.2	5.8	5.3	5.4	0.2

TxDOT-Amarillo-Dallam-unfractionated RAP

Sieve Sizes	#1	#2	#3	#4	#5	#6	#7	AVE	STDEV
3/4	100.0	100.0	100.0	100.0	100.0	100.00	100.0	100.0	0.0
1/2	95.9	97.9	99.0	98.7	98.3	97.0	97.0	97.7	1.1
3/8	89.7	94.7	90.3	90.8	92.9	90.7	90.7	91.4	1.8
#4	73.1	81.6	67.1	67.8	68.3	73.8	73.8	72.2	5.1
#8	43.5	53.4	43.9	47.7	46.4	46.5	46.5	46.8	3.3
#16	29.3	36.5	31.6	35.3	33.9	31.9	31.9	32.9	2.5
#30	21.6	26.2	24.3	27.4	25.6	23.4	23.4	24.6	2.0
#50	15.5	18.7	18.5	20.8	18.6	17.1	17.1	18.0	1.7
#100	10.0	12.0	12.4	13.7	12.1	11.2	11.2	11.8	1.2
#200	6.4	7.6	8.0	8.8	7.5	7.2	7.2	7.5	0.7
AC (%)	7.5	8.1	7.7	8.6	8.2	8.0	7.4	7.9	0.4

TxDOT-Amarillo-Deafsmith (1/2"-No.4)- lab fractionated

Sieve Size	#1	#2	#3	#4	#5	AVE	STDEV
1/2	100.0	100.0	99.9	99.7	100.0	99.9	0.1
3/8	87.1	86.3	84.6	88.8	88.4	87.1	1.7
#4	39.3	31.6	38.2	41.4	38.9	37.9	3.7
#8	25.6	17.4	24.9	27.8	25.5	24.3	4.0
#16	21.0	14.1	20.3	23.0	21.1	19.9	3.4
#30	17.9	11.9	17.1	19.6	18.0	16.9	2.9
#50	14.3	9.5	13.5	15.9	14.5	13.5	2.4
#100	9.3	6.0	8.3	10.8	9.3	8.7	1.8
#200	5.3	3.3	6.3	6.7	5.2	5.4	1.3
AC (%)	3.52	2.62	3.5	3.6	3.34	3.3	0.4

TxDOT-Amarillo-Deafsmith (Passing-No.4)–lab fractionated

Sieve Size	#1	#2	#3	#4	#5	AVE	STDEV
1/2	100.0	100.0	100.0	100.0	100.0	100.0	0.0
3/8	100.0	100.0	100.0	100.0	100.0	100.0	0.0
#4	100.0	100.0	99.9	99.9	100.0	99.9	0.0
#8	79.3	81.4	78.7	77.9	84.4	80.4	2.6
#16	60.1	59.6	60.7	59.6	67.7	61.5	3.5
#30	46.1	42.4	47.0	47.2	53.8	47.3	4.1
#50	33.7	28.4	34.7	35.3	39.4	34.3	4.0
#100	21.1	16.3	21.8	22.0	24.7	21.2	3.0
#200	12.5	8.5	12.5	13.3	14.6	12.3	2.3
AC (%)	6.2	5.3	6.2	6.4	6.5	6.1	0.5

C1: Crushed RAP

Sieve Size	#1	#2	#3	#4	#5	#6	#7	AVE	STDEV
3/4	100	100	100	100	100	100	100	100.0	0.0
1/2	99.1	99.3	99.1	95.4	99.7	97.8	98.4	98.4	1.5
3/8	93.6	93.7	95.5	86.8	96.1	90.6	92.5	92.7	3.2
#4	76.3	74.4	77.9	69.9	77.2	71.2	74.5	74.5	3.0
#8	57.5	54.4	58.1	55.7	60.0	52.0	56.3	**56.3**	**2.6**
#16	45.7	41.8	44.7	45.6	47.5	40.0	45.1	44.3	2.5
#30	36.5	32.2	33.6	35.3	35.5	31.1	35.5	34.2	2.0
#50	27.4	23.1	23.0	23.6	23.1	22.6	25.5	24.0	1.8
#100	18.7	15.3	14.8	14.7	14.7	15.4	17.0	15.8	1.5
#200	13.8	11.3	11.0	10.6	10.8	11.5	12.4	**11.6**	**1.1**
AC (%)	**5.5**	**5.0**	**5.1**	**5.1**	**5.0**	**4.6**	**5.5**	**5.1**	**0.3**

C2: Crushed RAP

Sieve Size	#1	#2	#3	#4	#5	#6	#7	AVE	STDEV
3/4	100.0	100.0	100.0	100.0	100.0	100.00	100.0	100.0	0.0
1/2	98.0	99.2	98.1	98.5	95.7	98.9	98.8	98.1	1.1
3/8	90.6	95.2	92.7	94.0	84.0	91.5	91.9	91.4	3.6
#4	67.8	74.3	69.1	69.5	53.9	68.1	69.8	67.5	6.4
#8	46.1	52.3	47.8	47.4	36.0	46.9	48.6	46.5	5.0
#16	34.5	39.7	36.0	35.6	28.1	34.5	36.3	35.0	3.5
#30	27.6	31.8	28.9	28.9	23.8	27.2	29.6	28.3	2.5
#50	21.8	25.1	22.6	22.7	19.8	20.6	23.4	22.3	1.8
#100	12.9	15.1	13.4	13.1	12.4	11.5	13.5	13.1	1.1
#200	7.9	9.5	8.3	7.9	7.8	6.8	8.2	8.1	0.8
AC (%)	4.5	4.7	4.4	4.3	4.2	4.2	4.6	4.4	0.2

C2: Crushed RAP+Shingles

Sieve size	#1	#2	#3	#4	#5	#6	#7	AVE	STDEV
3/4	100.0	100.0	100.0	100.0	100.0	100.00	100.0	100.0	0.0
1/2	98.3	100	99.0	97.7	98.7	99.1	97.3	98.6	0.9
3/8	93.6	94.2	93.4	91.7	92.9	93.2	92.6	93.1	0.8
#4	75.0	75.2	73.6	70.6	70.3	72.8	73.6	73.0	2.0
#8	59.4	58.1	57.4	55.5	54.3	57.0	57.4	**57.0**	**1.7**
#16	45.9	45.6	44.9	45.1	43.6	45.7	44.9	45.1	0.8
#30	34.4	35.8	35.0	37.1	35.7	37.0	35.1	35.7	1.0
#50	25.4	28.3	27.7	31.0	29.9	30.6	27.4	28.6	2.0
#100	15.0	17.6	17.3	20.7	20.2	20.2	16.6	18.2	2.2
#200	8.6	10.5	10.5	13.0	13.0	13.0	10.2	**11.3**	**1.8**
AC(%)	7.5	8.1	7.7	8.6	8.2	8.0	7.4	**7.9**	**0.4**

C3: Crushed RAP

Sieve size	#1	#2	#3	AVE	STDEV
3/4	100.0	100.0	100.0	100.0	0.0
1/2	99.3	100.0	100.0	99.8	0.4
3/8	97.7	96.9	97.1	97.3	0.4
#4	79.6	77.7	77.1	78.2	1.3
#8	59.1	57.5	56.1	**57.6**	**1.5**
#16	48.0	47.1	45.9	47.0	1.0
#30	40.1	40.6	39.2	39.9	0.7
#50	26.3	28.9	27.7	27.6	1.3
#100	11.3	15.5	13.5	13.4	2.1
#200	5.9	8.9	7.4	**7.4**	**1.5**
AC (%)	4.0	4.2	4.3	**4.2**	**0.1**

C4: Crushed Coarse RAP

Sieve Sizes	#1	#2	#3	#4	#5	#6	AVE	STDEV
3/4	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0
1/2	96.1	93.9	94.2	94.4	96.6	94.9	95.0	1.1
3/8	79.6	68.1	70.2	73.8	70.5	70.6	72.1	4.1
#4	30.2	21.1	19.2	22.6	23.2	18.9	22.5	4.1
#8	21.5	14.3	13.6	15.9	16.8	12.8	15.8	3.1
#16	17.2	11.2	11.8	13.2	14.4	10.9	13.1	2.4
#30	14.9	9.6	10.5	11.9	12.9	10.0	11.6	2.0
#50	13.1	8.2	9.3	10.6	11.5	9.0	10.3	1.8
#100	7.7	7.9	5.5	6.2	6.7	5.4	6.6	1.1
#200	4.4	5.2	3.1	3.4	3.6	2.9	3.8	0.9
AC (%)	2.7	2.3	2.1	2.4	2.7	2.3	2.4	0.2

C4: Crushed Fine RAP

Sieve Sizes	#1	#2	#3	#4	#5	#6	#7	AVE	STDEV
3/4	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0
1/2	99.5	100.0	100.0	99.5	100.0	100.0	100.0	99.8	0.3
3/8	98.6	98.8	99.1	97.5	99.1	99.5	99.0	98.8	0.6
#4	83.2	84.6	84.9	84.5	85.6	87.6	85.7	85.2	1.4
#8	57.0	58.0	56.2	57.2	59.2	63.2	60.1	58.7	2.4
#16	43.9	45.2	42.5	43.4	45.6	49.2	46.9	45.2	2.3
#30	36.8	38.7	35.7	36.4	38.1	40.8	39.4	38.0	1.8
#50	27.7	29.5	26.4	26.2	27.5	29.7	29.5	28.1	1.5
#100	15.8	16.3	14.2	13.7	14.1	15.5	15.9	15.1	1.0
#200	8.0	8.2	6.8	6.6	6.8	7.9	8.3	7.5	0.7
AC (%)	5.6	5.1	5.1	5.3	5.6	5.3	5.3	5.3	0.2

C5: Crushed Coarse RAP

Sieve Sizes	#1	#2	#3	#4	AVE	STD
3/4	100.0	100.0	100.0	100.0	100.0	0.0
1/2	96.8	98.5	98.8	98.6	98.2	0.9
3/8	85.5	88.1	86.6	88.3	87.1	1.3
#4	57.2	61.9	60.8	61.3	60.3	2.1
#8	41.7	45.3	45.3	44.3	44.1	1.7
#16	31.1	33.9	34.5	33.1	33.1	1.5
#30	24.7	26.8	27.6	26.4	26.4	1.2
#50	19.5	20.9	21.6	20.9	20.7	0.9
#100	11.4	12.1	12.5	12.4	12.1	0.5
#200	6.5	6.9	7.1	7.2	6.9	0.3
AC (%)	3.6	3.7	3.6	3.7	3.6	0.1

RAP Variability: Summary

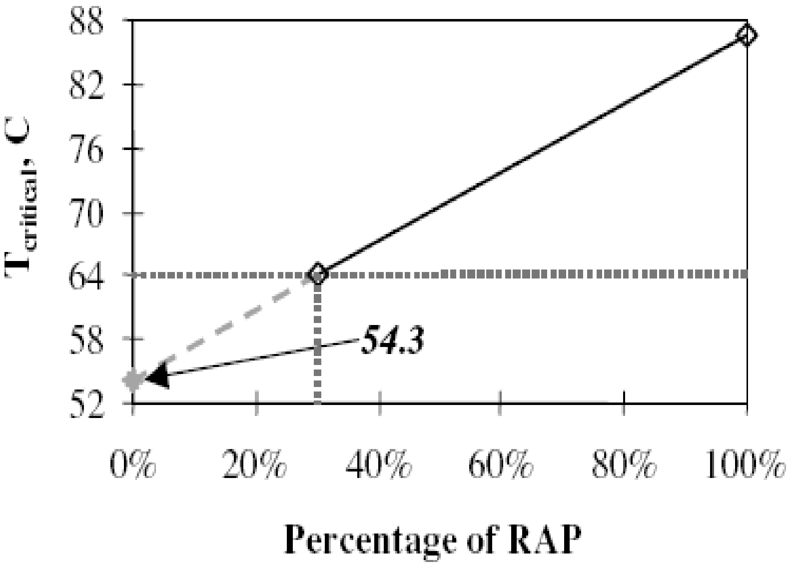
- In terms of aggregate gradation and RAP binder content
  - TxDOT unfractionated RAPs (single source) in Amarillo do not vary much.
  - Contractors' crushed/fractionated RAPs are consistent as well.
- Further crushing/fractionating fine RAP to No.4 minus may introduce too much fines.

RAP Characterization

- 3 key RAP parameters
  - Aggregate gradation (aggregate properties)
  - RAP binder content
  - RAP binder PG
- Lab testing
  - Ignition oven test
  - RAP binder extraction and recovery test
  - ***New technique for RAP binder evaluation***

RAP Binder Characterization

- RAP binder extraction
- RAP binder recovery
- RAP binder testing: DSR and BBR
  - Say PG88-10
- Virgin binder selection
  - PG70-22??
  - PG64-22??
  - PG58-28??



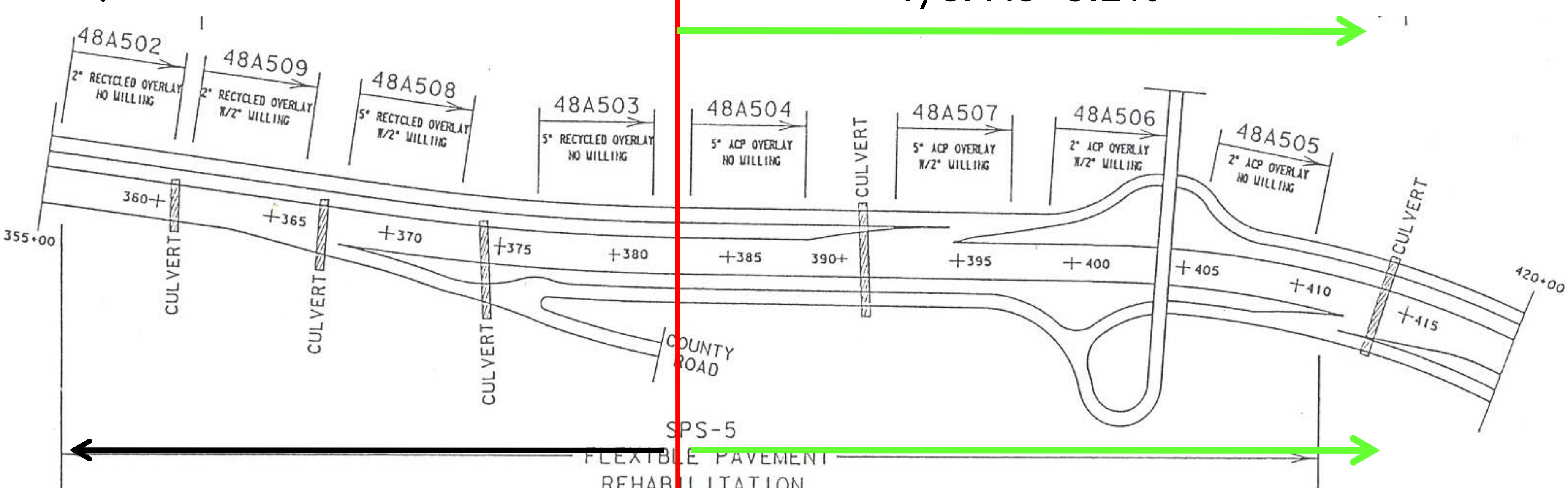
RAP Mix Design

- Run ignition oven test to determine aggregate gradation and asphalt content
- Treat RAP as a virgin aggregate, except that: DO NOT leave the RAP at mix temperature overnight like the virgin aggregates.
- Not much different from the conventional mix design: meeting density requirements and passing Hamburg test.
- ***RAP mix design practice in Texas***

High RAP Test Section on US175, near Dallas

RAP Sections:
Virgin binder-AC5 +35%RAP
TyC: Total AC=4.5%

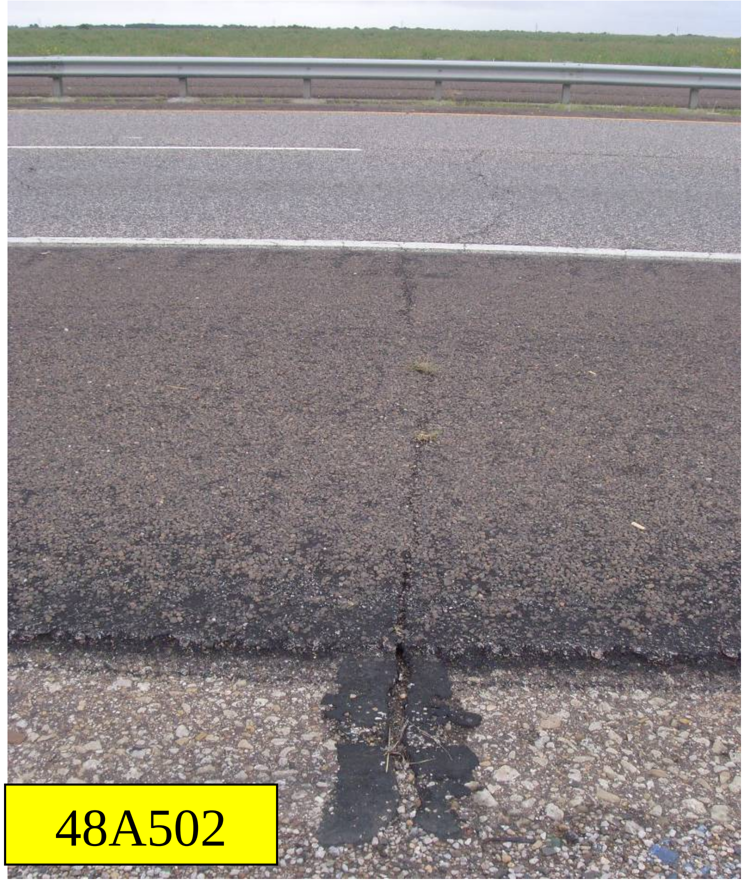
Non-RAP Sections:
Asphalt binder: AC10+3%latex
TyC: AC=5.2%



After **17** years, overall performance of the RAP Sections is still OK: no rutting and lots of cracking.

After 17 years, virgin mix sections still have excellent conditions in terms of both rutting and cracking.

Cracking Conditions on Sept. 9, 2008

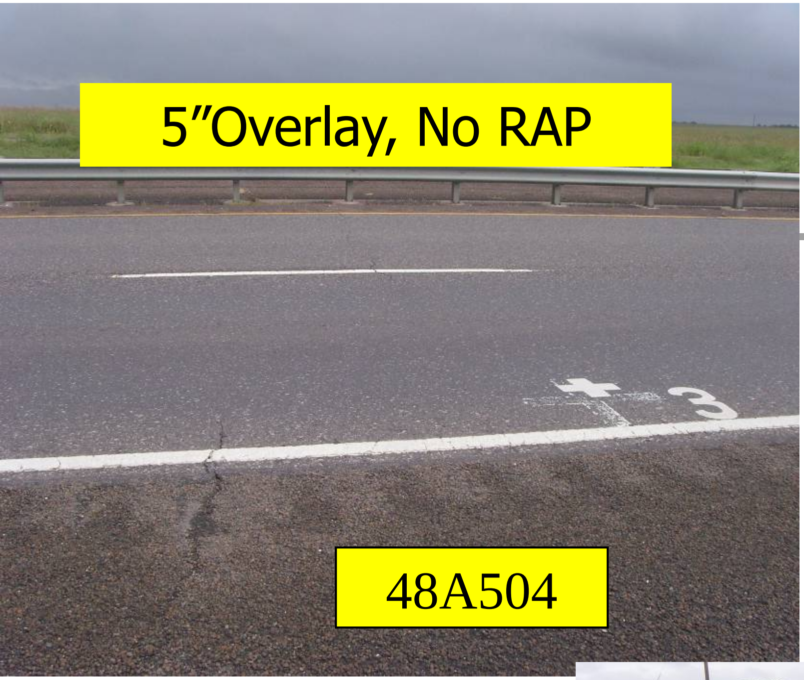


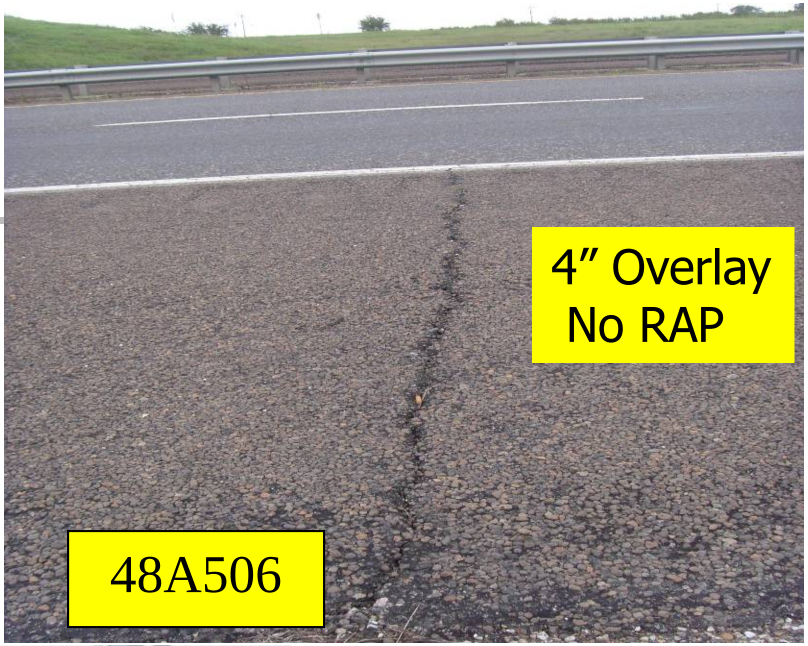
2″ Overlay

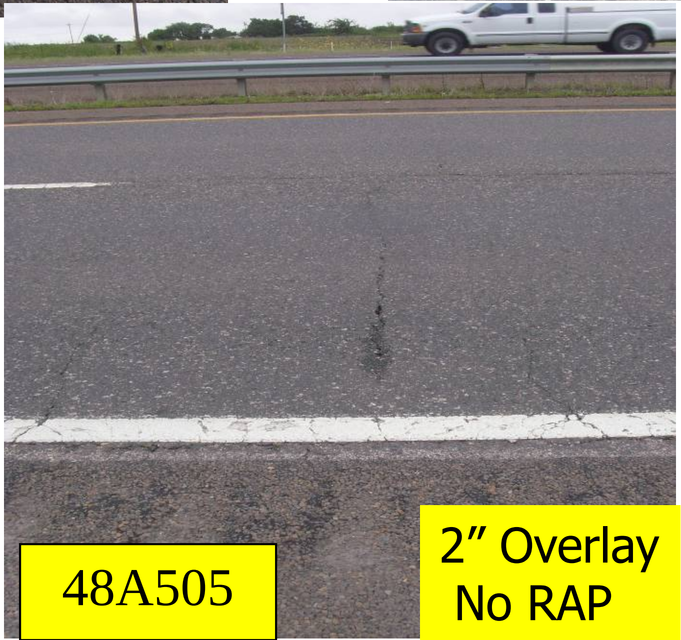
AC5+35%

RAP Sections

Cracking Conditions on Sept. 9, 2008







Summary

- It is possible to design and construct high RAP mixes with good field performance. In order to do so, need to:
  - Manage stockpile well
  - Fractionate RAP stockpiles
  - Characterize RAP material (gradation, binder…)
  - ***Balanced mix design***: rutting, cracking, and moisture damage
  - Good field construction: no segregation,….

Thank you!

Questions?

TxDOT Reserch Project 0-6092
RAP Workshop

Balanced RAP Mix Design

Fujie Zhou, Texas Transportation Institute

Buda, Texas

Texas Asphalt Pavement Association

8/27/2009

Presentation Outline

- Introduction
- RAP mix design challenges
- Repeatability of Overlay Test
- Balanced RAP mix design concept
- Case studies: Amarillo test sections

Introduction

- RAP Mix design (***Tex-204-F***)
  - Known:
    - Virgin aggregates
    - RAP: gradation, binder content, and binder properties
    - Virgin binder type (or RAP percentage)
  - Unknown: **Virgin AC / RAP % / Virgin binder type???**
  - Meet criteria
    - Density
    - VMA
    - Hamburg

Introduction

- RAP mix design steps:
  - Determine RAP Properties: Gradation, AC content, binder properties
  - Determine RAP Blend Binder Properties
  - Develop Mix Design (density and VMA)
  - Evaluate mix Performance: **rutting, moisture, cracking**

RAP Mix Design Challenges-I

- RAP material characterization
  - Ignition oven test: *correction factor??*
    - Aggregate gradation
    - RAP binder content
  - Extraction and recovery test: *remove solvent??*
    - Aggregate gradation
    - RAP binder content
    - RAP binder properties-DSR and BBR test
- RAP-virgin binder blending: 0-100%??

RAP Mix Design Challenges-II

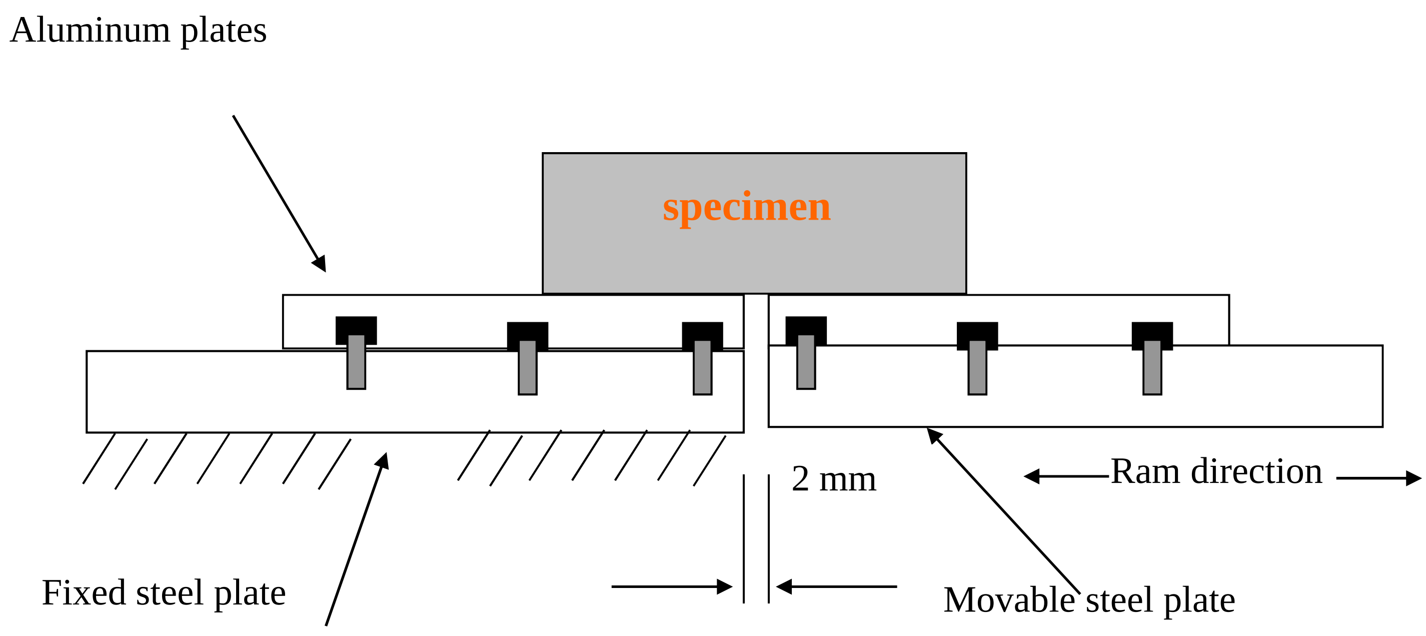
- Issues in terms of performance
  - Cracking
  - Moisture damage
  - Compaction
  - Rutting

Overlay Test for Cracking

- Overlay test concept
- Overlay test vs. field cracking performance
- Overlay test repeatability/round-robin test

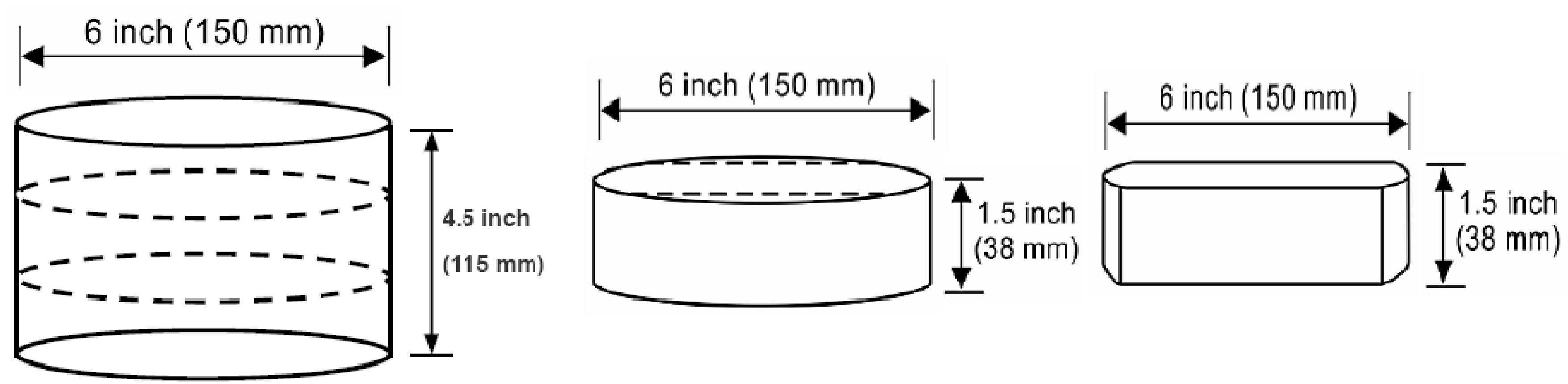
TTI Overlay Tester

- Overlay Test Concept



Overlay Test Sample

- Sample size: 6'' long by 3'' wide by 1.5'' high
- Sample preparation: field core, Superpave Gyratory Compactor

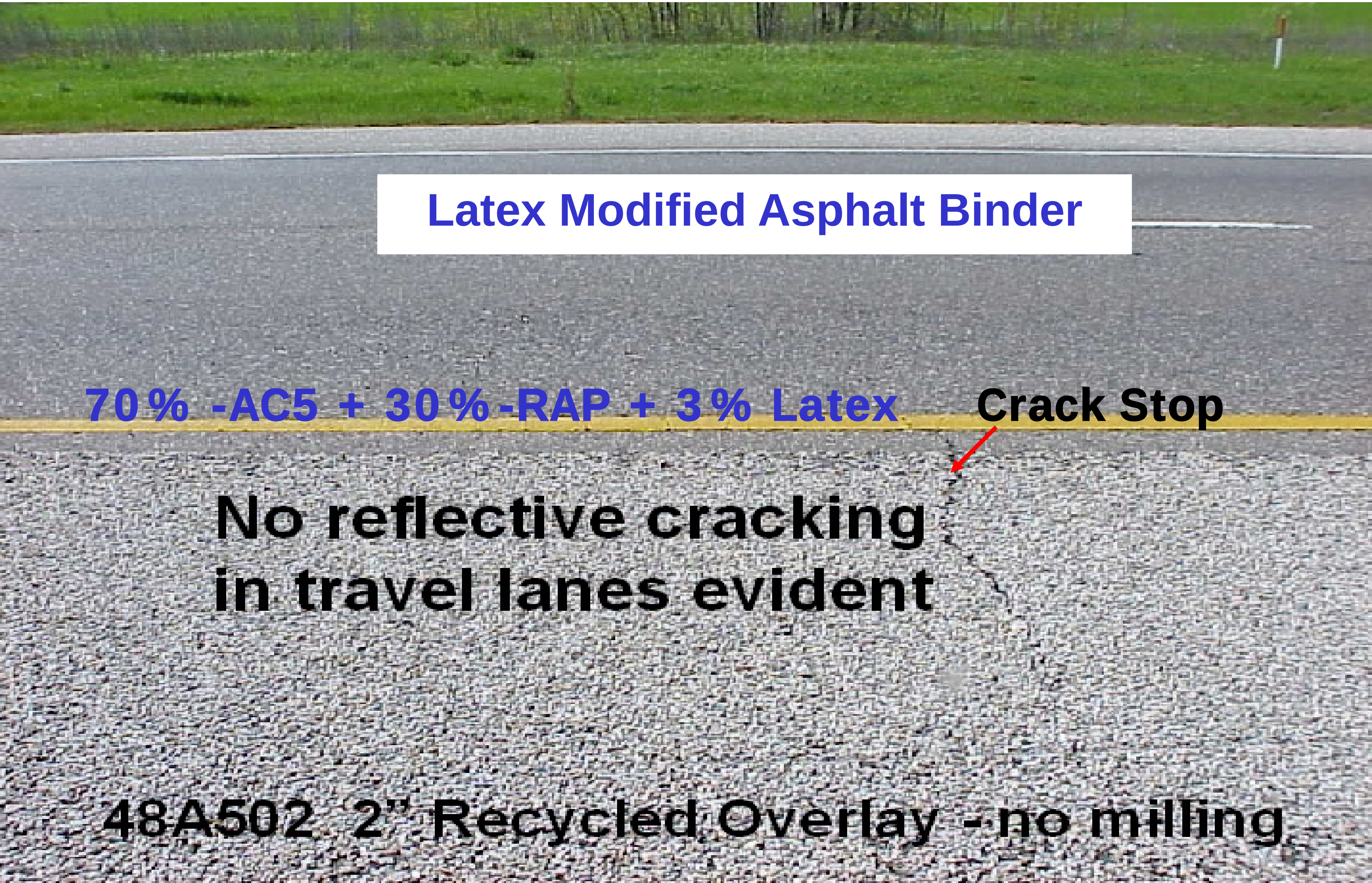


Overlay Test Validation

- Seven field case studies
  - 1) SPS5, 2) US175, 3) US84, 4) SH6, 5) SH3, 6) IH10, and 7) IH20

- Accelerated Pavement Test
  - FHWA-ALF fatigue test

US 175 Dallas District 10 years old



Hot In-Place Recycling

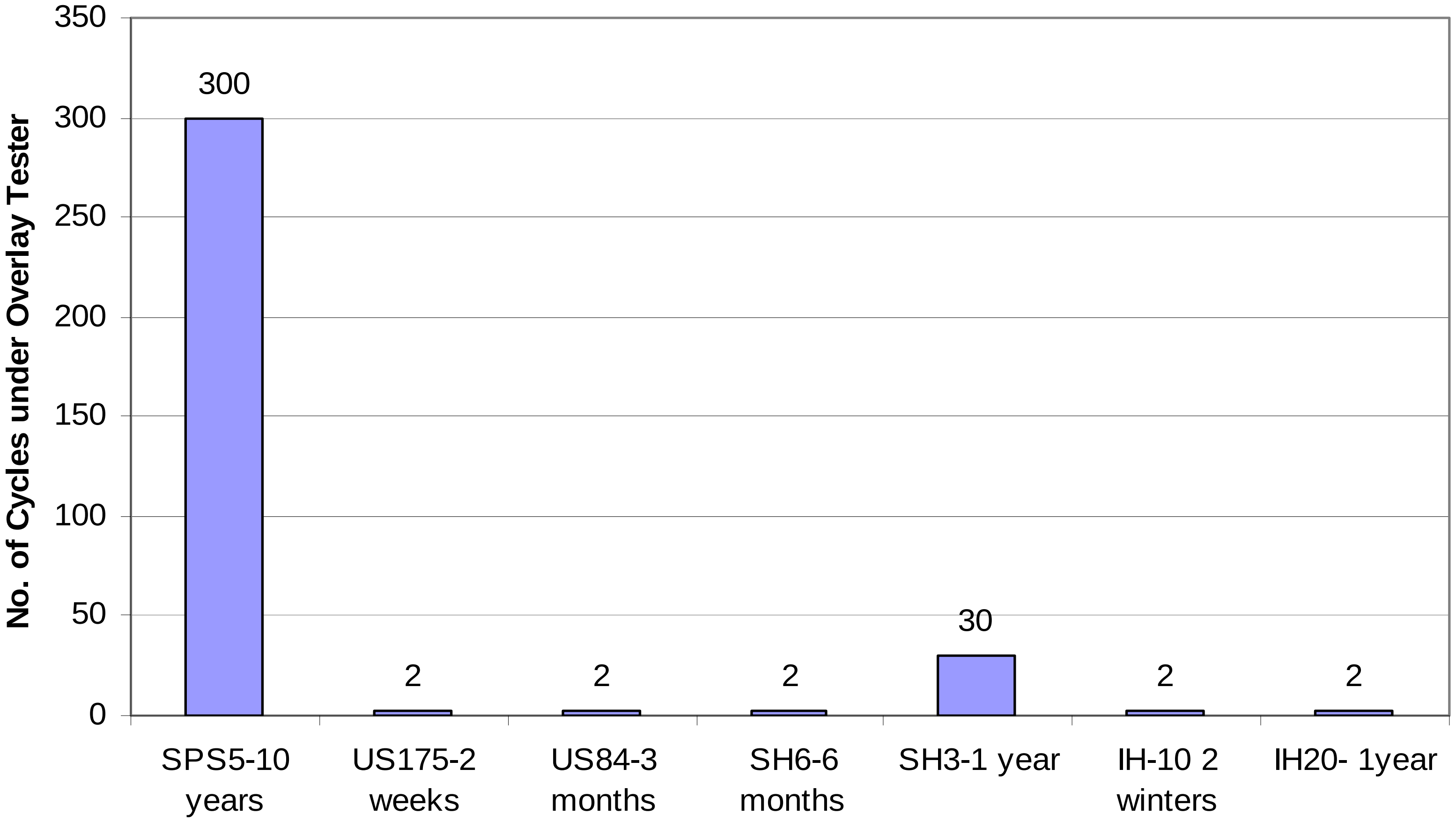
SH6: after 1 winter

SH3: after 1 year

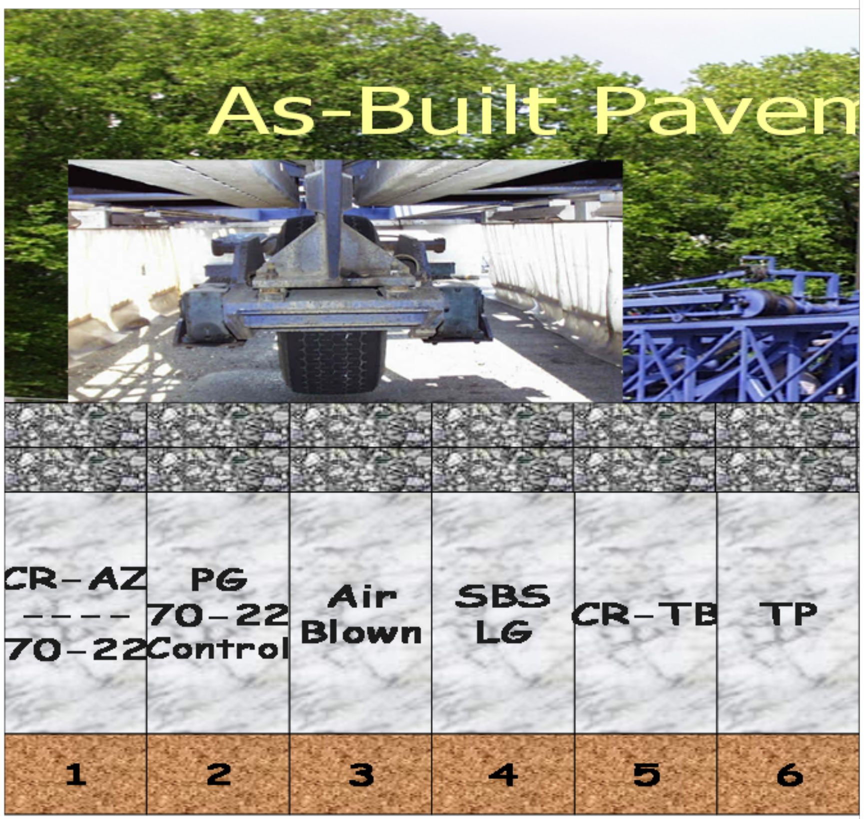
IH10: cracked after 2 years

IH20: cracked after 1 year

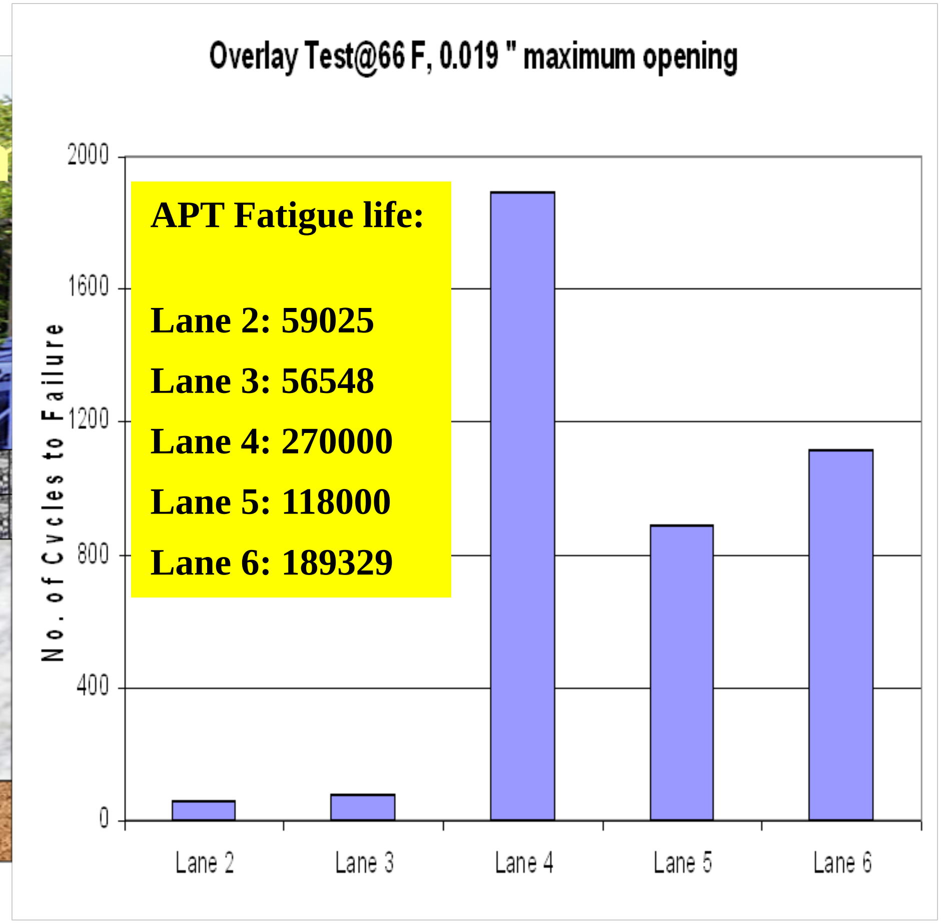
Overlay Test Validation: 7 Field Cases



Overlay Test Validation: APT Fatigue Cracking



FHWA-ALF Fatigue Test Sections

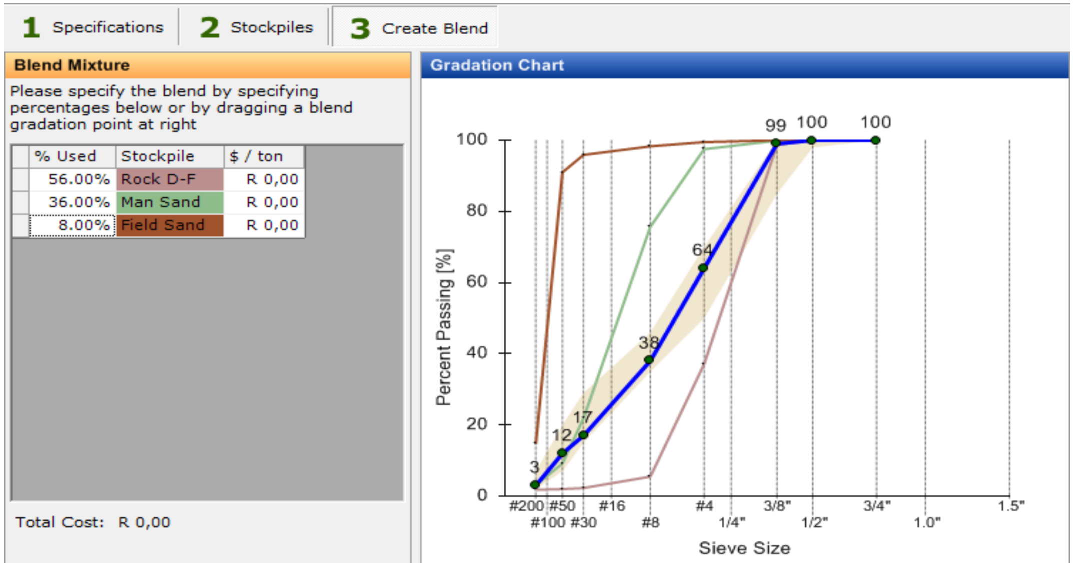


Overlay Test Repeatability and Round-Robin Test

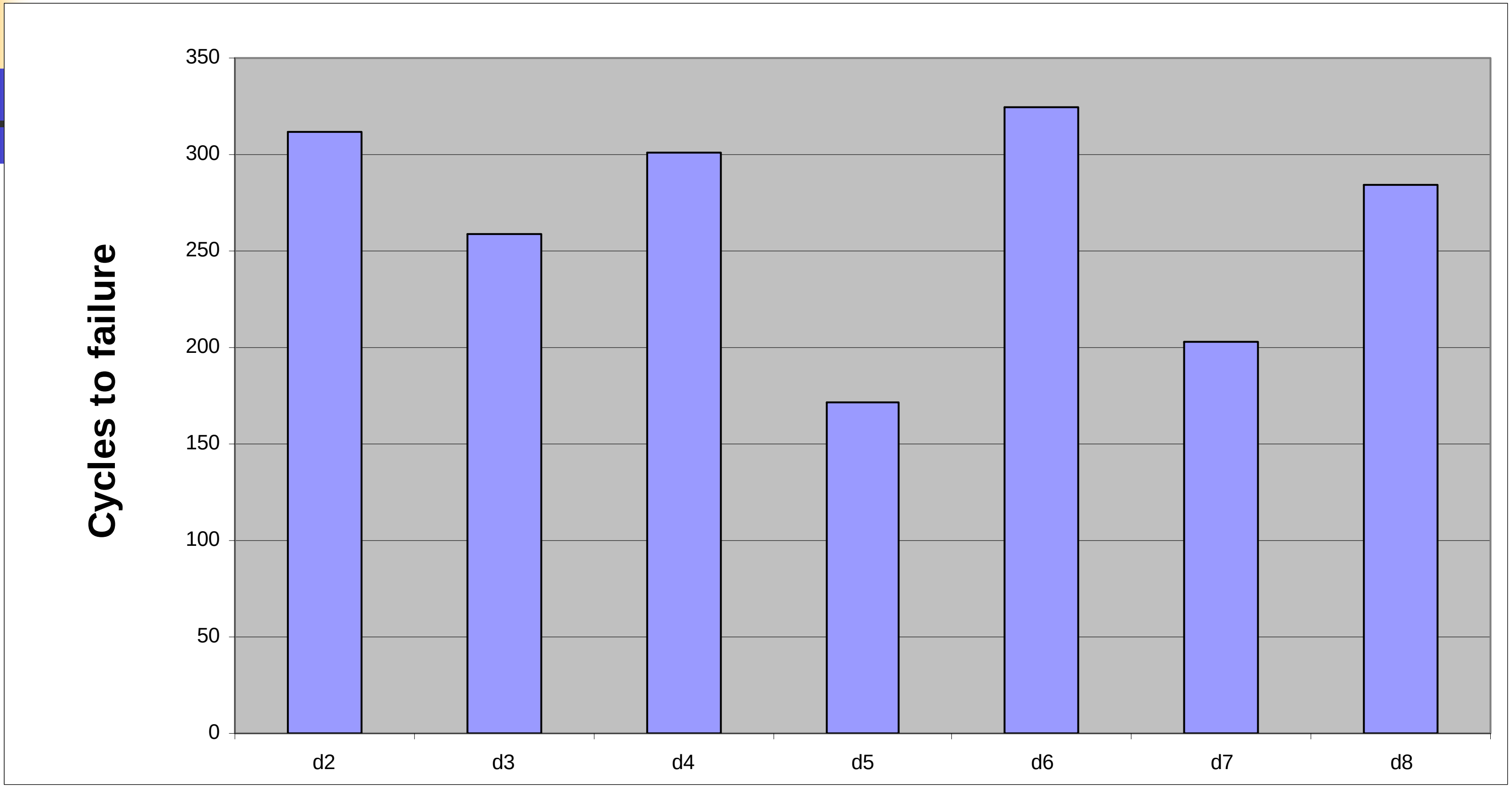
Mix type: Type D

Binder: 5% PG 70-22 (Valero)

Aggregate: Limestone (Chico)

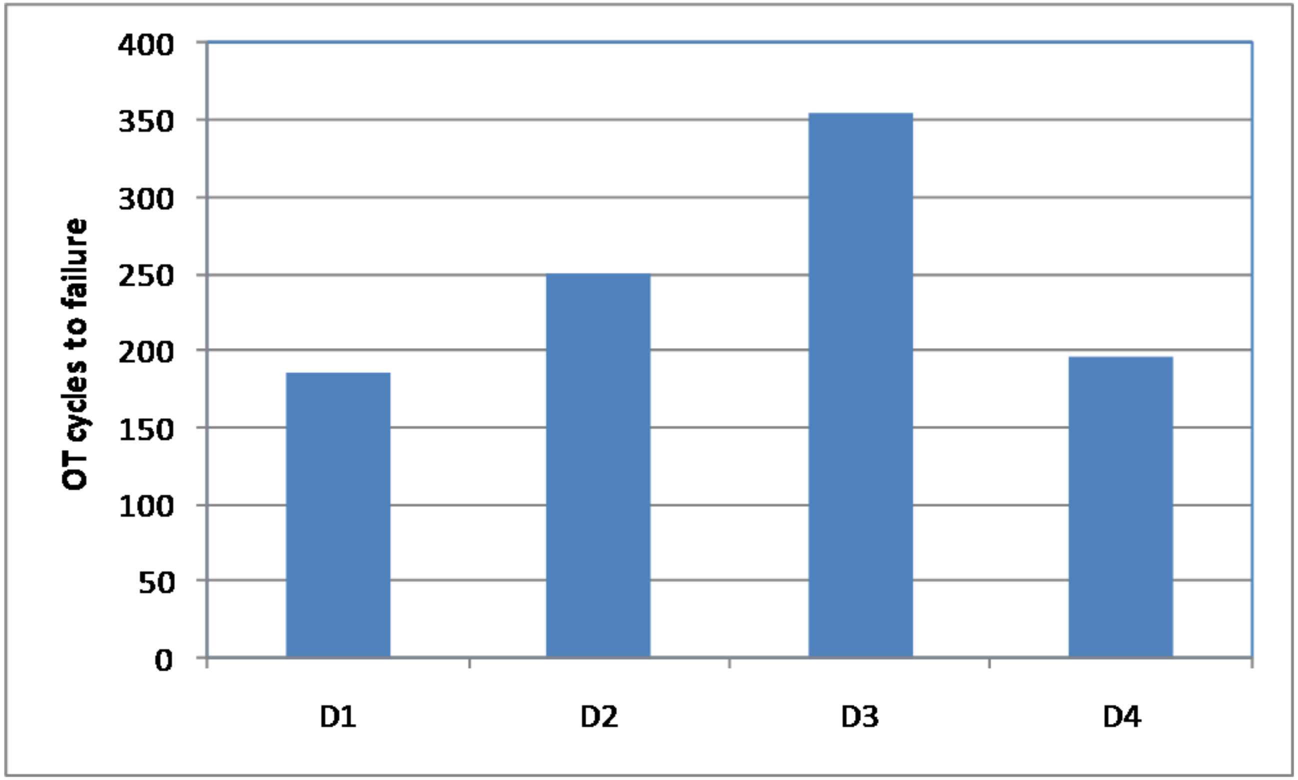


TTI-TxDOT at Cedar Park



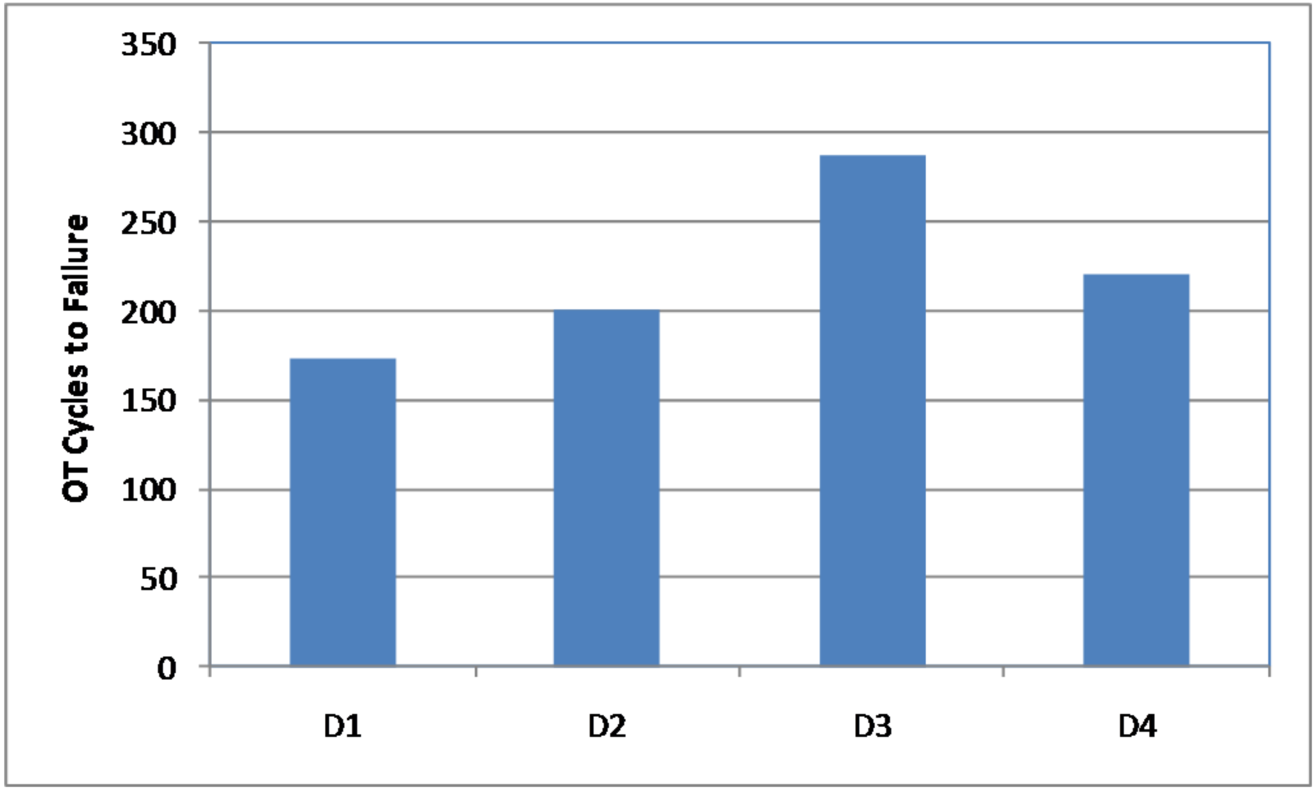
Mean = 265
Stdev = 57
COV = 21%
Range = 174 - 312

Atlanta District



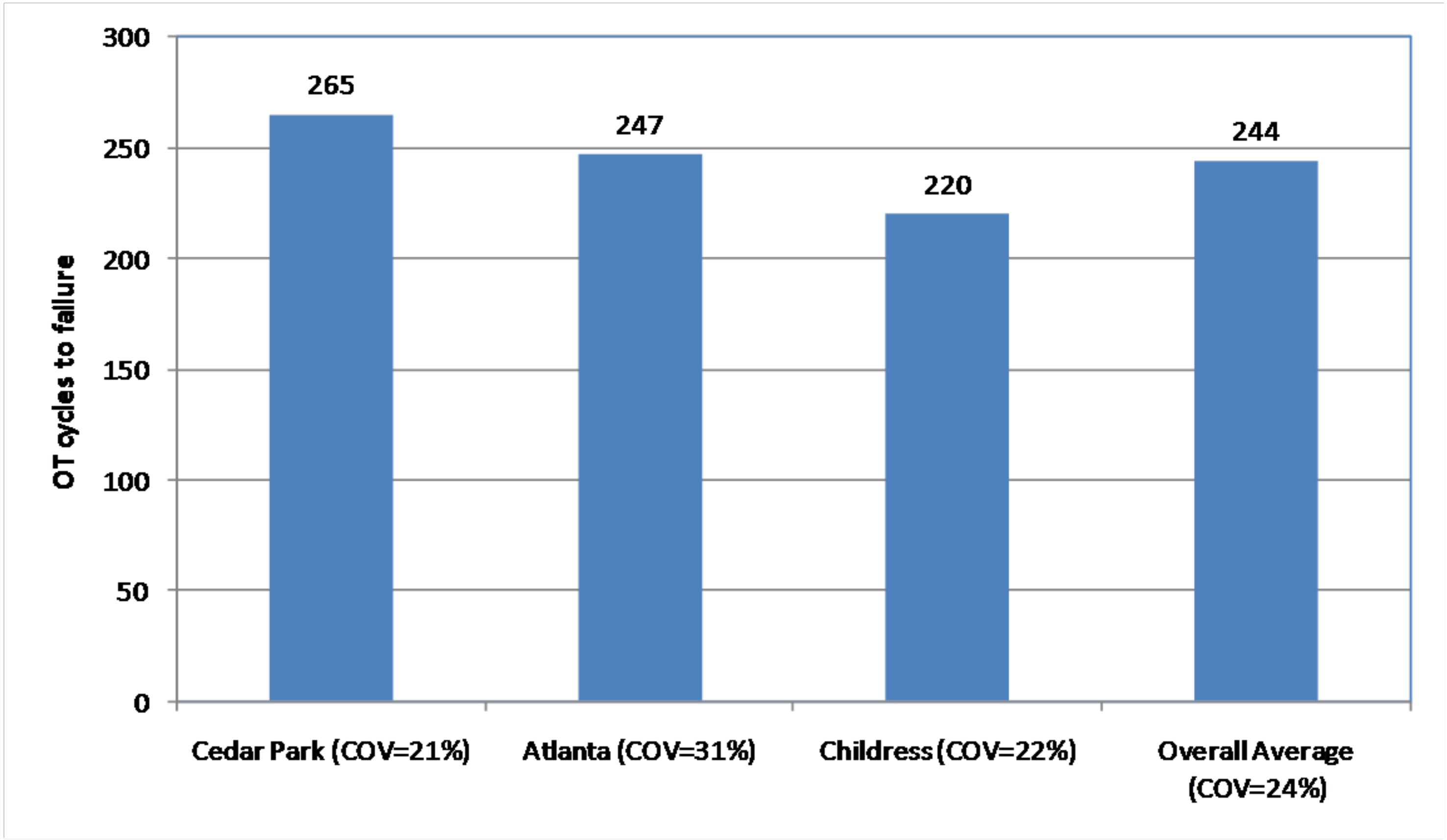
Mean = 247
Stdev = 77
COV = 31%
Range= 186 - 355

Childress District



Mean = 220
Stdev = 48
COV = 22%
Range= 173 - 287

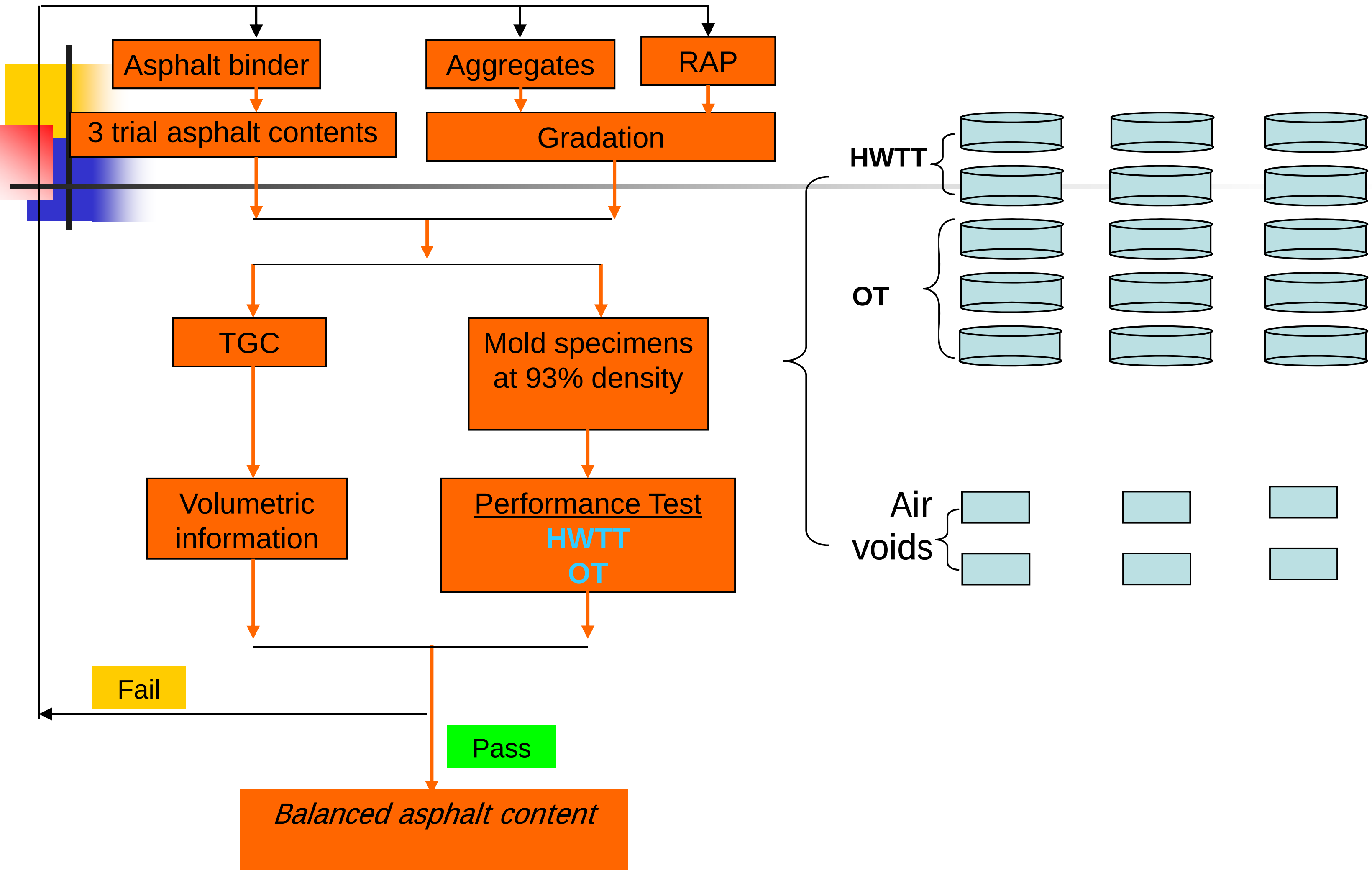
Average Test Results So Far



Balanced RAP Mix Design Concept

- Rutting/moisture: Hamburg test
- Cracking: Overlay test
- Flushing/bleeding: 98% density-TGC

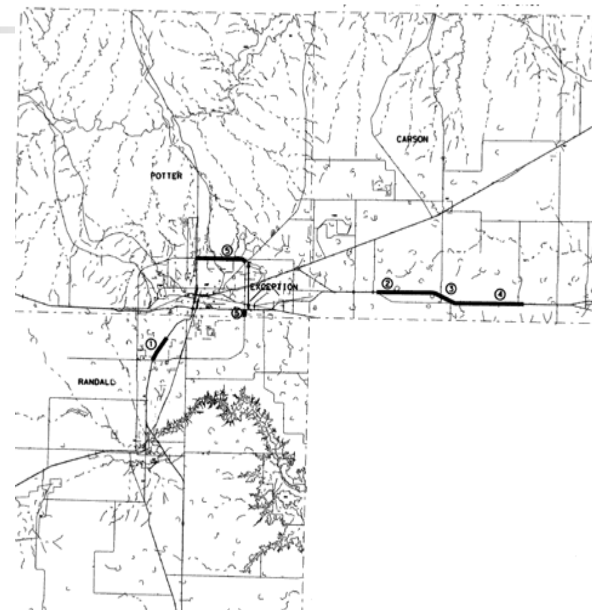
Balance RAP Mix Design Approach

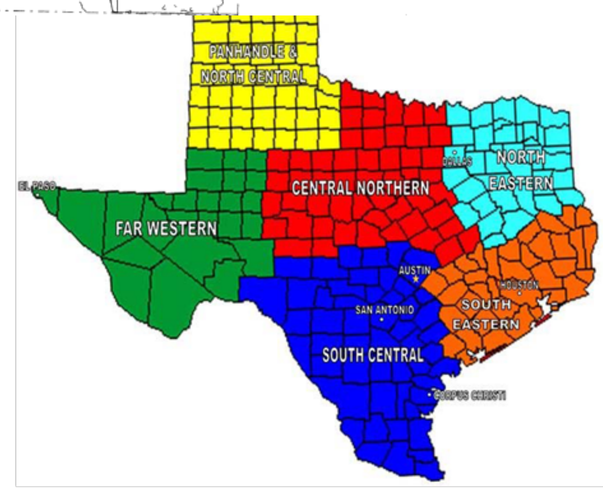


Case Studies: Amarillo Test Sections

Experimental test sections on IH40:

- 0% RAP section: Control section
- 20% RAP-II section: TTI designed
- 35% RAP section: TTI designed





Type C: 20% RAP+PG64-28

Upper limit for AC: 98% Density/TGC

TEXAS DEPARTMENT OF TRANSPORTATION

HMACP MIXTURE DESIGN : SUMMARY SHEET

File Version: 07/15/08 13:33:34

SAMPLE ID:	31290	SAMPLE DATE:	
LOT NUMBER:		LETTING DATE:	JULY 2008
SAMPLE STATUS:		CONTROLLING CSJ:	168-09-155
COUNTY:	RANDALL	SPEC YEAR:	2004
SAMPLED BY:		SPEC ITEM:	341
SAMPLE LOCATION:		SPECIAL PROVISION:	
MATERIAL CODE:	HMAC	MIX TYPE:	ITEM341_C_Coarse_Surface
MATERIAL NAME:			
PRODUCER:	R.K.HALL CONSTRUCTION LTD.		
AREA ENGINEER:	JOE CHAPPELL P.E.	PROJECT MANAGER:	

COURSE\LIFT:		STATION:		DIST. FROM CL:		CONTRACTOR DESIGN # :	31290

Target Density, %:	98.0
Number of Gyrations:	TGC

CRM* Content

TEST SPECIMENS							Mixture Evaluation @ Optimum Asphalt Content			
								Hamburg Wheel Tracking Test		
Asphalt Content (%)	Specific Gravity Of Specimen (Ga)	Maximum Specific Gravity (Gr)	Effective Gravity (Ge)	Theo. Max. Specific Gravity (Gt)	Density from Gt (Percent)	VMA (Percent)	Indirect Tensile Strength (psi)	Number of cycles	Rut depth (mm)	Overlay Tester Min. Number of Cycles
4.7	2.381	2.464	2.645	2.461	96.8	14.1				
5.2	2.389	2.444	2.642	2.443	97.8	14.2				
5.7	2.386	2.422	2.636	2.426	98.4	14.8				

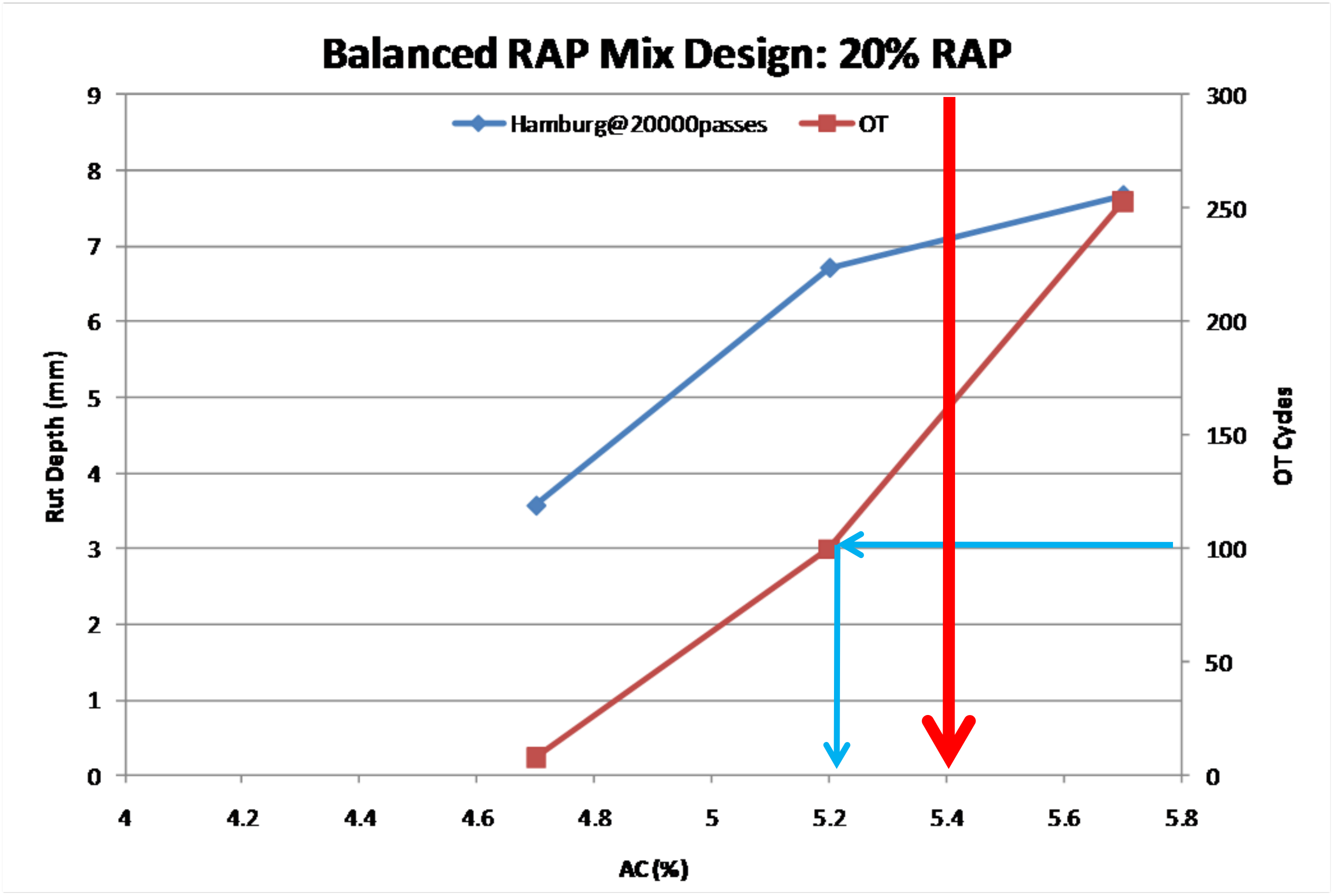
Effective Specific Gravity:	2.641
Optimum Asphalt Content :	5.4
VMA @ Optimum AC:	14.5

Estimated Percent of Stripping, %:	0%

Interpolated Values	
Specific Gravity (Ga):	2.388
Max. Specific Gravity (Gr):	2.436
Theo. Max. Specific Gravity (Gt):	2.437

Hamburg and OT results

- Upper AC limit: 5.4%
- Hamburg: no problem
- OT: min. 100
- Final AC: 5.3%



Type C: 35% RAP +PG58-28 (AC10)

Upper limit for AC: 98% Density/TGC

TEXAS DEPARTMENT OF TRANSPORTATION

HMACP MIXTURE DESIGN : SUMMARY SHEET

File Version: 07/15/08 13:33:34

SAMPLE ID:	31290	SAMPLE DATE:	
LOT NUMBER:		LETTING DATE:	JULY 2008
SAMPLE STATUS:		CONTROLLING CSJ:	168-09-155
COUNTY:	RANDALL	SPEC YEAR:	2004
SAMPLED BY:		SPEC ITEM:	341
SAMPLE LOCATION:		SPECIAL PROVISION:	
MATERIAL CODE:	HMAC	MIX TYPE:	ITEM341_C_Coarse_Surface
MATERIAL NAME:			
PRODUCER:	R.K.HALL CONSTRUCTION LTD.		
AREA ENGINEER:	JOE CHAPPELL P.E.	PROJECT MANAGER:	

COURSE\LIFT:		STATION:		DIST. FROM CL:		CONTRACTOR DESIGN # :	31290

Target Density, %:	98.0
Number of Gyrations:	

CRM* Content

TEST SPECIMENS							Mixture Evaluation @ Optimum Asphalt Content			
								Hamburg Wheel Tracking Test		
Asphalt Content (%)	Specific Gravity Of Specimen (Ga)	Maximum Specific Gravity (Gr)	Effective Gravity (Ge)	Theo. Max. Specific Gravity (Gt)	Density from Gt (Percent)	VMA (Percent)	Indirect Tensile Strength (psi)	Number of cycles	Rut depth (mm)	*Overlay Tester Min. Number of Cycles*
4.7	2.382	2.477	2.660	2.464	96.7	14.2				
5.2	2.387	2.440	2.637	2.446	97.6	14.4				
5.7	2.383	2.423	2.638	2.429	98.1	15.0				

Effective Specific Gravity:	2.645

Estimated Percent of Stripping, %:	**0%**

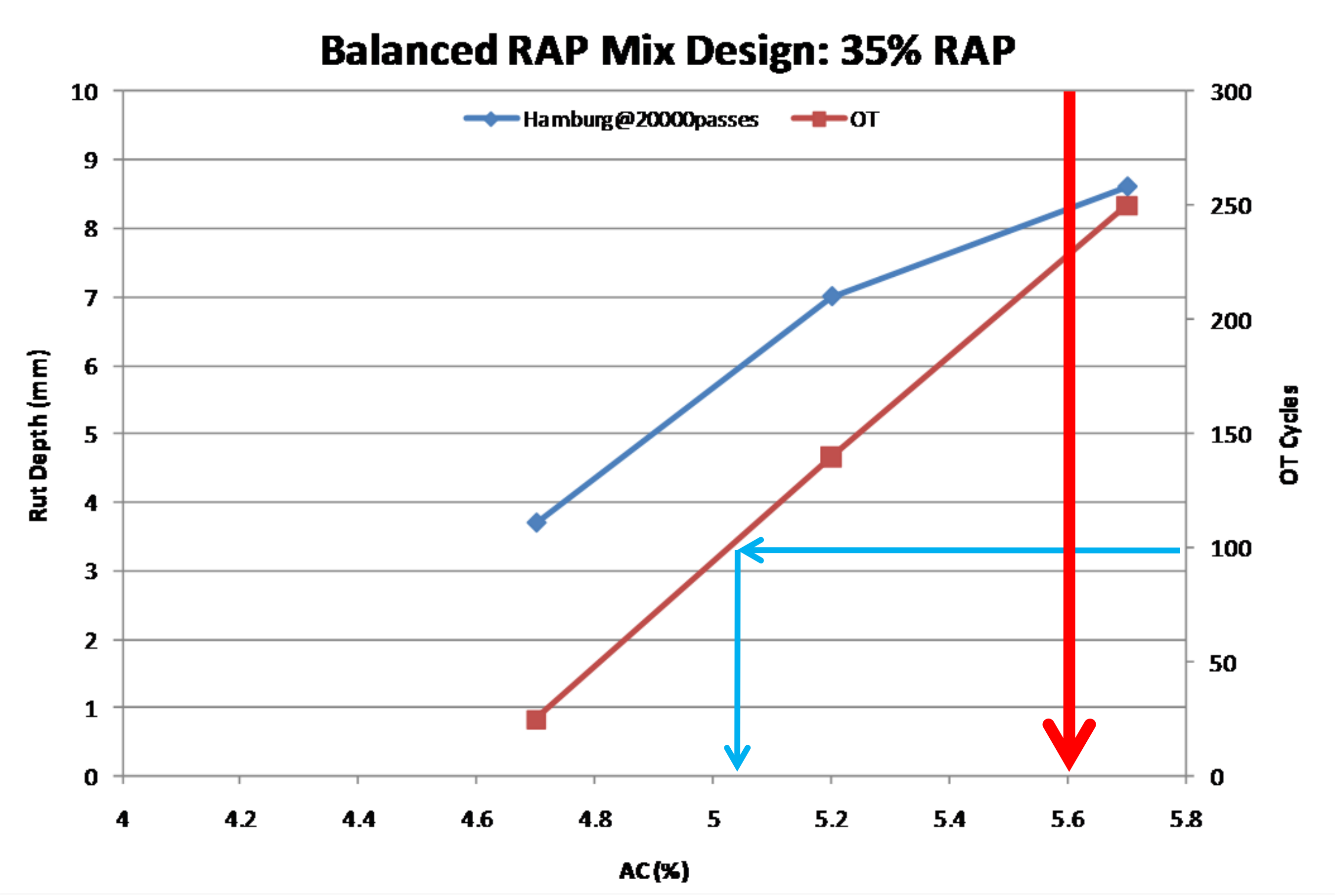
Optimum Asphalt Content :	5.6
VMA @ Optimum AC:	14.9

Interpolated Values	
Specific Gravity (Ga):	2.384
Max. Specific Gravity (Gr):	2.426
Theo. Max. Specific Gravity (Gt):	2.432

Remarks:

Hamburg and OT Results

- Upper AC limit: 5.6%
- Hamburg: no problem
- OT: min. 100
- Final AC: 5.5%



Field Test Section Construction

Step 1: FWD Test

Step 2: Blowing the Surface

Step 3: Spraying Tack Coat

Step 4: Unloading mix

Step 5: Transferring the mix into Shuttle Buggy

Step 6: Feeding the Mix into Paver

Step 7: Paving

Step 8: Compacting

Beginning Location of Test Section 1

Beginning Location of Test Section 2

Beginning Location of Test Section 3

Completed Road

Coring

Cored Samples

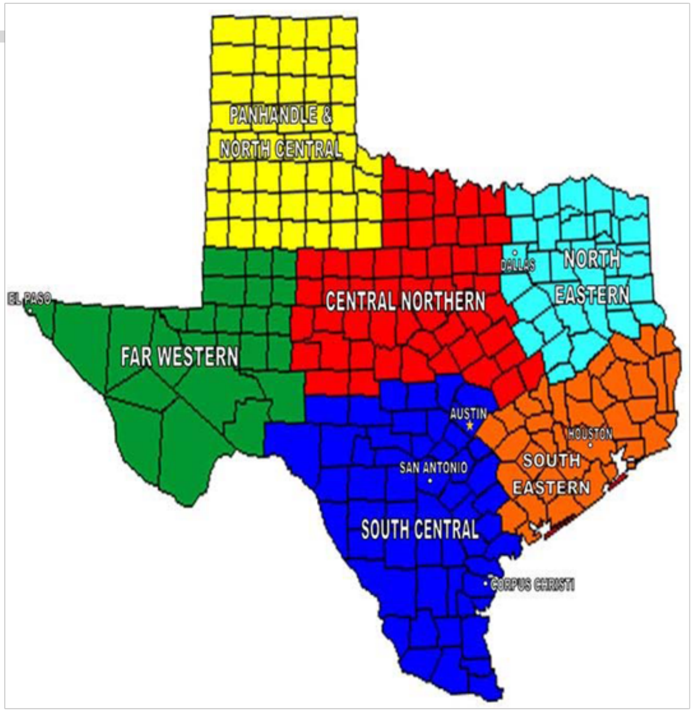
Currently, still evaluating the plant mixes and field cores.

Will monitor the performance of these test sections.

Need help finding field test sections!

Looking for test sections in other districts:

- Control: 0 RAP
- Medium RAP: 20-30%
- High RAP: 35-45%



Thank you!

Questions?

RAP Related Mix Design Issues

TxDOT & TxAPA Workshop
Buda (Near Dripping Springs), Texas

August 27, 2009

Maghsoud Tahmoressi, PE
PaveTex

RAP Utilization

- RAP is currently used as an economical tool to extend the aggregate and asphalt supply
- In hot climates such as Texas, the true benefits of RAP usage may be its ability to stiffen the binder to resist rutting
- Technical advances have been made to allow this beneficial use of RAP
- How do all of the above figure in the mix design?

Effects of RAP on HMA Quality

- Volumetric Properties:
  - Density & VMA: Current Design Method Tex-204-F takes care of this
- Mixture Quality and Performance:
  - Current design procedure does not adequately account for this, i.e., there is no definition of good RAP vs. bad RAP and long term performance is not addressed

Developing the Mix Design

- Combined Aggregate Gradation
- Handling RAP in the Lab
- Modifications to Standard Mix Design Method

RAP Mix Design Steps

- Determine RAP Properties: Gradation & AC Content
- Determine RAP Blend Binder Properties
- Develop Mix Design and Mix Performance

Determine RAP Properties

- RAP Variability:
  - Need extra samples if RAP is highly variable
- Sampling RAP
  - Where and when to sample?
    - From road, millings, processed stockpile?

RAP Characterization

- Gradation and AC Content: Needed for Mix Design
  - Ignition Oven: What to do about Corrections? Wing it?
  - Solvent Extraction: What's that?
- RAP Moisture Content
- RAP Binder Properties
  - Recovery of Binder from RAP
    - Abson Recovery Tex-211-F

Determine RAP Properties

- Extraction and Recovery of RAP Binder and Aggregates

RAP Binder Properties: Why Do We Care?

- Liquid Asphalt in RAP can improve high temperature properties of mix (i.e., improve Hamburg)
  - Age of RAP
  - RAP Percentage
- Liquid Asphalt in RAP can increase cracking and raveling potential
- So is RAP Good or Bad???
  - Improper selection of virgin binder grade
  - RAP Percentage

Binder Blending Method

- Determine RAP Binder Properties
  - Extract RAP asphalt by solvent extraction
  - Recover asphalt by Abson Distillation

– Determine RAP Critical Temp (Tc)
In Texas, High Temp Grade is the biggest factor

RAP Binder Properties

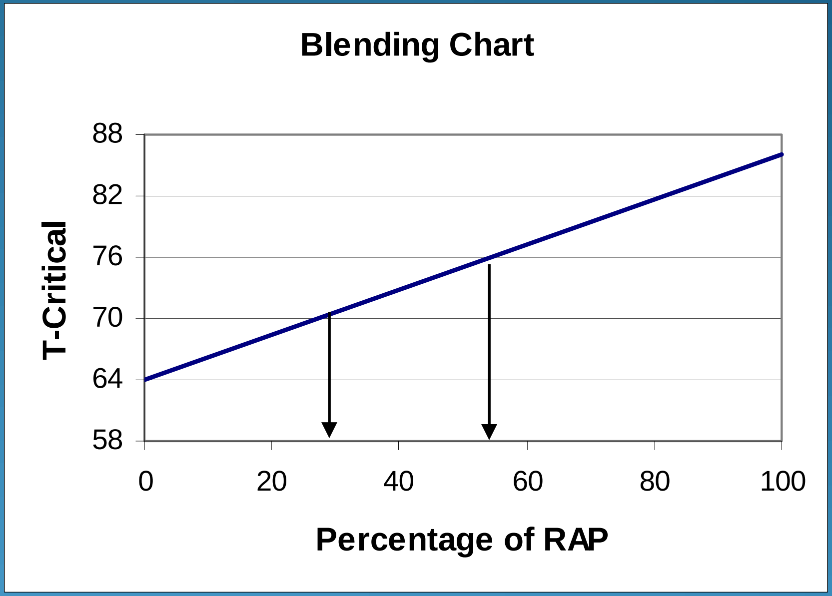
- Extraction & Recovery of Binder–Abson Method
- RAP Binder Properties–Pen & DSR
- Binder Grade Selection–What do plans call for? Are the plans specified grade correct?
- Determine RAP Content
  - How much RAP to use? How much did the boss bid?

How Does RAP Influence HMA Performance?

- RAP and Virgin Asphalt Blending Charts
  - This assumes complete blending of old and new asphalt
  - All tests used in this method are well defined

Blending Charts

- Known Virgin and RAP Grade:
- Example: PG 64-xx is virgin and PG 84-xx is RAP Grade



How Does RAP Influence HMA Performance?

- Black Rock Effect: Asphalt in RAP does not blend with virgin asphalt
  - May be true with low RAP % or very old RAP
- Total Blending of old and new liquid asphalt: Not very likely
- Partial Blending
- How do we know what happens?

Binder Blending Method

- Most current research supports the concept of a tiered system
- Blending occurs at higher RAP contents. At low RAP contents blending effects are not significant

Virgin Binder Grade Selection

- Less than 20% RAP: No change in Binder Grade
- 20-30% RAP: One Grade Lower
- More 30% Binder: Use Blending Chart
- This strategy assumes blending occurs only at high RAP percentages: May not be a good assumption

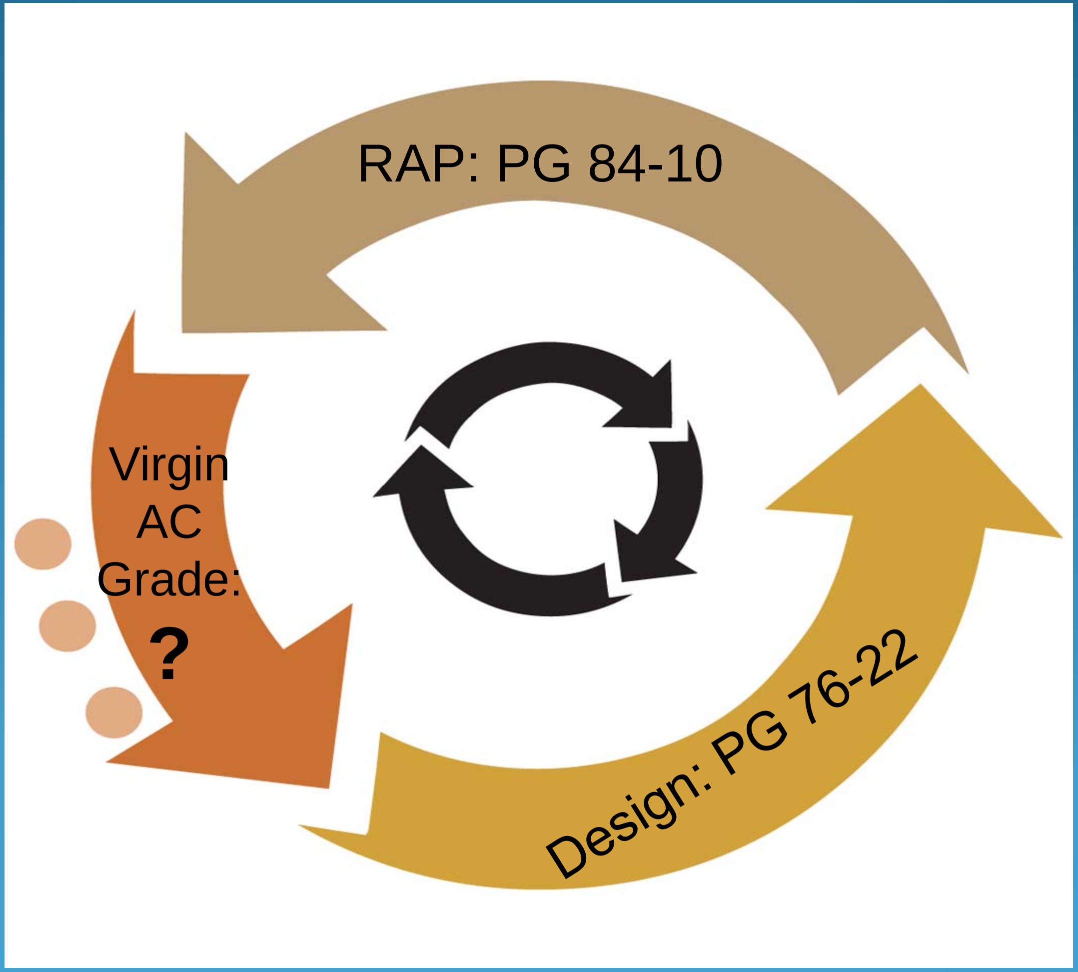
Alternative to Blending Charts

- When acceptable mixture performance tests are available, RAP usage can be optimized to yield desired mix test results
- Current Potential Tests:
  - Rutting: Hamburg Test
  - Moisture Damage: Hamburg Test
  - Cracking Resistance: Overlay, Tensile strength, Resilient Modulus, ???
  - Raveling & Flushing: VMA & VFA

Handling RAP in the Lab

- Heat and mix RAP into a homogeneous material
- Do we need to split RAP sample? No, keep it simple
- When do we add RAP? Keep it simple! Add it to dry batch
- Treat RAP like a black rock

RAP as a Modifier



Thank you!

Questions?

IMPACT OF RAP ON MIXTURES' PROPERTIES

Including RAP in HMA mixtures

RAP MIX

+

Virgin Aggregate

Target Binder Grade
PG64-22, PG58-34…

Impact of RAP on mixtures' properties

Stiffness

Rutting resistance

Fatigue resistance

Low temperature cracking

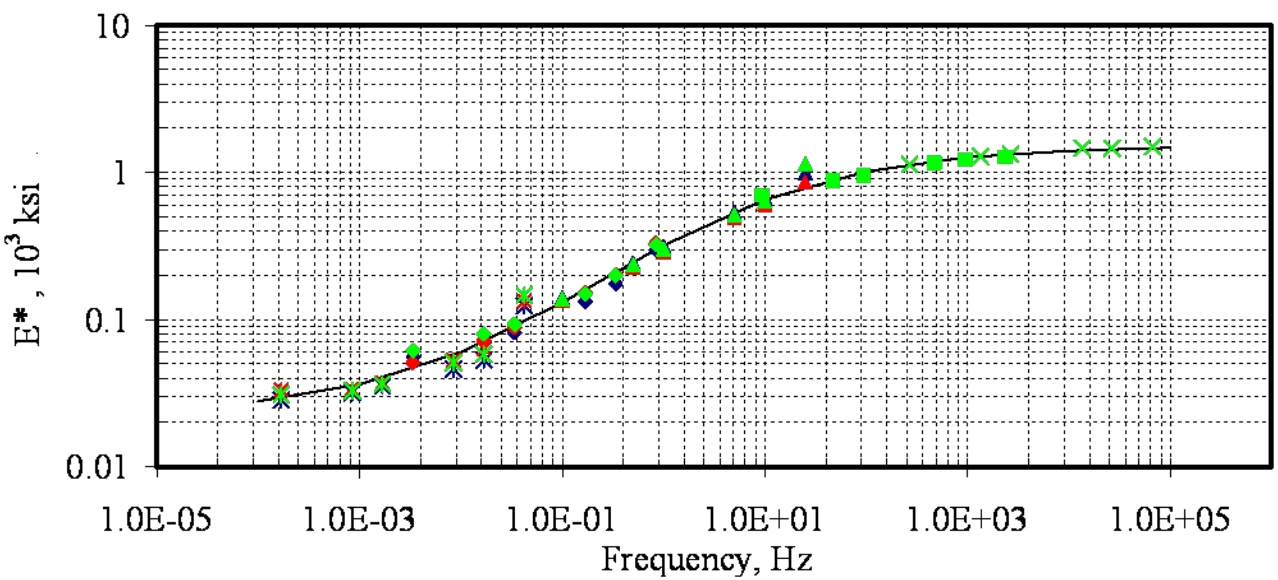
Moisture resistance

Impact of RAP on mixtures' properties

Stiffness

- Dynamic Modulus, |E*|

Dynamic modulus testing setup



Impact of RAP on mixtures' properties

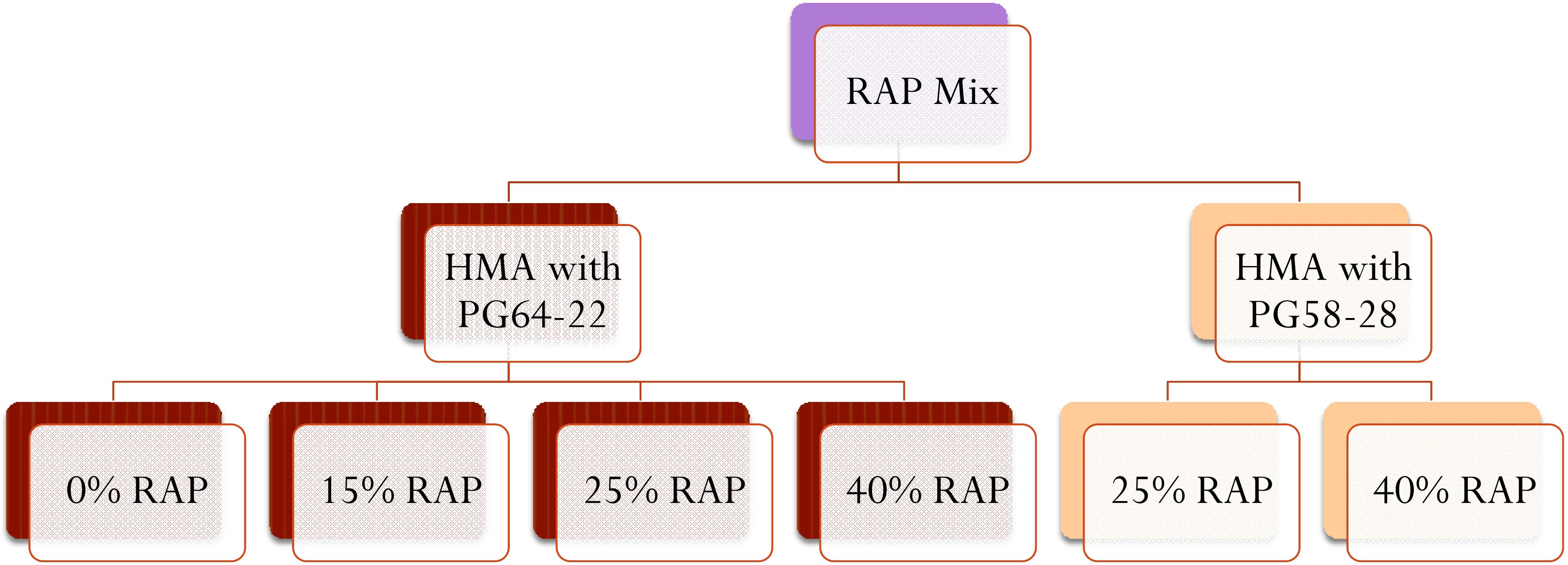
Stiffness

- *Li et al. (2004):* 10 mixes at 0, 20, and 40% RAP, two virgin asphalt binders (PG58-28 and PG58-34), and two RAP sources (RAP and millings).
- 20-40% RAP $\rightarrow |E^*| \uparrow$.
- No significant impact for RAP on $|E^*|$ at low temperatures and high frequencies.

Impact of RAP on mixtures' properties

Stiffness

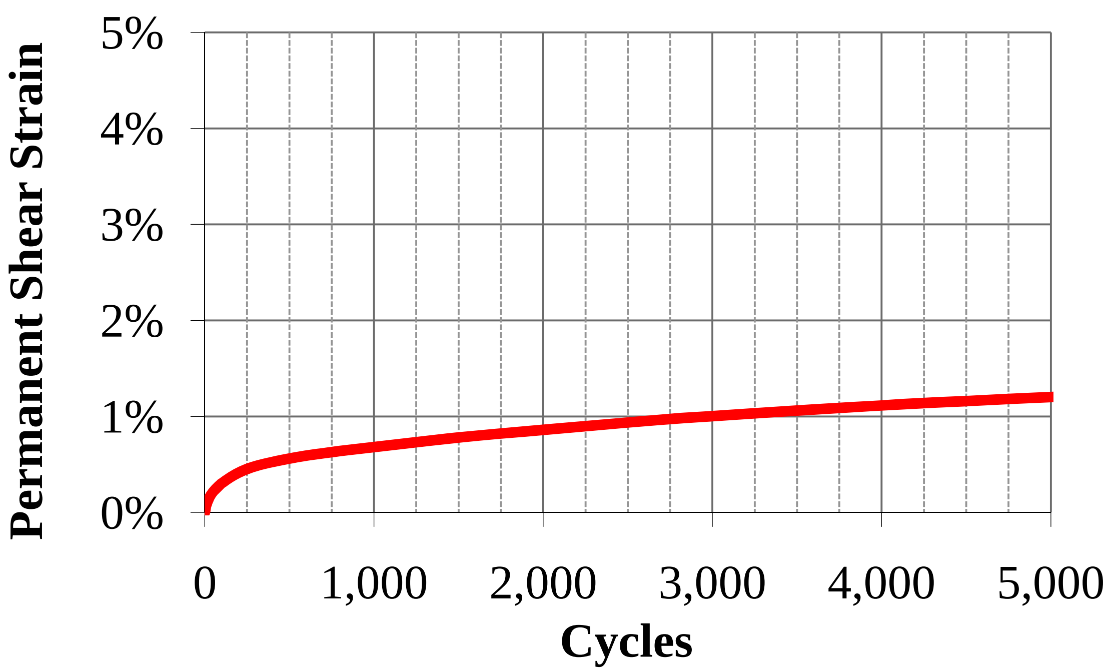
- *McDaniel et al. (2006):*
  - 15-25% RAP → No significant impact on |E*|.
  - 40% RAP → ↑|E*| at higher temperatures.

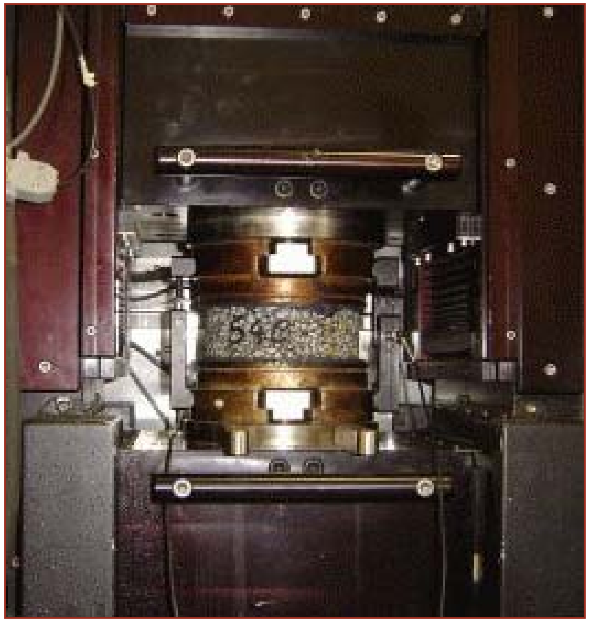


Impact of RAP on mixtures' properties

Rutting Resistance

- Repeated Shear at Constant height (RSCH)

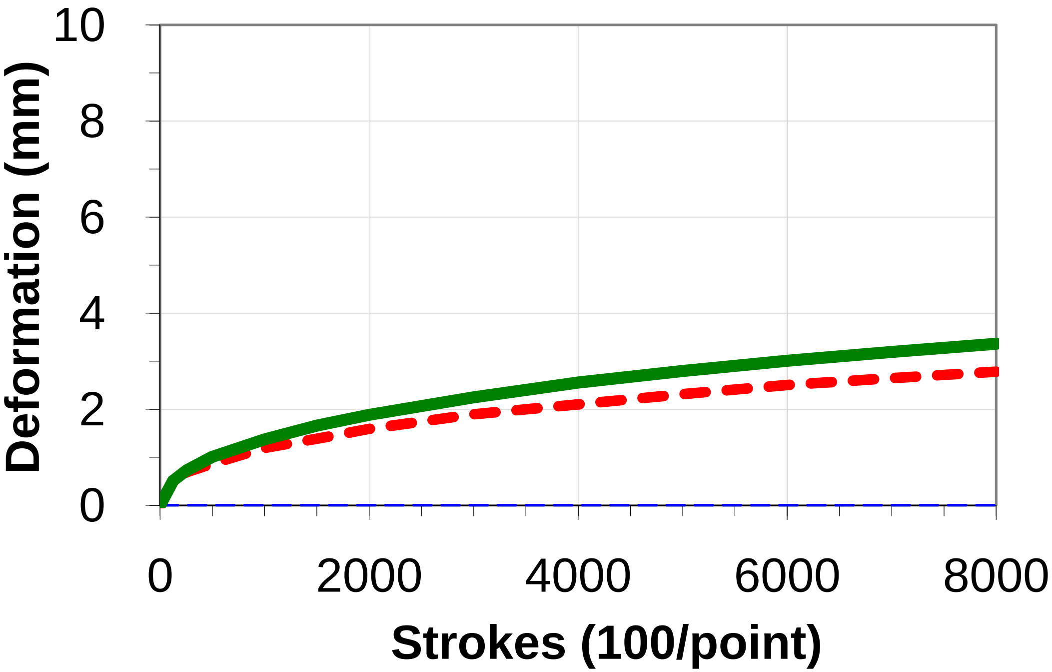




Impact of RAP on mixtures' properties

Rutting Resistance

- Asphalt Pavement Analyzer (APA)



Impact of RAP on mixtures' properties

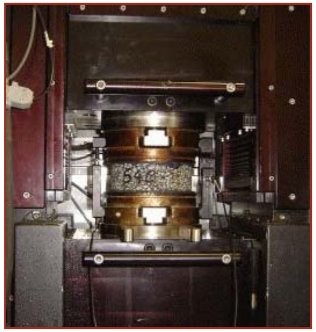
Rutting Resistance

- *NCHRP 9-12 (2000)*: impact of 0,10, 20, and 40% RAP content on mixtures' resistance to rutting.

Generally,

↑ RAP content → ↓Shear deformation & accumulated shear strain

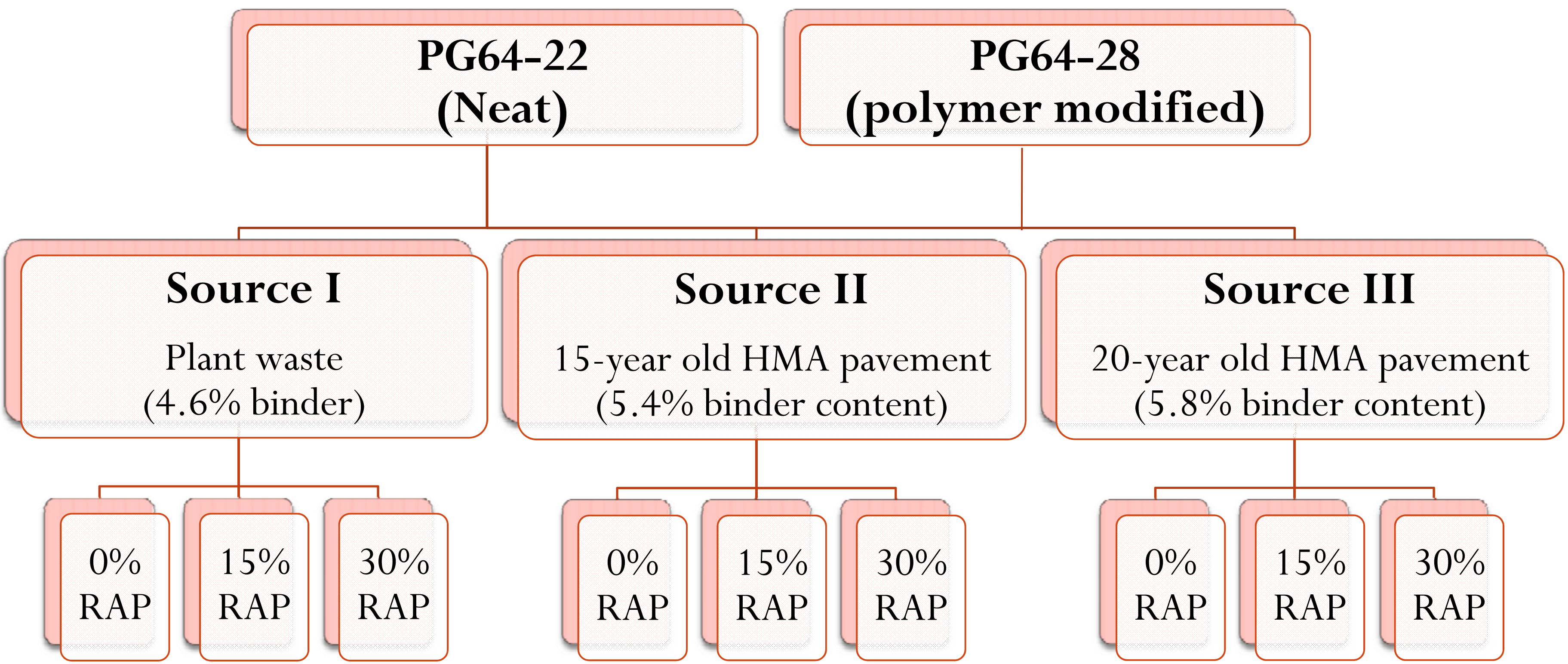
→ ↑ rutting resistance



Impact of RAP on mixtures' properties

Rutting Resistance

- *Hajj et al. (2007):*

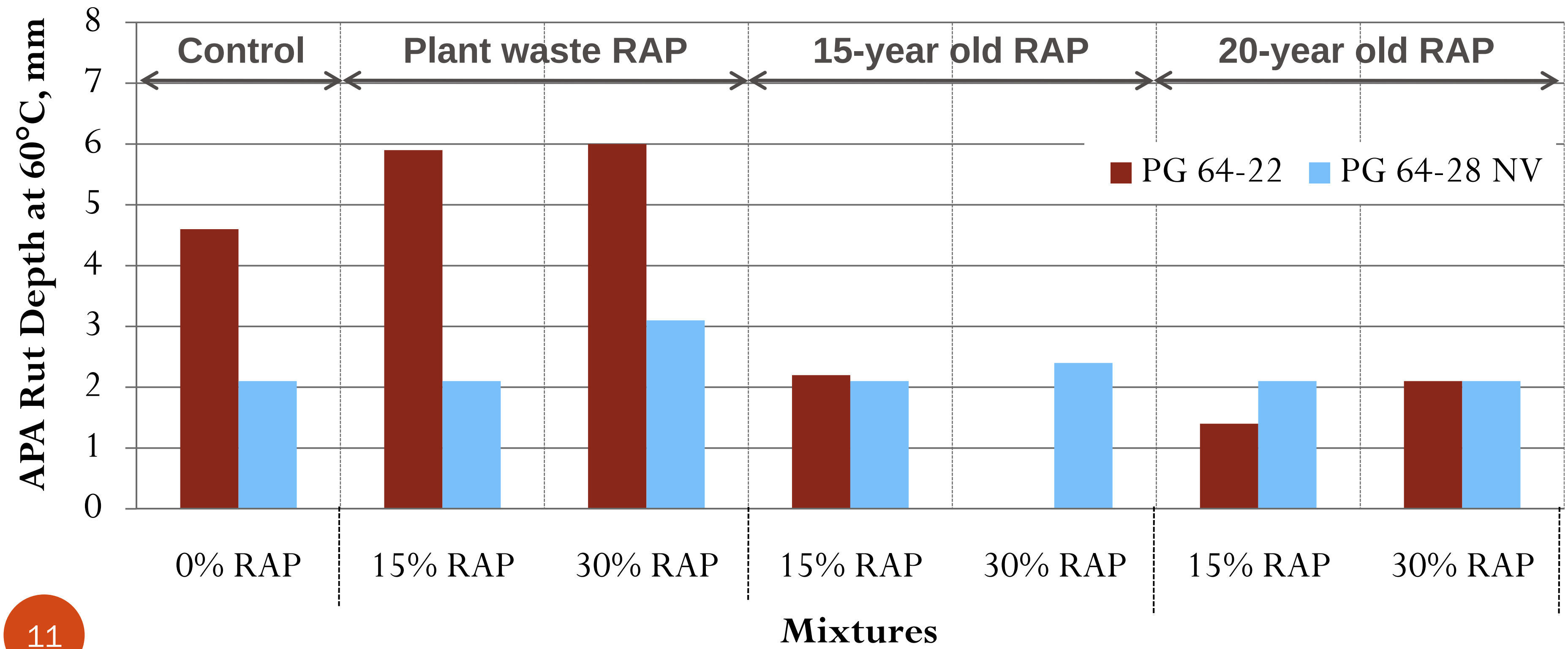


Impact of RAP on mixtures' properties

Rutting Resistance

- *Hajj et al. (2007): APA Tests*

Passed NDOT APA criterion of 8 mm at 60°C → good rutting resistance



Impact of RAP on mixtures' properties

Rutting Resistance

- *Xiao et al. (2007):* Effect of RAP (0 - 38%) and rubber on APA rutting resistance of HMA mixes.

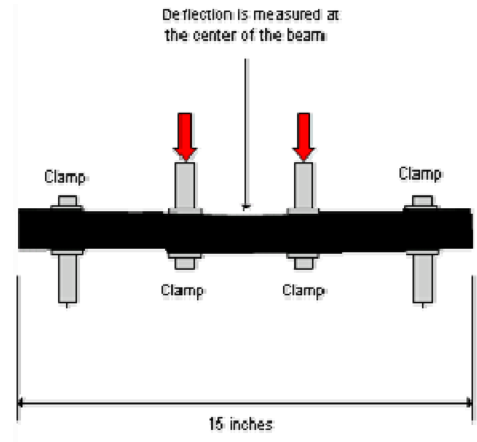
  - $\uparrow$ RAP content $\rightarrow$ $\uparrow$rutting resistance
  - Rubberized binder increases the rutting resistance

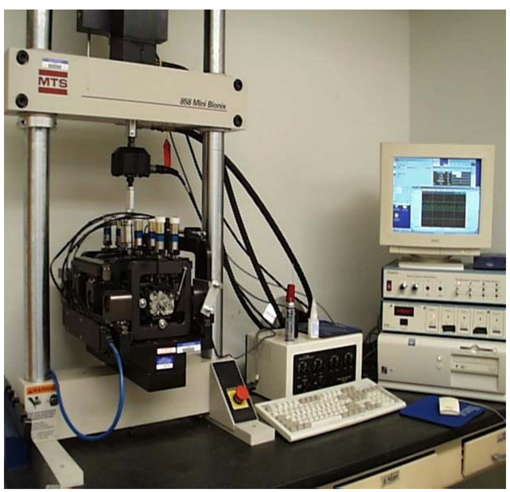
Impact of RAP on mixtures' properties

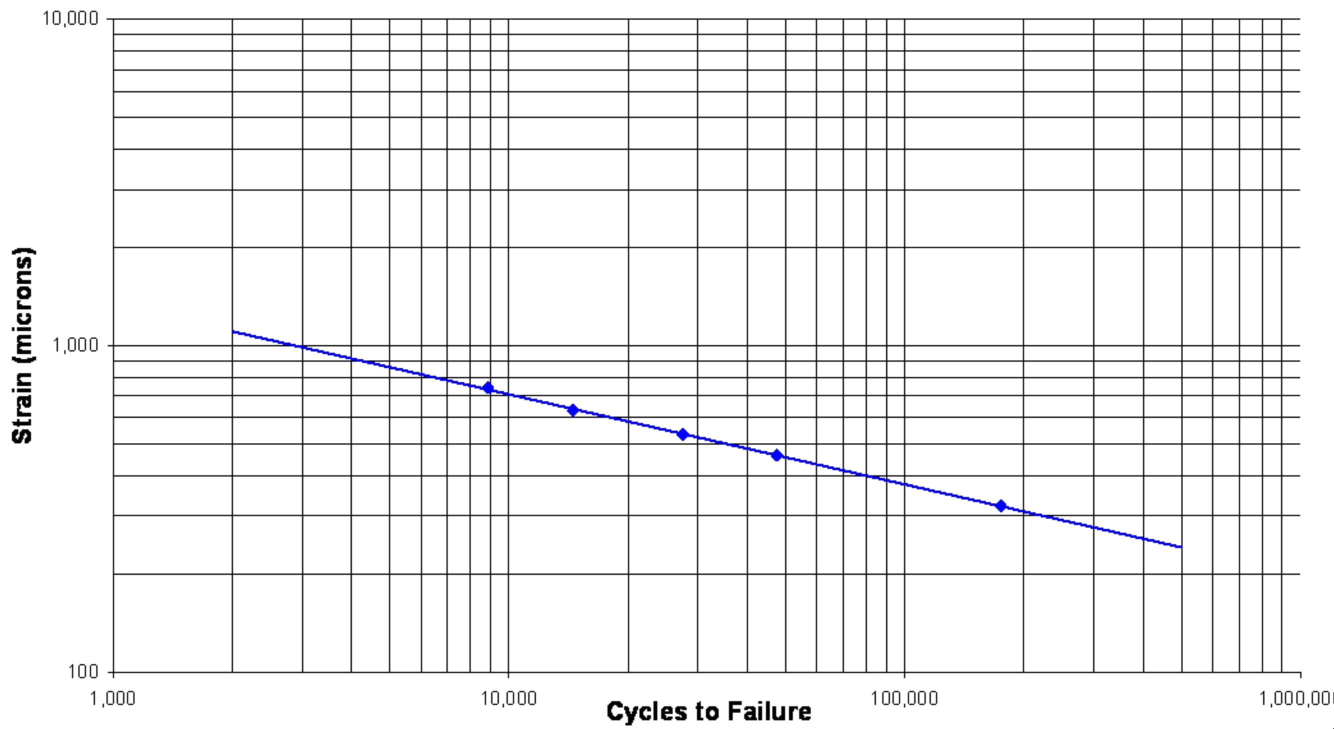
Fatigue Resistance

- *Flexural Beam Fatigue Test*

$$N_f = k_1 \left(\frac{1}{\varepsilon} \right)^{k_2}$$







Impact of RAP on mixtures' properties

Fatigue Resistance

- *Puttaguanta et al. (1996):* Estimated fatigue life of 0, 25, and 50% RAP mixes at 5, 22, and 40°C.

    - At 5°C, 25 and 50% RAP mixes→ ↓ fatigue resistance.

    - At 22°C and 40°C all three mixes performed similarly.

Impact of RAP on mixtures' properties

Fatigue Resistance

- *NCHRP 9-12 (2000):* impact of 0,10, 20, and 40% RAP content on mixes' resistance to fatigue.
  - 10% RAP → no significant impact fatigue resistance.
  - 20 and 40% RAP → ↓ fatigue resistance.
  - 40% RAP mix resistance < 20% RAP mix resistance.

Impact of RAP on mixtures' properties

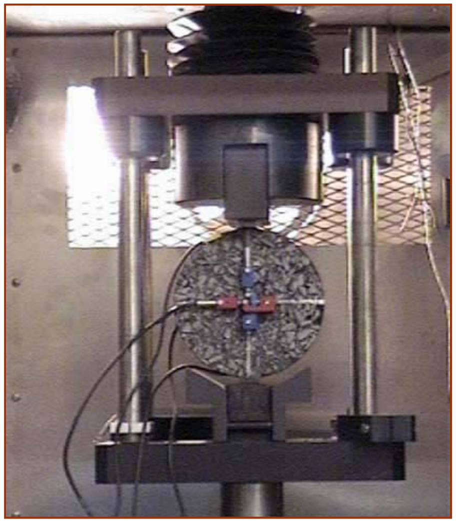
Fatigue Resistance

- *Hajj et al. (2007):* mixtures with 0, 15, and 30% RAP.
  - PG64-22 (neat):
    15% RAP → better or equivalent fatigue resistance.
  - PG64-28 (polymer modified):
    15-30% RAP → significant ↓in fatigue resistance.

Impact of RAP on mixtures' properties

Resistance to Low Temperature Cracking

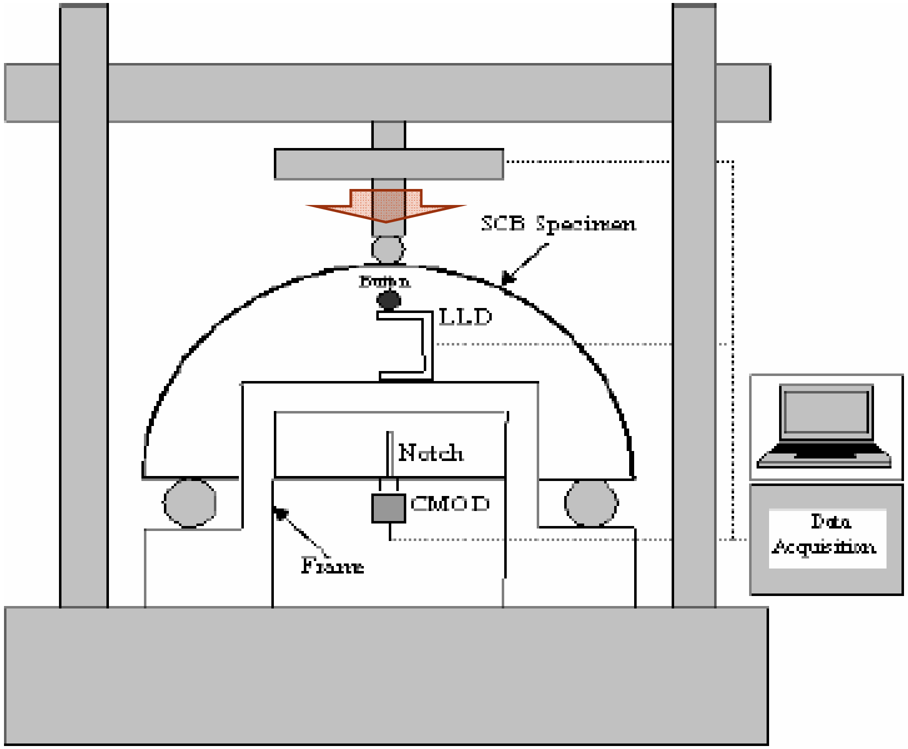
- *Indirect Tensile (IDT) creep stiffness*



Impact of RAP on mixtures' properties

Resistance to Low Temperature Cracking

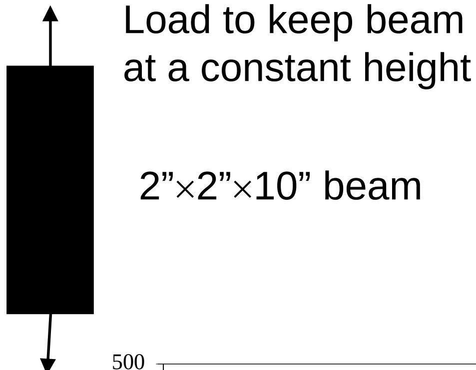
- *Semi Circular Beam (SCB) fracture test*

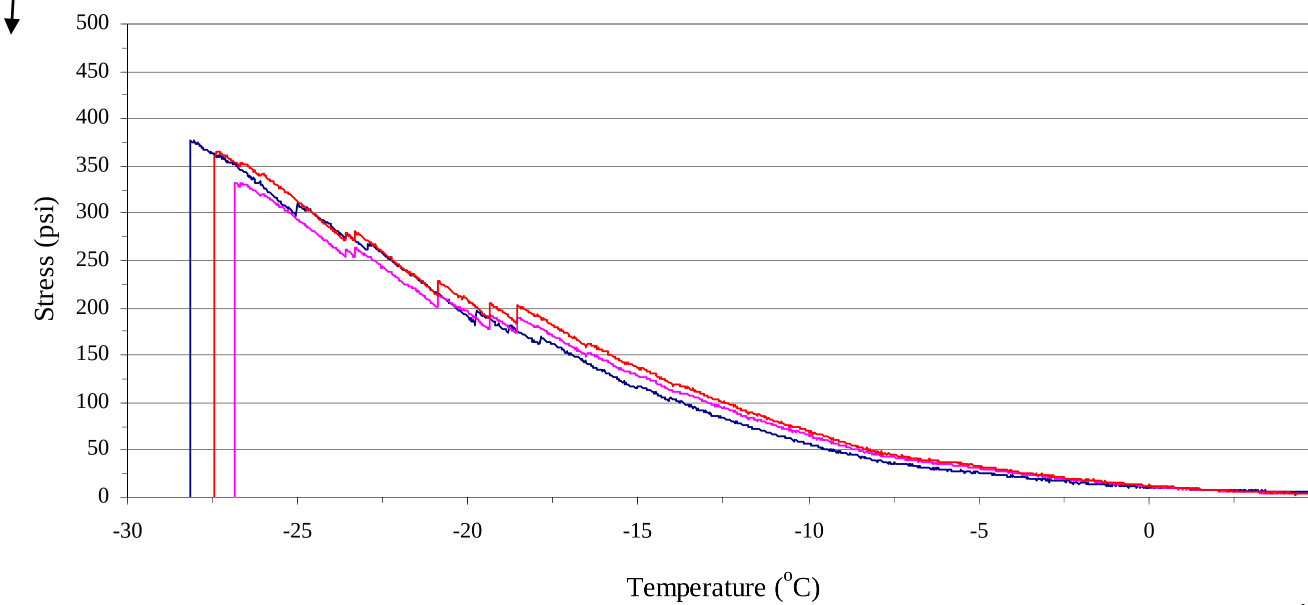


Impact of RAP on mixtures' properties

Resistance to Low Temperature Cracking

- *Thermal Stress Restraint Specimen (TSRST)*





Impact of RAP on mixtures' properties

Resistance to Low Temperature Cracking

- *NCHRP 9-12 (2000):* Resistance to low temperature cracking using IDT.
  - 10% RAP → no impact on low temperature cracking resistance.
  - >10% RAP → ↓ low temperature cracking resistance.

Impact of RAP on mixtures' properties

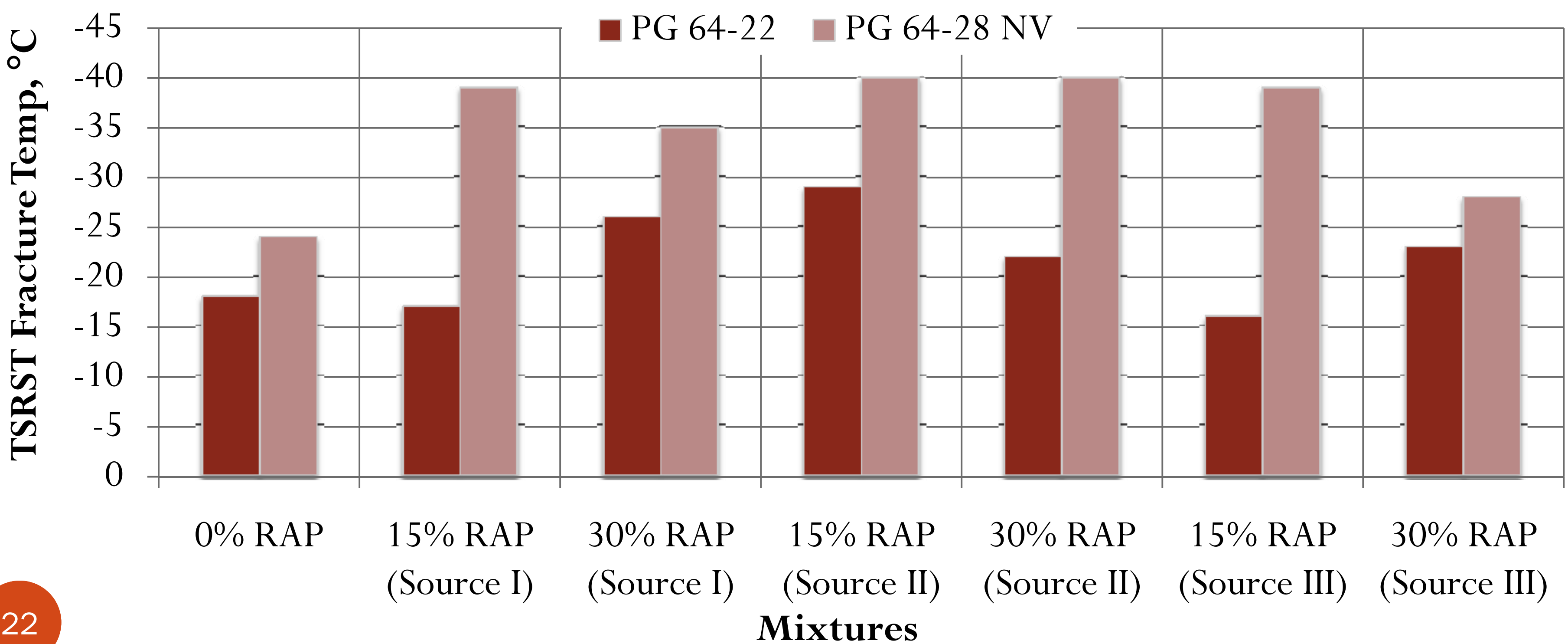
Resistance to Low Temperature Cracking

- *Li et al. (2004 & 2006):* 10 RAP mixes with 0-40% RAP using IDT test and SCB fracture test.
  - IDT test: ↑RAP → ↓ resistance to low temperature cracking.
  - SCB fracture test:
    - RAP content has significant effect on low temperature cracking.
    - 20% RAP → no impact on low temperature cracking resistance.
    - >20% RAP → significant ↓ in resistance to low temperature cracking.

Impact of RAP on mixtures' properties

Resistance to Low Temperature Cracking

- *Hajj et al. (2007):* RAP mixes with 0,15, and 30% RAP using TSRST



Impact of RAP on mixtures' properties

Resistance to Moisture Damage

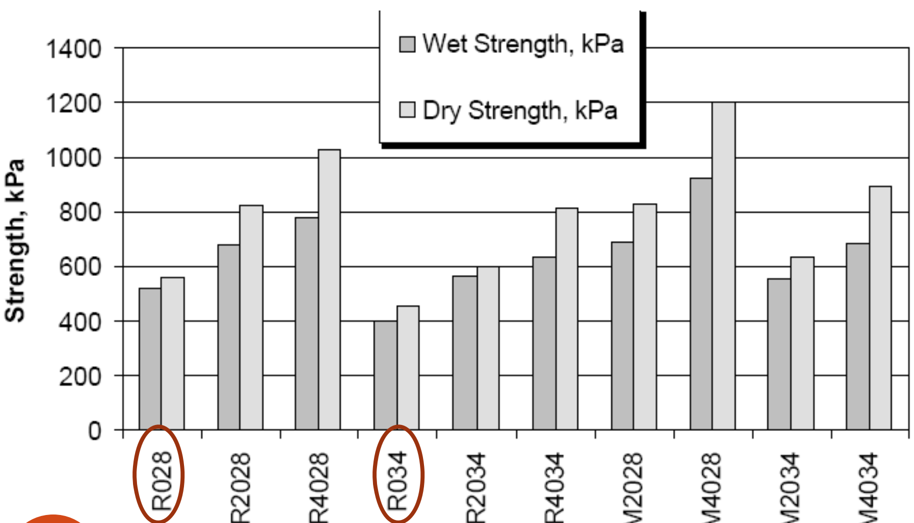
- *Puttaguanta et al. (1996):* mixes with 0, 25, and 50% RAP using AASHTO T283 test
    - 25 and 50% RAP → significant ↑ in moisture resistance.

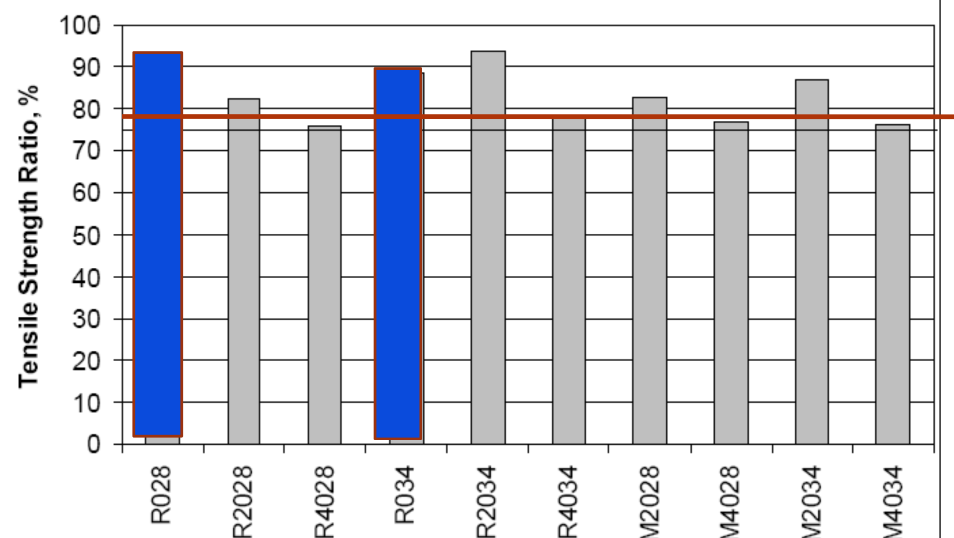
Property	Virgin mix	RAP mix		Allowable limit
		25%	50%	
Tensile strength ratio, %	59	81	91	> 80
Resilient modulus ratio, %	68	85	90	> 80

Impact of RAP on mixtures' properties

Resistance to Moisture Damage

- *Li et al. (2004):* 10 RAP mixtures with 0-40% RAP using AASHTO T283 test.
  - TSR of 20 and 40% RAP mixes > 75% (criterion)
  - ↑RAP→ ↑TS (both wet and dry) but ↓TSR

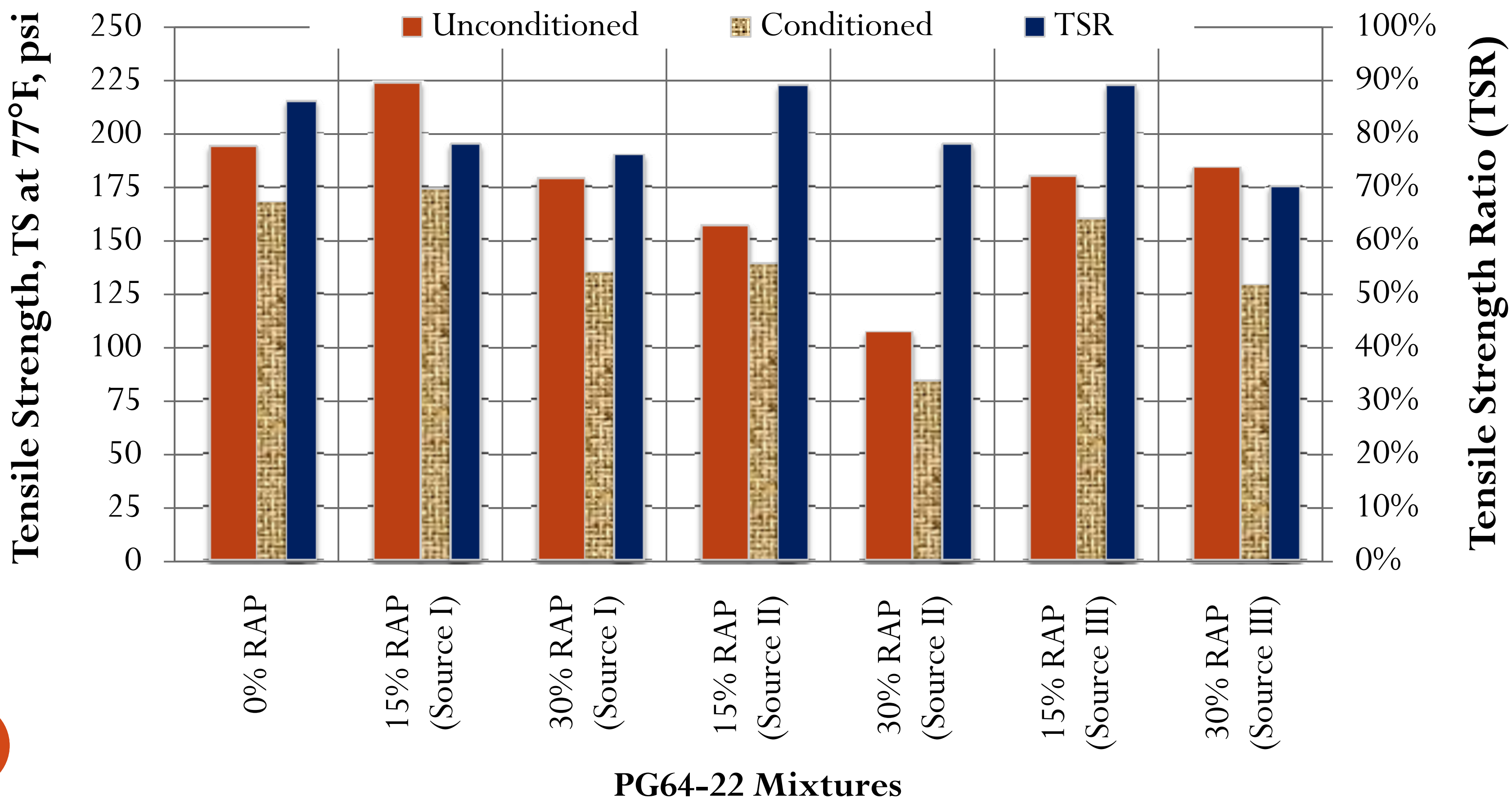




Impact of RAP on mixtures' properties

Resistance to Moisture Damage

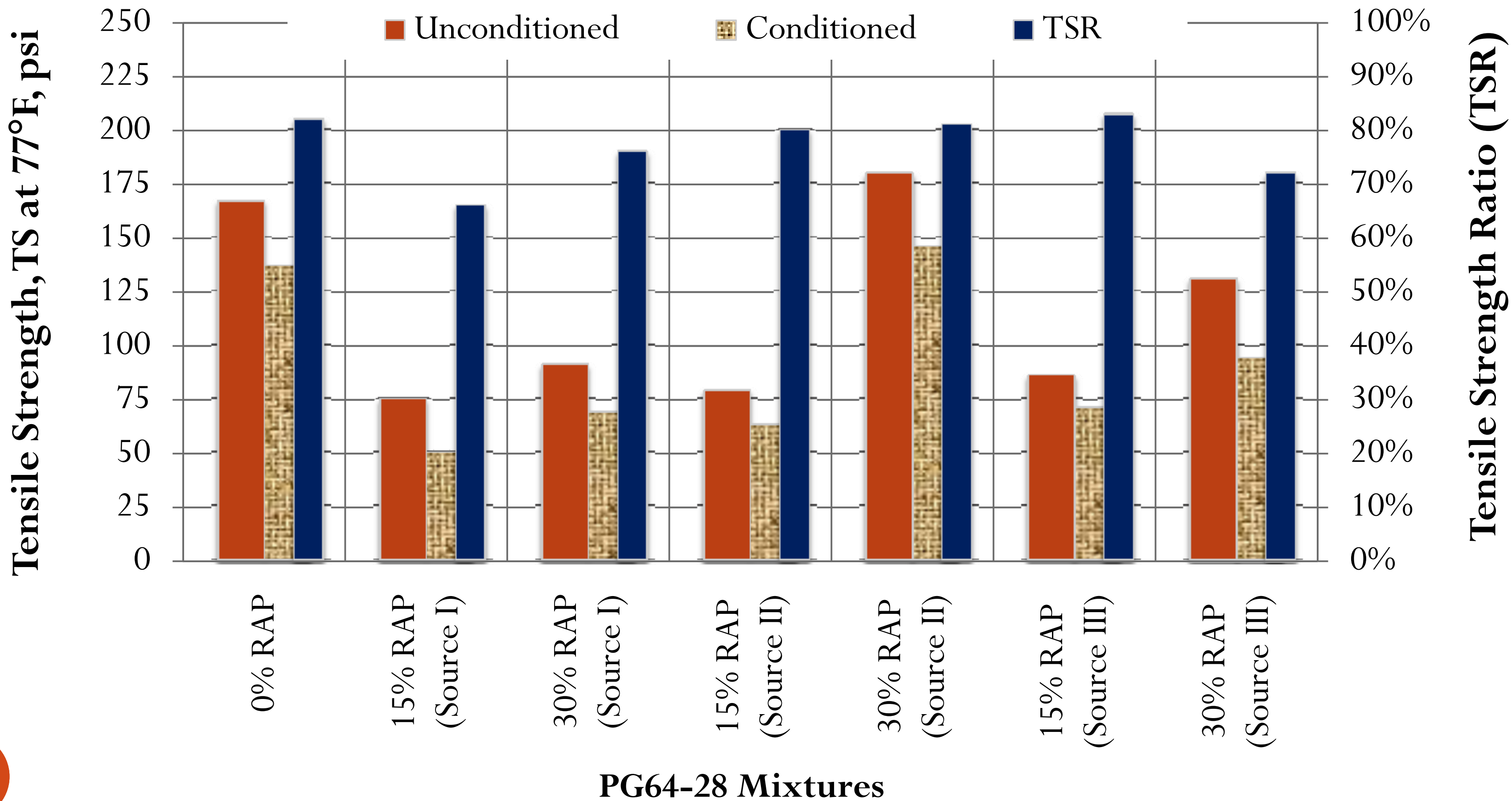
- *Hajj et al. (2007):* RAP mixtures with 0,15, and 30% RAP using AASHTO T283 test.



Impact of RAP on mixtures' properties

Resistance to Moisture Damage

- *Hajj et al. (2007):* (cont'd)



Impact of RAP on mixtures' properties

Resistance to Moisture Damage

- *Hajj et al. (2007): (cont'd)*

  - 15 and 30% RAP → acceptable moisture resistance (TSR>70).

  - 15 and 30% RAP → ↓TS conditioned and unconditioned.

PERFORMANCE REVIEW OF RAP CONTAINING MIXES IN

HIGHWAY PAVEMENTS

Field performance

Highway Pavements

- *CALTRANS:* Evaluated life expectancy of 15% RAP containing pavements & compared to other treatments applied in California

Environmental Zone	Expected Service Lives (years) Based on			Triggering Failure Mode
	Structural Performance	Distress Performance	Roughness Performance	
North Coast	18	21	17	Ride quality
Desert	15	9	15	Distress
Mountain	11	13	15	Structural

Field performance

Highway Pavements

- *Louisiana Department of Transportation:* Compared the performances of 5 RAP sections (20-50%) and 4 virgin mix pavement sections and determined that:
  - after 6 - 9 years: longitudinal and transverse cracking and rutting were the major type of distresses
  - 20-50% RAP sections perform equal to virgin sections
  - no significant differences between recovered binder from virgin and RAP sections

Field performance
Highway Pavements

- *Georgia Department of Transportation:* Compared performances of 5 projects; each with a RAP and a control section. Additionally, 13 RAP projects and 10 virgin projects were also compared.
  - After 1.5 – 2.25 years: RAP pavements were performing as well as virgin pavements.
  - Recovered binder tests → good resistance to fatigue cracking and rutting.

Field performance

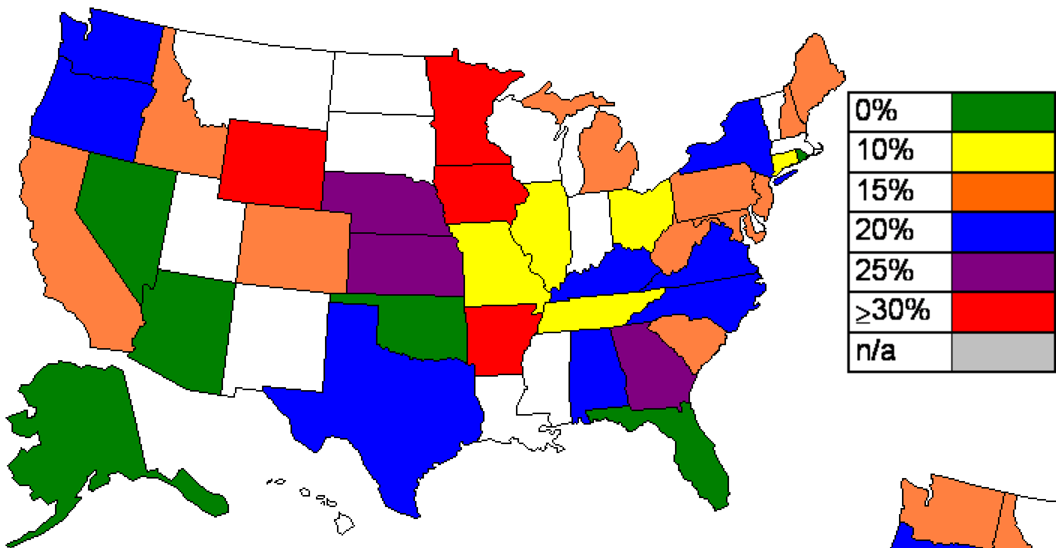
Highway Pavements

- *Connecticut Recycled Highway Pavements:* Under LTPP, 24 projects throughout North America were monitored; among which 3 Connecticut sections had 20% RAP.
  - Good field performance after 8 years in service.
  - No fatigue and transverse cracking.
  - Lower rutting than other sections.
  - Slightly higher non-wheel path longitudinal cracking.

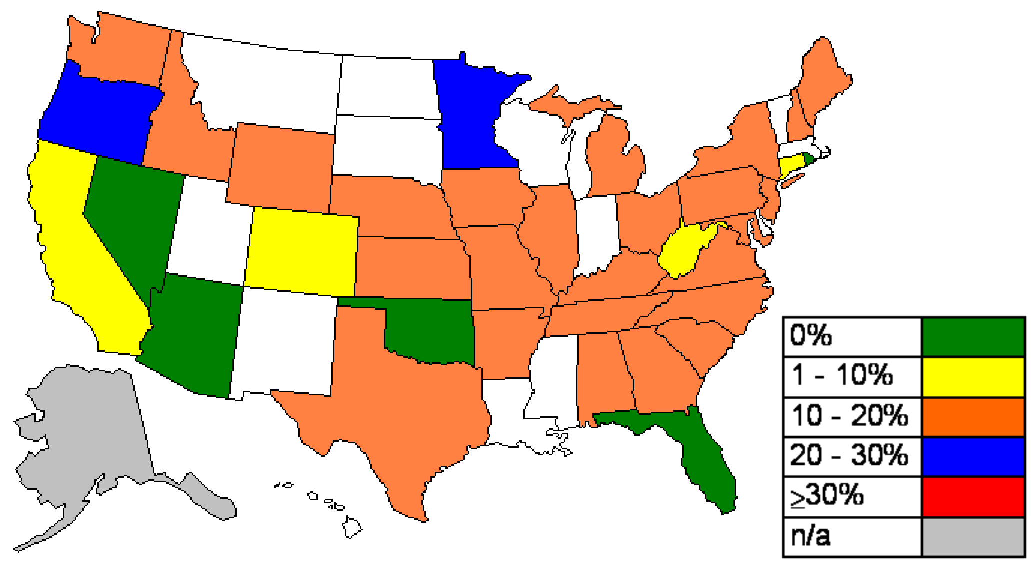
STATE HIGHWAY AGENCIES' USE OF RAP

State highway agencies' use of RAP

RAP in HMA Surface Mixes (After NCDOT)



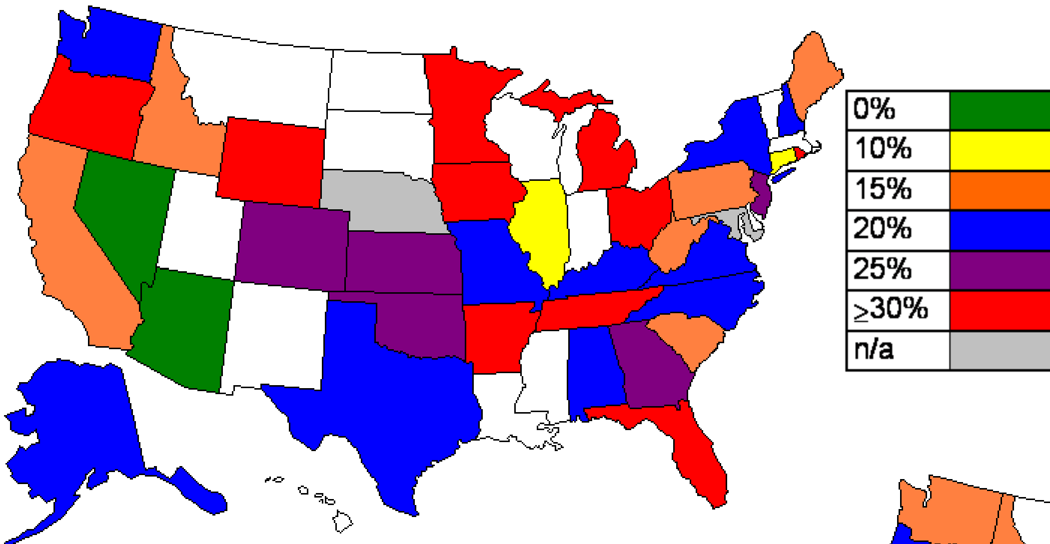
Specified use of RAP



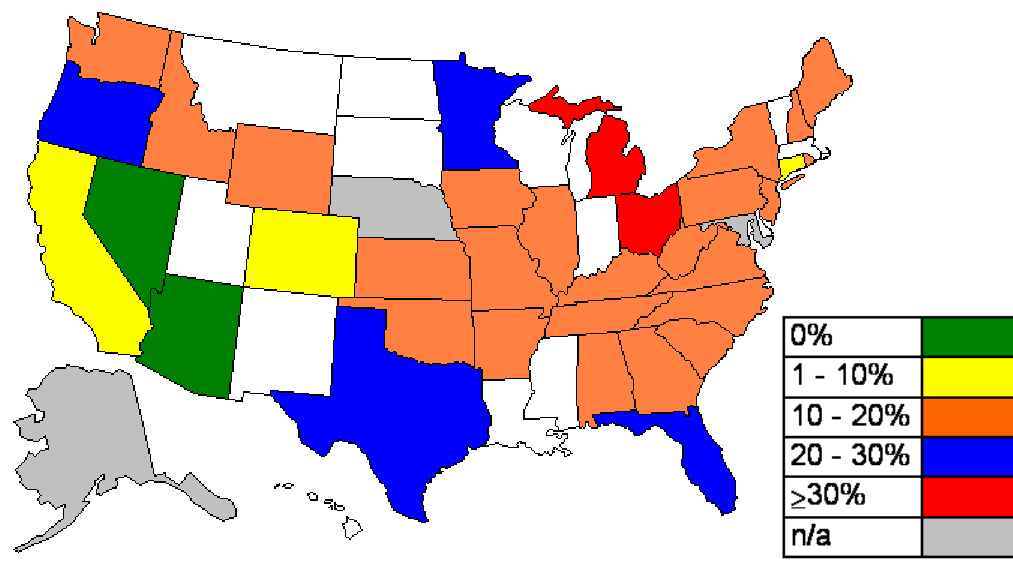
Average use of RAP

State highway agencies' use of RAP

RAP in HMA Intermediate Mixes (After NCDOT)



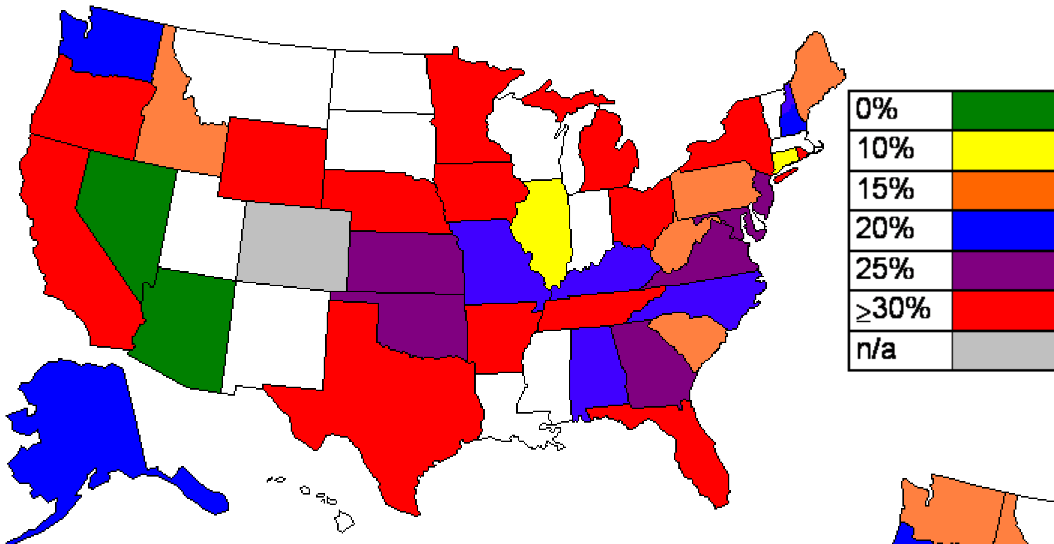
Specified use of RAP



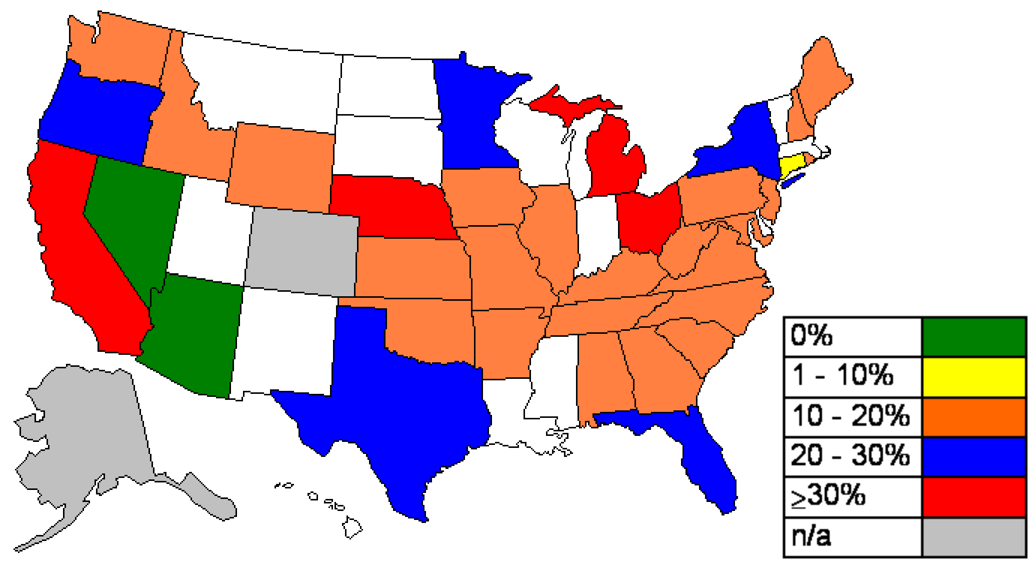
Average use of RAP

State highway agencies' use of RAP

RAP in HMA Base Mixes (After NCDOT)



Specified use of RAP



Average use of RAP

State highway agencies' use of RAP

- Most highway agencies allowed RAP in HMA Mixes.
- Most specs limit practical use of higher % RAP in mixes.
- Most highway agencies specs change with:
  - mix type: dense graded mix, SMA, open graded mix…
  - production method: batch plant vs. drum mix plant.

State highway agencies' use of RAP

- Most highway agencies allow max 10-25% of RAP in surface mixes and a higher percent RAP in base mixes.
- Some agencies restrict RAP in surface course for pavements with high applied ESAL.
- Some highway agencies require approval for the RAP sources prior to their usage in the mix.

State highway agencies ' use of RAP

- Some highway agencies specify max size for RAP material > max size of regular HMA mix.
- Some highway agencies restrict or limit RAP to 10% with polymer modified HMA mixes.
- Most highway agencies require an adjustment to the binder grade when > 15-20% RAP is used.
- RAP is used with Marshall, Hveem, and Superpave mix design methods.

Thank you!

Questions?

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Estimating Low Temperature PG-Grade of Binders in RAP without Extraction: UWM + UNR

Impact of current extraction techniques on properties of extracted RAP aggregates: UNR + NCAT

Concept of Testing

- Replace extraction & testing with testing RAP mortar
  - Mortar: Void-less mix of selected gradation of RAP with binder

- Estimate allowable percent of RAP based on RAP properties and final PG grade

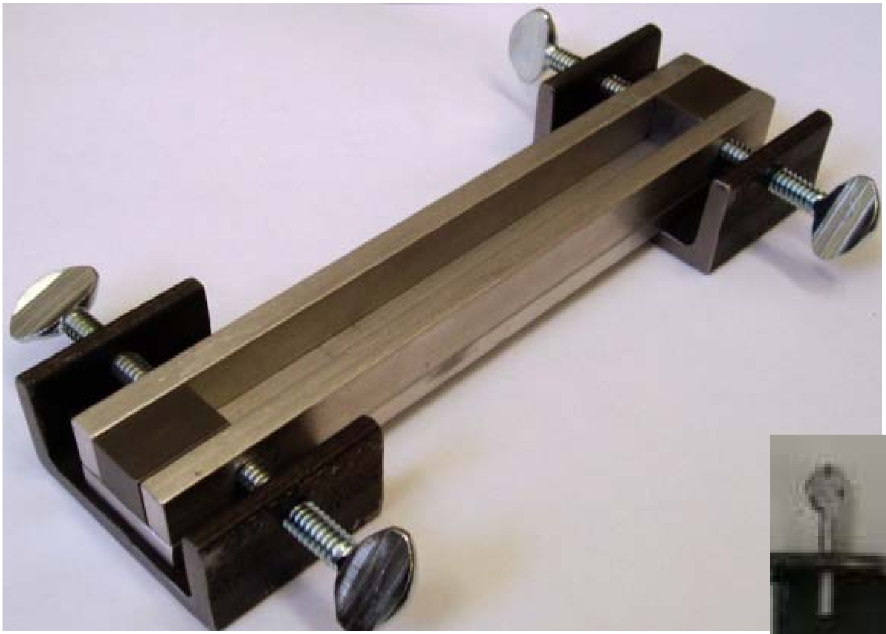
- Low Temp PG
  - Most critical
  - Start with BBR

Challenges / Solutions

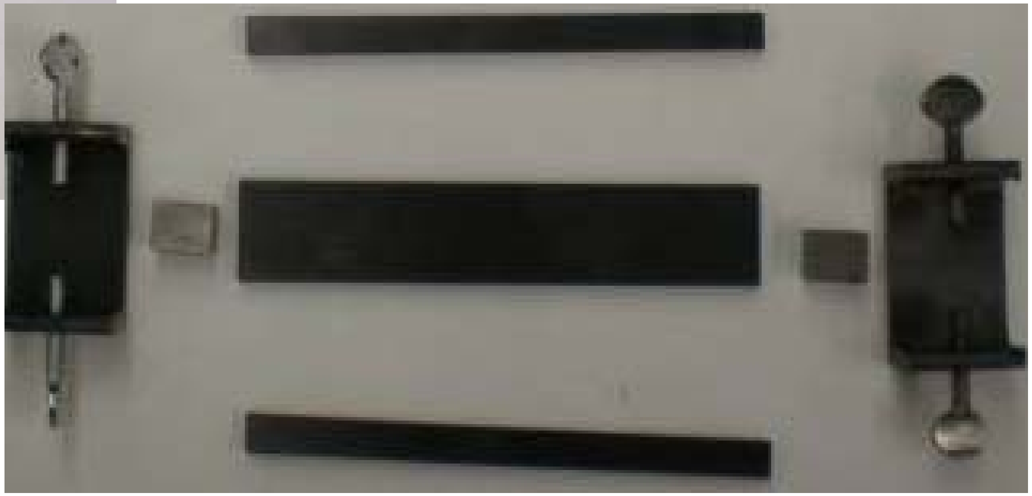
- BBR is not designed for testing mortars
  - Not enough load to cause enough deflection
  - Cannot exceed load–cell limits
  - Mold is too narrow for casting mortars

- Solutions
  - Change mold – **Done**
  - Increase temperature of testing and use models – **Done**

Mold Modification

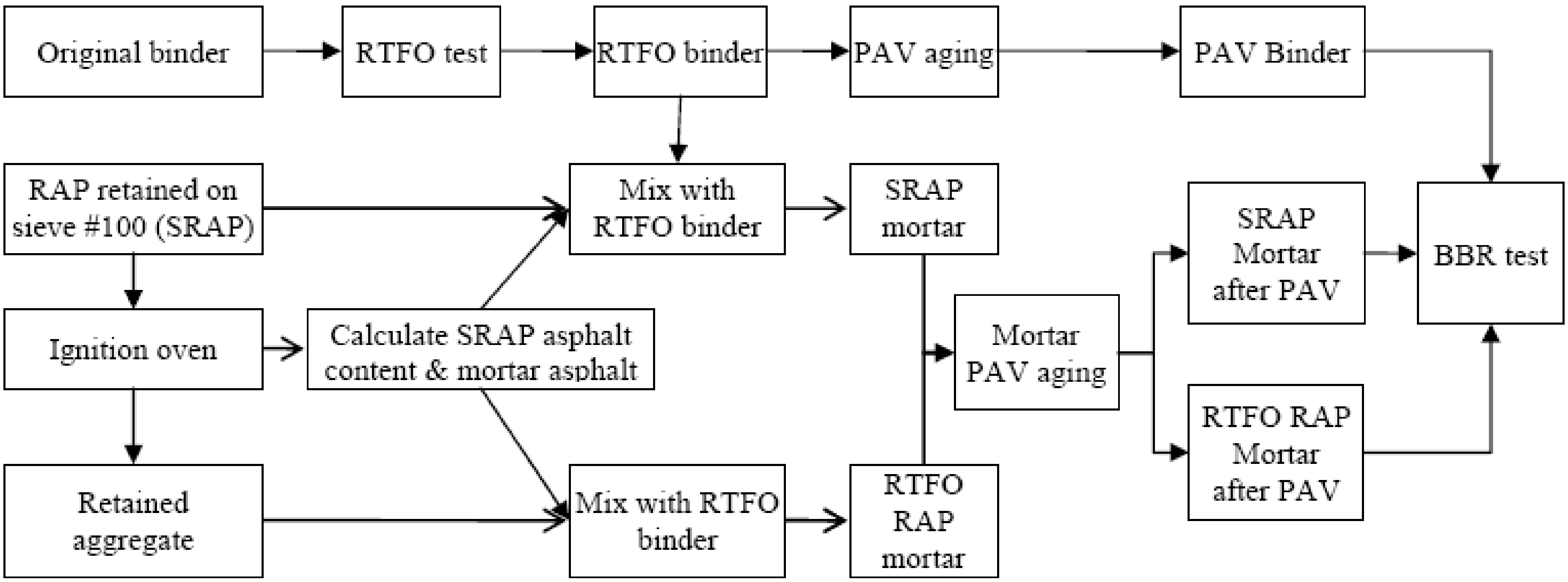


1. Wider Sample: 12.5 x 10.0 mm
2. Teflon coated
3. Stronger end holders



Testing Method

Flow Chart of Material Preparation and Testing



SRAP Sample

Mortar Samples

Research Methodology

- Blending the SRAP and the RAP aggregates with the fresh binder, after RTFO aging, will produce "RAP mortars."

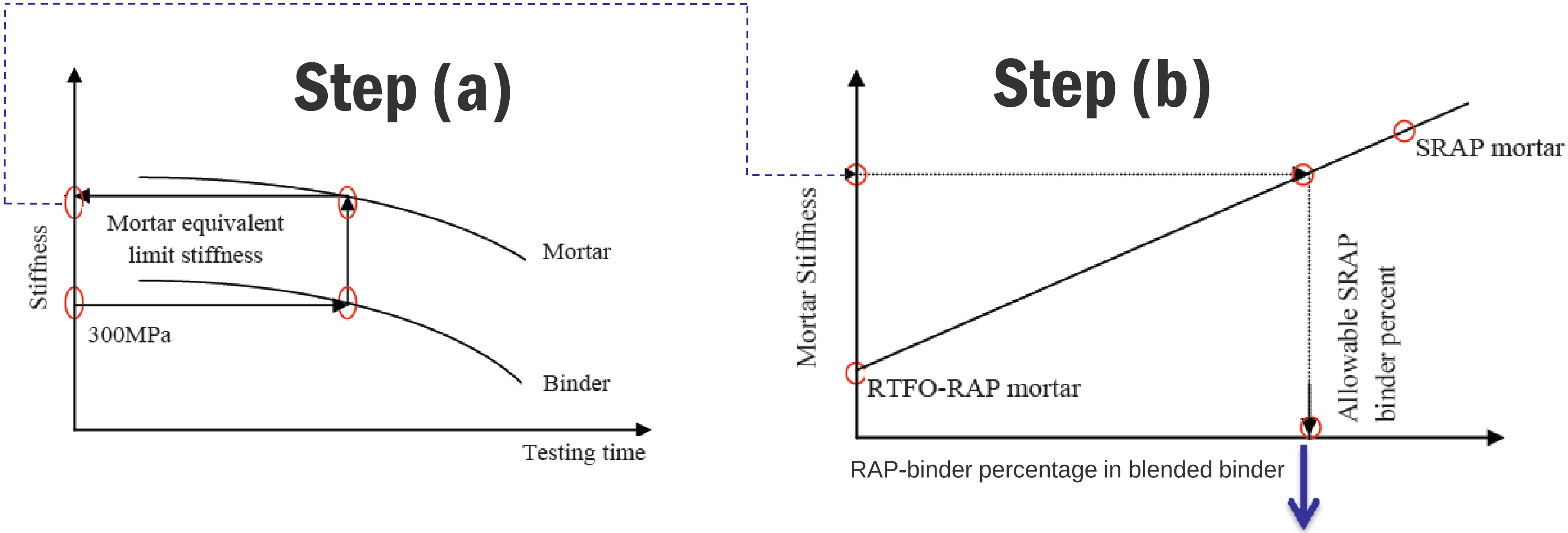
- The only difference between the SRAP mortar and RFTO-RAP mortar is the binder stiffness.

Allowable Limit of RAP Binder Based on The Target PG Grade

- At a specific low temperature:
  - determine the equivalent limiting values for the RTFO-RAP mortar stiffness and m-value based on the loading time at which the binder reaches the PG grading limits of S = 300 MPa and m=0.3.
  - identify the S and m-value properties of the RTFO-RAP and SRAP mortars at 60 sec loading time.

Allowable limit of RAP binder based on the target PG grade

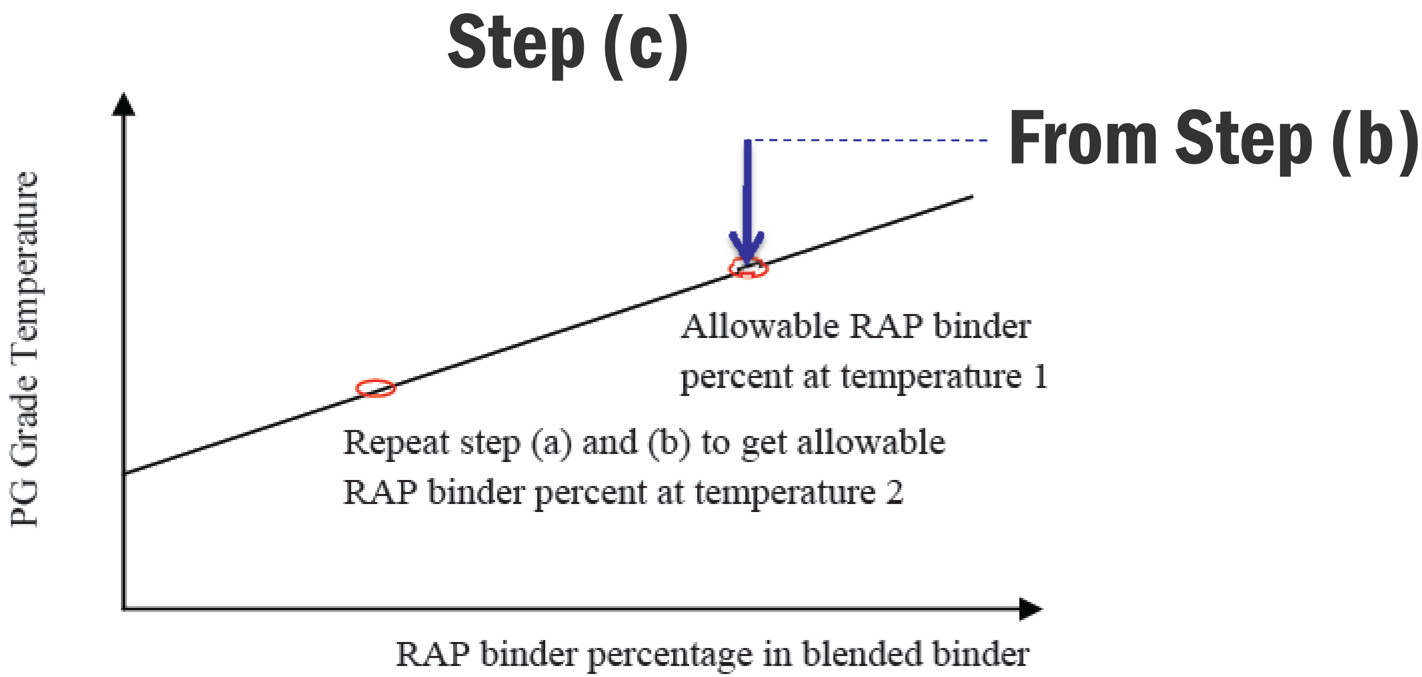
- **Allowable limit of RAP binder based on PG grade of blended binder:**



To Step (c)...

Allowable limit of RAP binder based on the target PG grade

- **Allowable limit of RAP binder based on PG grade of the blended binder:**



Allowable limit of RAP binder based on the target PG grade

- Typically:
  - Target PG is fixed
  - RAP source is fixed

- For a given virgin binder an allowable percent RAP is evaluated

- If the percent RAP with the virgin binder is not satisfactory then use a different virgin binder grade

Example

- City of Reno specs:
  - Final PG grade: PG64-22
  - Desired RAP content: 30%

- Define virgin binder grade to meet COR specs.

Example

- RAP source: I-80 open grade in Reno
- SRAP: Sieved RAP material passing No. 50 sieve & retained on No. 100 sieve.
- RAP binder content: 5.46% TWM

Example

- Virgin binder: PG64-22
- Produce RTFO-RAP mortar
- Produce SRAP mortar

Example

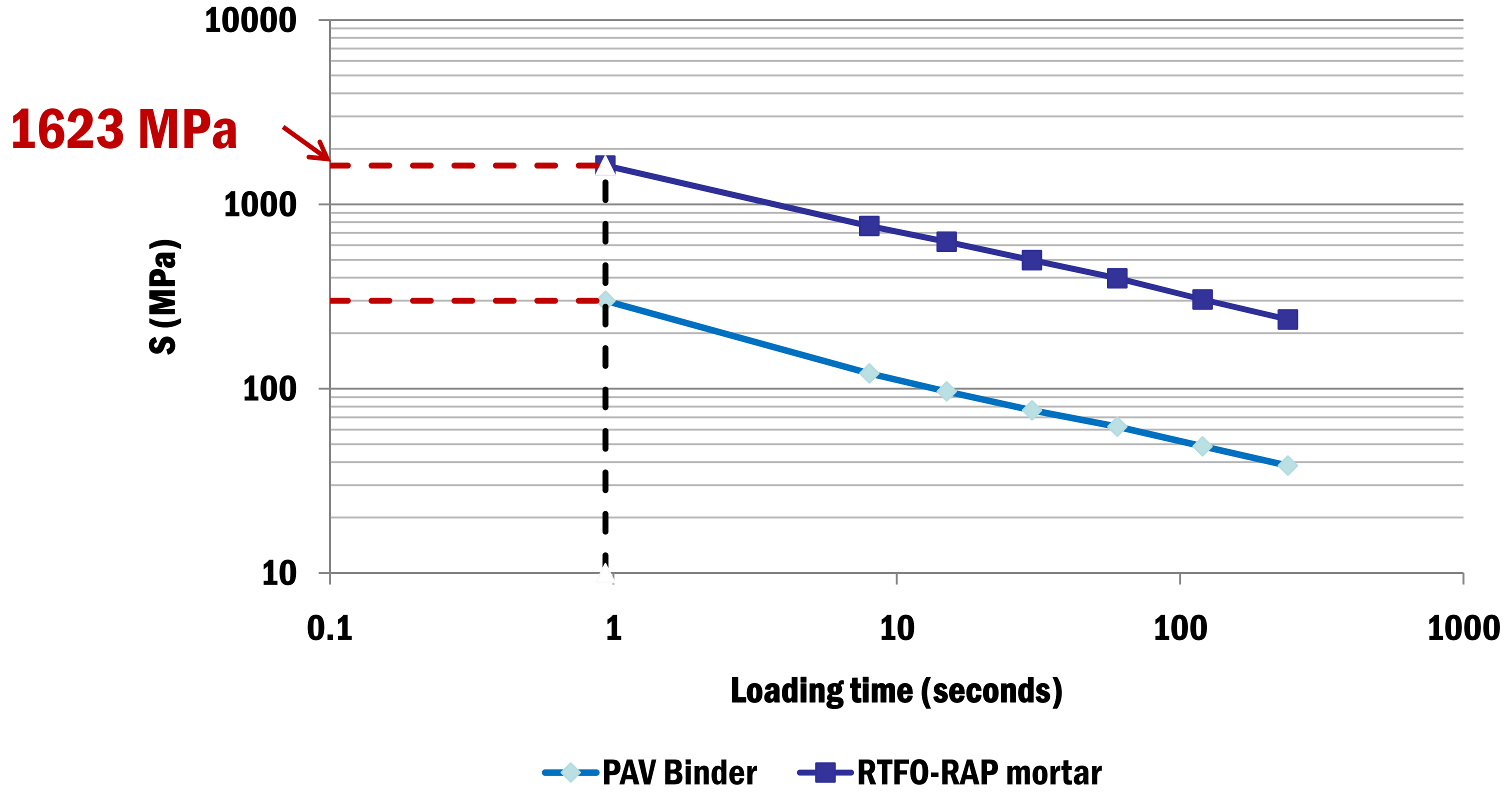
PAV Binder (RTFO + PAV)								Test Temperature (°C):	-6.00
Time (s)	Replicate 1		Replicate 2		Replicate 3		Average			
	S (MPa)	m-value	S (MPa)	m-value	S (MPa)	m-value	S (MPa)	COV (%)	m-value	COV (%)
8	111.0	0.283	121.0	0.286	131.0	0.288	121.0	8.3	0.286	0.9
15	92.1	0.302	96.6	0.304	101.2	0.303	96.6	4.7	0.303	0.3
30	74.1	0.324	79.2	0.328	75.6	0.331	76.3	3.4	0.328	1.1
60	58.8	0.345	65.9	0.351	61.9	0.361	62.2	5.7	0.352	2.3
120	45.9	0.367	50.1	0.371	49.9	0.375	48.6	4.9	0.371	1.1
240	35.3	0.389	40.1	0.396	39.3	0.399	38.2	6.7	0.395	1.3

Example

RTFO-RAP Mortar							Test Temperature (°C):		-6.00
							Total PAV binder (%):		20.00
Time (s)	Replicate 1		Replicate 2		Replicate 3		Average			
	S (MPa)	m-value	S (MPa)	m-value	S (MPa)	m-value	S (MPa)	COV (%)	m-value	COV (%)
8	753.4	0.278	802.4	0.264	733.6	0.270	763.1	4.6	0.271	2.6
15	617.8	0.322	661.9	0.300	601.5	0.338	627.1	5.0	0.320	6.0
30	488.1	0.336	505.1	0.340	500.5	0.344	497.9	1.8	0.340	1.2
60	379.2	0.344	397.2	0.350	415.0	0.360	397.1	4.5	0.351	2.3
120	290.1	0.352	307.1	0.372	317.1	0.376	304.8	4.5	0.367	3.5
240	217.8	0.360	237.8	0.382	256.6	0.386	237.4	8.2	0.376	3.7

Example

Establish Limits for RTFO-RAP Mortar



Example
Establish Limits for RTFO-RAP Mortar

- RTFO-RAP Mortar Limits at -6°C:
  - S-Limit = 1623 MPa
  - m-Limit = 0.303

Example

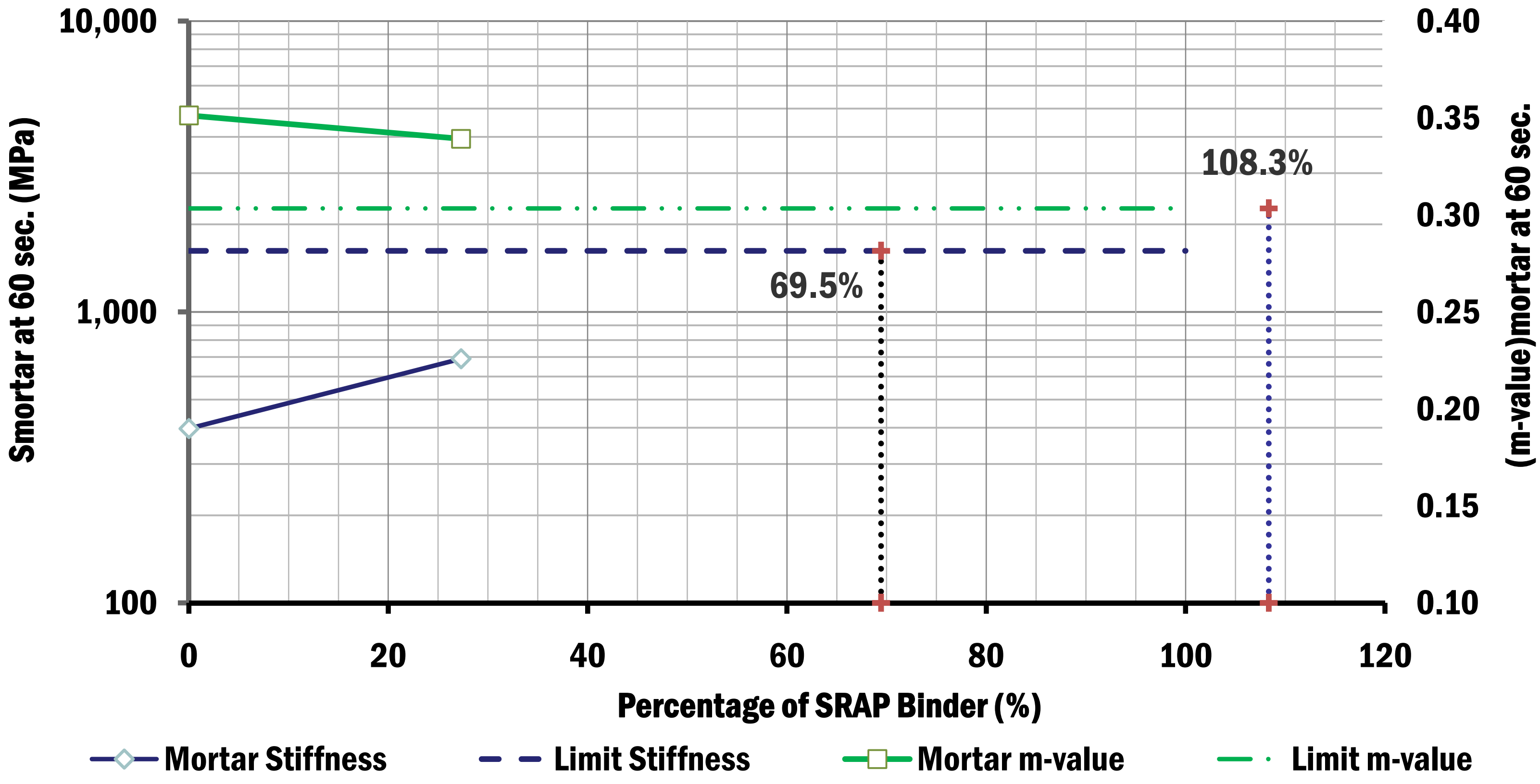
SRAP Mortar									Test Temperature (°C):	-6.00
SRAP binder content (%):				5.46	PAV binder (%):		14.54		Total PAV binder (%):	20
Time (s)	Replicate 1		Replicate 2		Replicate 3		Average			
	S (MPa)	m-value	S (MPa)	m-value	S (MPa)	m-value	S (MPa)	COV (%)	m-value	COV (%)
8	1009.8	0.271	1029.8	0.258	940.8	0.255	993.5	4.7	0.261	3.4
15	912.8	0.315	922.3	0.294	842.6	0.291	892.6	4.9	0.300	4.3
30	807.8	0.329	813.4	0.334	743.1	0.330	788.1	5.0	0.331	0.7
60	703.9	0.336	714.8	0.343	653.0	0.339	690.6	4.8	0.339	1.0
120	605.9	0.345	609.1	0.363	556.5	0.360	590.5	5.0	0.356	2.7
240	514.8	0.352	520.3	0.373	475.4	0.369	503.5	4.9	0.364	3.0

Example

- %SRAP binder = 5.46 / 20 = 27.3%

- RTFO-RAP Mortar (i.e., 0% SRAP Binder)
  - S_{60} = 397.1 MPa
  - m_{60} = 0.351
- SRAP Mortar (i.e., 27.3% SRAP Binder)
  - S_{60} = 690.6 MPa
  - m_{60} = 0.339

Example
SRAP Binder Limit Percent



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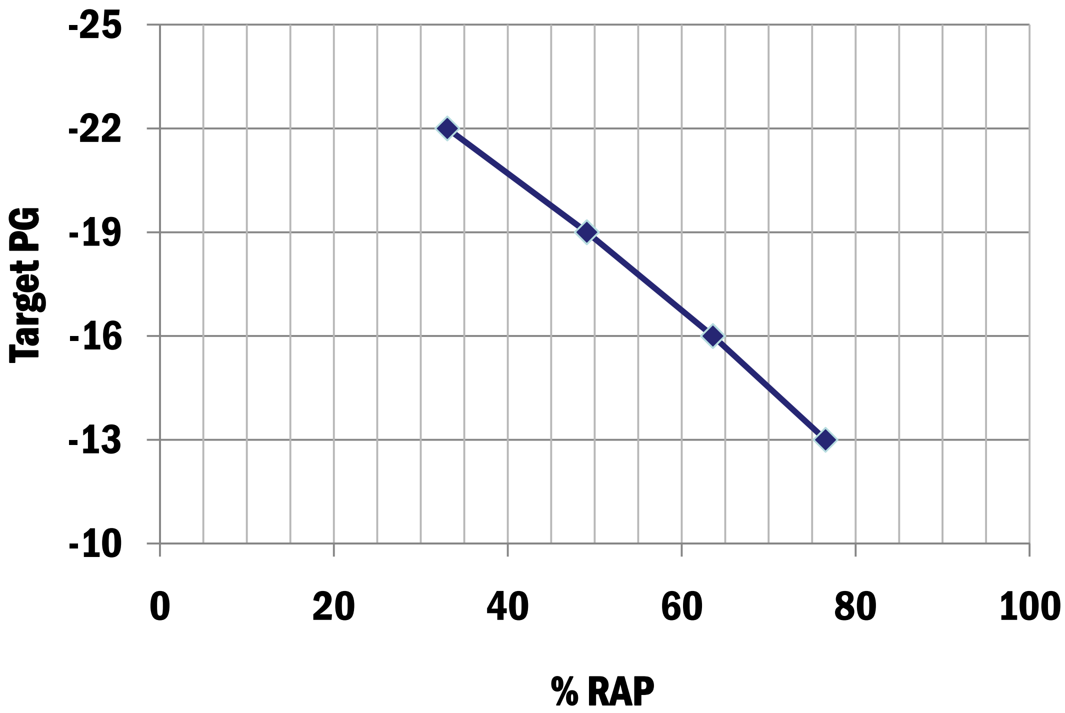
Example
Allowable %RAP

Fresh Asphalt Binder: PG64-22				% RAP Allowed in HMA
Target binder low temp PG grade (°C)	SRAP binder % Limit			
	Stiffness	m-value	Maximum	
-13.0	83.6	143.5	**83.6**	**76.5**
-16.0	69.5	108.3	**69.5**	**63.6**
-19.0	53.6	73.2	**53.6**	**49.1**
-22.0	36.1	38.1	**36.1**	**33.1**
-25.0	16.9	2.9	**2.9**	**2.7**

Example
Allowable %RAP



Example

Recommendations

- City of Reno specs of 30% RAP were met with the virgin binder of PG64-22.
- Methodology was verified with the extraction/recovery and blending chart technique.

Develop a System to Evaluate the Properties of RAP

- Evaluate impact of current extraction techniques on properties of extracted RAP aggregates.
- Extract aggregates from Lab-produced RAP mixes using:
  - Centrifuge (Trichloroethylene)
  - Reflux (Trichloroethylene)
  - Ignition oven

Develop a System to Evaluate the Properties of RAP

- Aggregate Sources:
  - Nevada: Rhyolite (UNR)
  - California: Granodiorite (UNR)
  - Alabama: Hard Limestone (NCAT)
  - Florida: Soft Limestone (NCAT)

Develop a System to Evaluate the Properties of RAP

- SP mix design: intermediate gradation.
- Subject ***loose*** samples to STOA (4 hrs at 275°F) followed by LTOA (5 days at 185°F).
- Extract aggregates from aged loose specimens.
- Measure extracted aggregates' physical properties.

Develop a System to Evaluate the Properties of RAP

- Average Extracted Binder Contents
  - Ignition oven is generally the closest to the design binder content, followed by the reflux, and lastly the centrifuge.

Develop a System to Evaluate the Properties of RAP

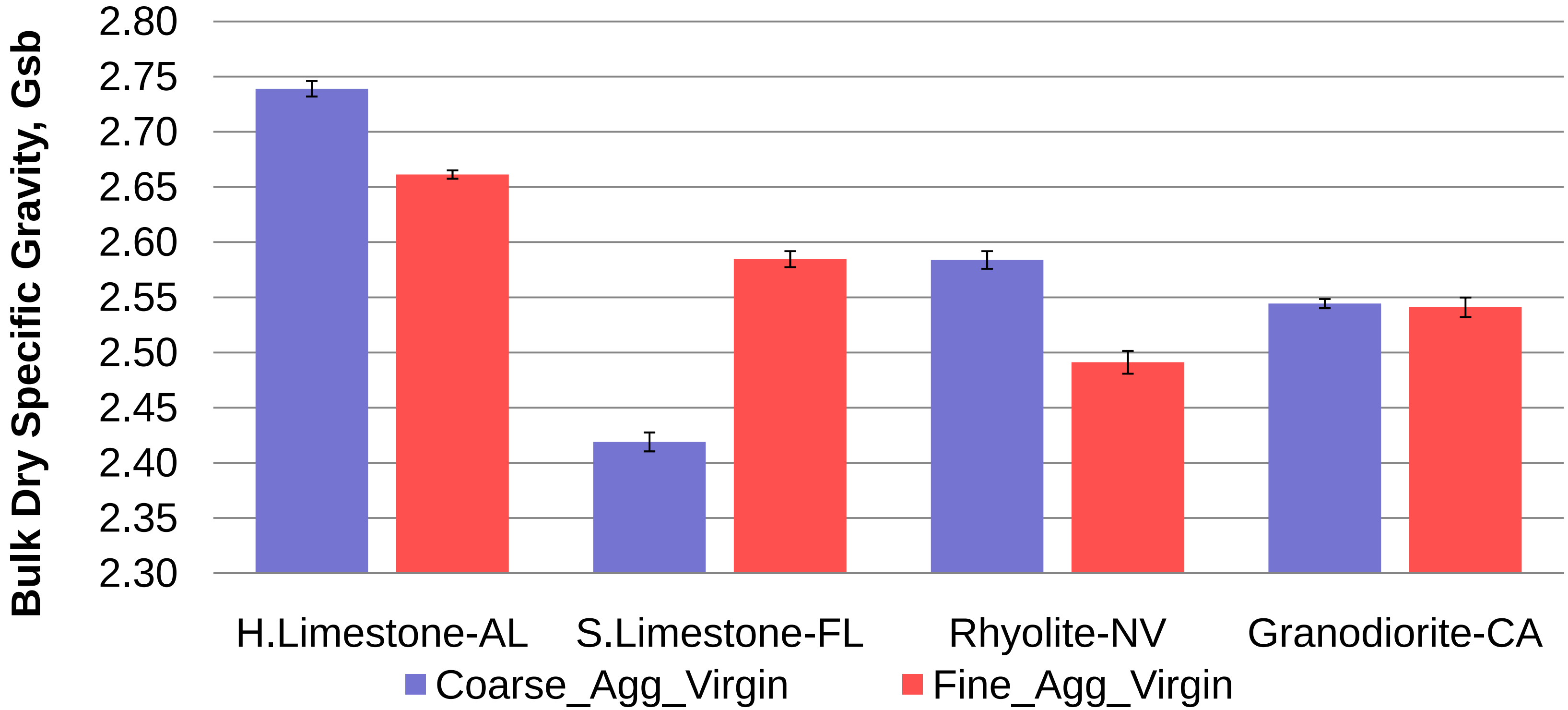
- Measured properties:
  - Gradation: AASHTO T27, T30
  - Specific gravities: AASHTO T84, T85
  - Absorption: AASHTO T84, T85
  - FAA: AASHTO T304
  - CAA: ASTM D5821
  - SE: AASHTO T176
  - LAA: AASHTO T96
  - Soundness: AASHTO T104
  - Durability Index: AASHTO T210
  - Cleanness Value: CT 227
  - AIMS

Develop a System to Evaluate the Properties of RAP

- This presentation focuses on:
  - Bulk Specific Gravity and Absorption of coarse aggregates
  - Bulk Specific Gravity and Absorption of fine aggregates

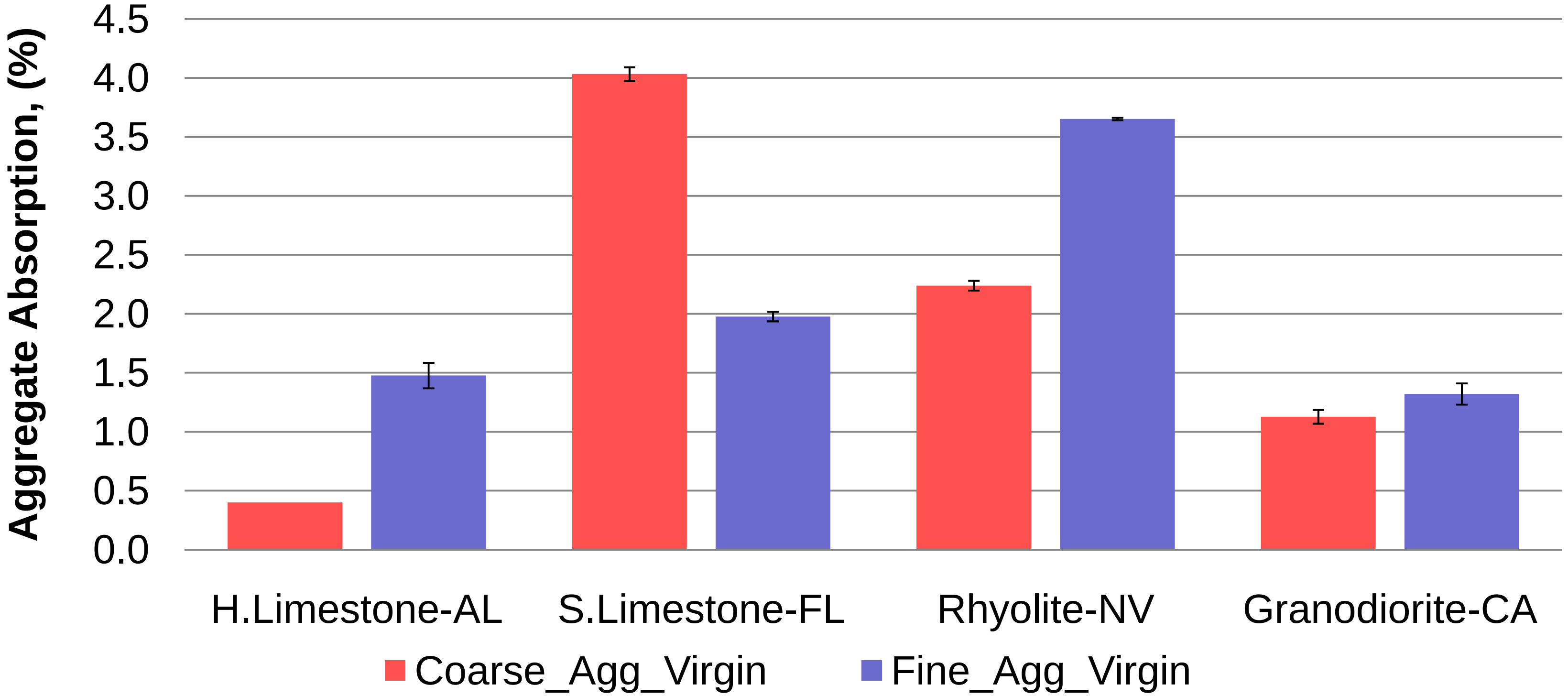
Develop a System to Evaluate the Properties of RAP

- **Overall BSG for all Virgin Aggregate Sources**



Develop a System to Evaluate the Properties of RAP

- **Overall Absorption for all Virgin Aggregate Sources**



Develop a System to Evaluate the Properties of RAP

- Mechanical Breakdown Experiment
  - A set of samples was batched and mixed with water following the same procedure as mixing with binder.
  - The mixtures were then dried and tested following the referenced AASHTO procedures.
  - No significant differences were found among the test results of the virgin and the mechanical breakdown aggregates.

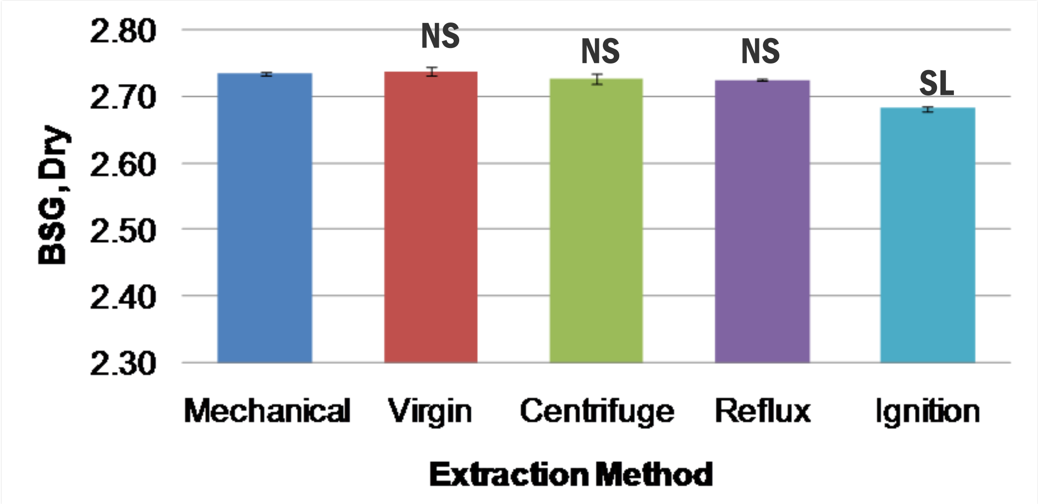
Test Results And Analysis

- Notations for the statistical tables:
  - NS – Values are not significantly different from the water mixing set
  - SL – Average reported values are significantly lower than the water mixing set
  - SH – Average reported values are significantly higher than the water mixing set

Coarse Aggregate – Bulk Specific Gravities (Gsb)

Hard Limestone
Alabama

		Within Treatment				Compared to Mechanical	
Extraction Method	Avg	STD	Maximum Difference	< 1s (0.009)	< d3s (0.030)	<d2sAve (0.035)	Maximum Difference
Mechanical	2.735	0.003	0.006	Yes	Yes	-	-
Virgin	2.739	0.007	0.013	Yes	Yes	Yes	0.004
Centrifuge	2.728	0.008	0.015	Yes	Yes	Yes	0.007
Reflux	2.725	0.002	0.003	Yes	Yes	Yes	0.010
Ignition	2.683	0.004	0.007	Yes	Yes	No	0.052



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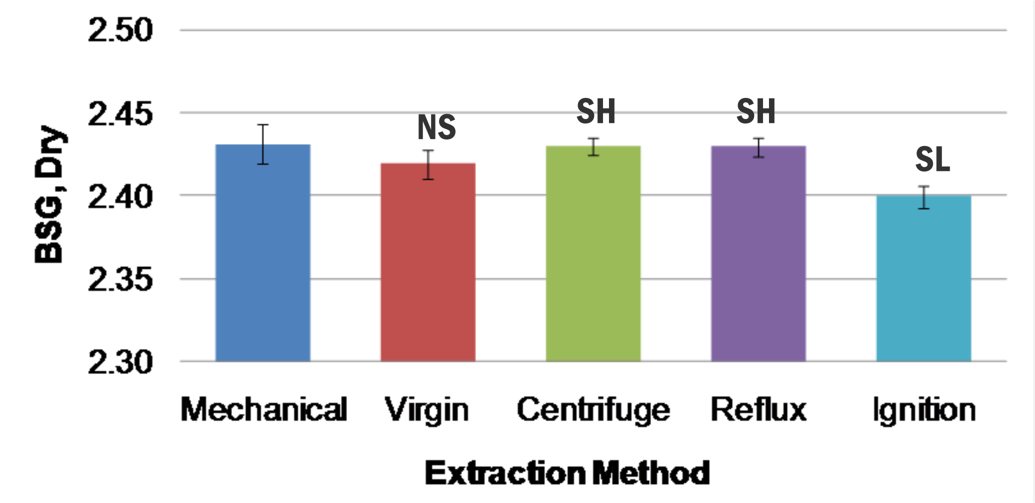
Coarse Aggregate – Bulk Specific Gravities (Gsb)

Soft Limestone Florida

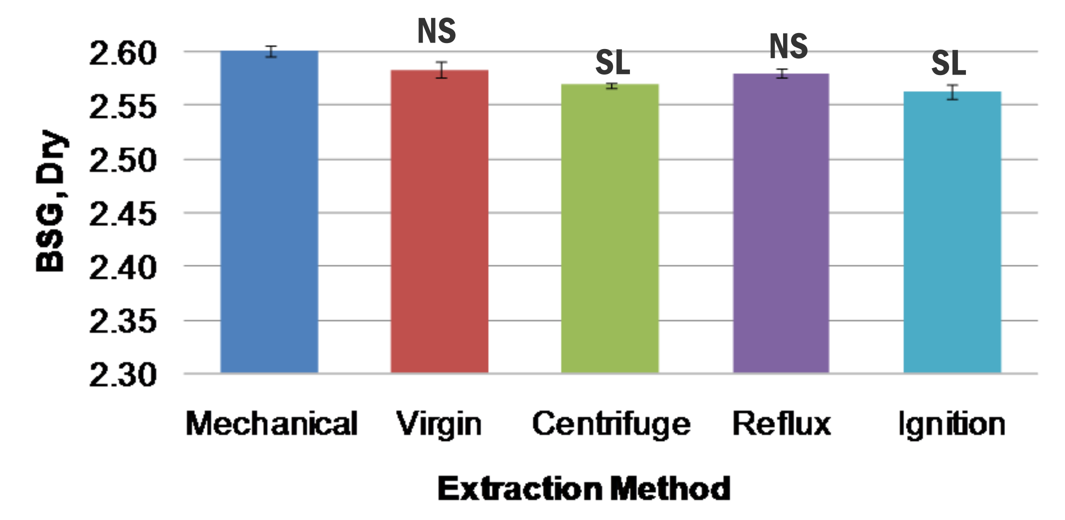
		Within Treatment				Compared to Mechanical	
Extraction Method	Ave	STD	Maximum Difference	< 1s (0.009)	< d3s (0.030)	<d2sAve (0.035)	Maximum Difference
Mechanical	2.431	0.012	0.017	No	Yes	-	-
Virgin	2.419	0.009	0.017	Yes	Yes	Yes	0.012
Centrifuge	2.430	0.005	0.009	Yes	Yes	Yes	0.001
Reflux	2.429	0.006	0.010	Yes	Yes	Yes	0.002
Ignition	2.400	0.007	0.013	Yes	Yes	Yes	0.031



Coarse Aggregate – Bulk Specific Gravities (Gsb)

Rhyolite Nevada

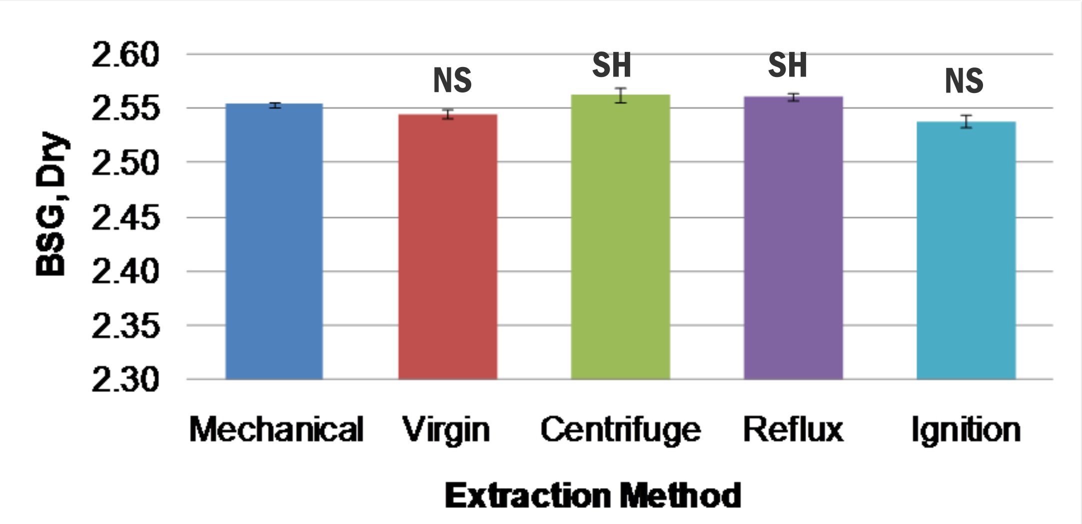
		Within Treatment				Compared to Mechanical	
Extraction Method	Ave	STD	Maximum Difference	< 1s (0.009)	< d3s (0.030)	<d2sAve (0.035)	Maximum Difference
Mechanical	2.601	0.005	0.009	Yes	Yes	-	-
Virgin	2.584	0.008	0.017	Yes	Yes	Yes	0.017
Centrifuge	2.569	0.003	0.005	Yes	Yes	Yes	0.032
Reflux	2.581	0.004	0.008	Yes	Yes	Yes	0.020
Ignition	2.564	0.007	0.014	Yes	Yes	No	0.037



Coarse Aggregate – Bulk Specific Gravities (Gsb)

Granodiorite
California

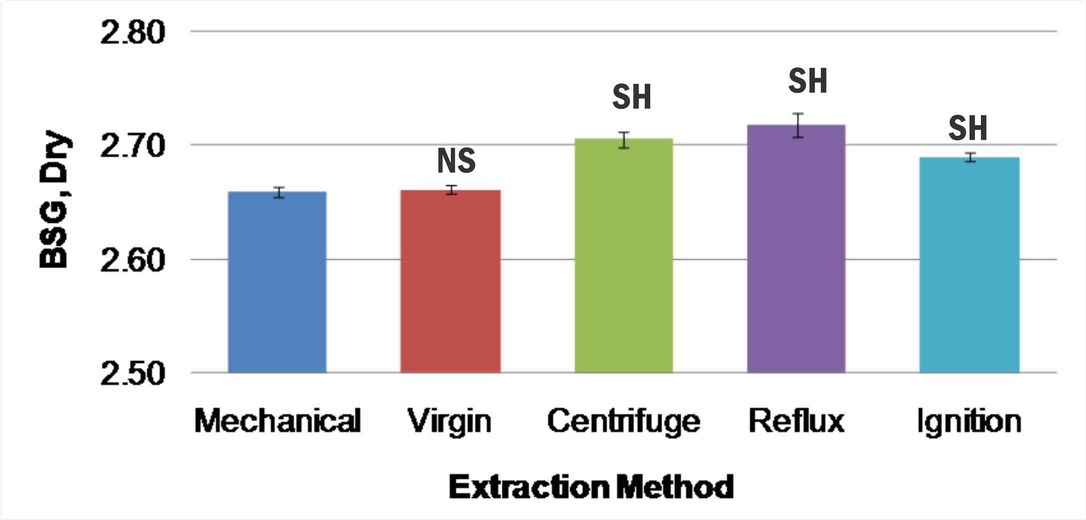
		Within Treatment				Compared to Mechanical	
Extraction Method	Ave	STD	Maximum Difference	< 1s (0.009)	< d3s (0.030)	<d2sAve (0.035)	Maximum Difference
Mechanical	2.553	0.003	0.005	Yes	Yes	-	-
Virgin	2.544	0.004	0.008	Yes	Yes	Yes	0.009
Centrifuge	2.562	0.007	0.014	Yes	Yes	Yes	0.009
Reflux	2.561	0.003	0.006	Yes	Yes	Yes	0.008
Ignition	2.538	0.006	0.012	Yes	Yes	Yes	0.015



Fine Aggregate – Bulk Specific Gravities (Gsb)

Hard Limestone Alabama

		Within Treatment				Compared to Mechanical	
Extraction Method	Ave	STD	Maximum Difference	< 1s (0.009)	< d3s (0.030)	<d2sAve (0.035)	Maximum Difference
Mechanical	2.659	0.005	0.007	Yes	Yes	-	-
Virgin	2.661	0.004	0.003	Yes	Yes	Yes	0.002
Centrifuge	2.706	0.007	0.004	Yes	Yes	No	0.047
Reflux	2.718	0.010	0.012	Yes	Yes	No	0.059
Ignition	2.690	0.004	0.002	Yes	Yes	Yes	0.031



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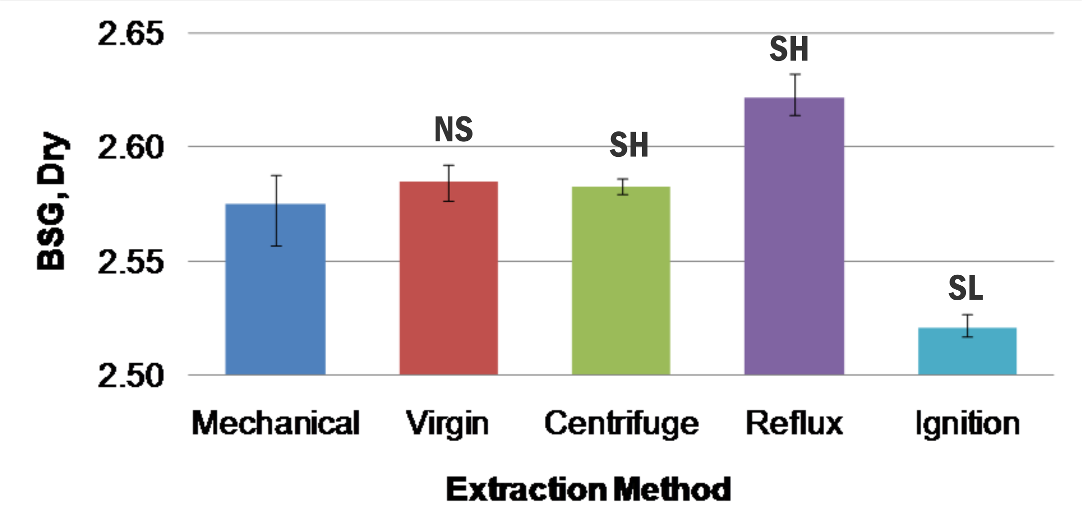
Fine Aggregate – Bulk Specific Gravities (Gsb)

Soft Limestone
Florida

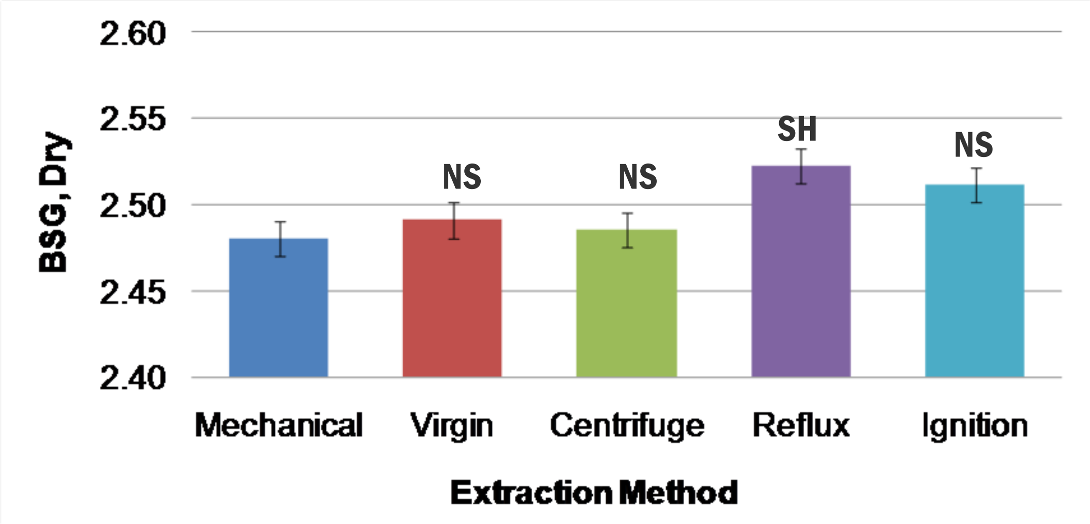
		Within Treatment				Compared to Mechanical	
Extraction Method	Ave	STD	Maximum Difference	< 1s (0.009)	< d3s (0.030)	<d2sAve (0.035)	Maximum Difference
Mechanical	2.575	0.013	0.018	No	Yes	-	-
Virgin	2.585	0.007	0.008	Yes	Yes	Yes	0.010
Centrifuge	2.583	0.004	0.003	Yes	Yes	Yes	0.008
Reflux	2.622	0.010	0.007	Yes	Yes	No	0.047
Ignition	2.521	0.006	0.004	Yes	Yes	No	0.054



Fine Aggregate – Bulk Specific Gravities (Gsb)

Rhyolite Nevada

		Within Treatment				Compared to Mechanical	
Extraction Method	Ave	STD	Maximum Difference	< 1s (0.009)	< d3s (0.030)	<d2sAve (0.035)	Maximum Difference
Mechanical	2.481	0.010	0.019	Yes	Yes	-	-
Virgin	2.491	0.010	0.019	Yes	Yes	Yes	0.010
Centrifuge	2.486	0.010	0.032	Yes	Yes	Yes	0.005
Reflux	2.522	0.010	0.025	Yes	Yes	Yes	0.041
Ignition	2.512	0.010	0.032	Yes	Yes	Yes	0.031



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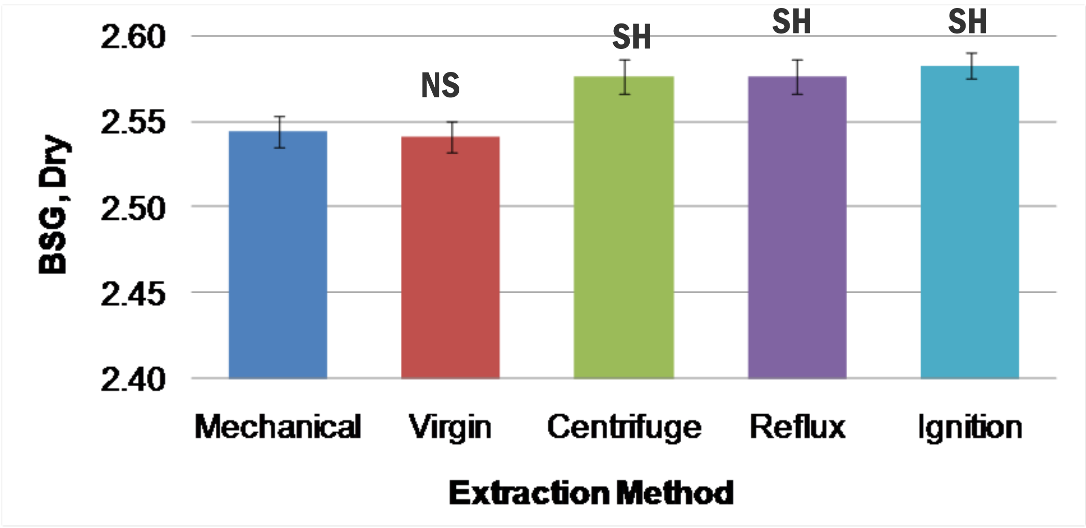
Fine Aggregate – Bulk Specific Gravities (Gsb)

Granodiorite
California

		Within Treatment				Compared to Mechanical	
Extraction Method	Ave	STD	Maximum Difference	< 1s (0.009)	< d3s (0.030)	<d2sAve (0.035)	Maximum Difference
Mechanical	2.544	0.009	0.027	Yes	Yes	-	-
Virgin	2.541	0.009	0.017	Yes	Yes	Yes	0.003
Centrifuge	2.577	0.010	0.021	Yes	Yes	Yes	0.033
Reflux	2.576	0.010	0.021	Yes	Yes	Yes	0.032
Ignition	2.583	0.008	0.015	Yes	Yes	Yes	0.039



Statistical Analyses

- **Summary of Statistically Non-Significant BSG Results**
  - Number of times statistically NS results were obtained.

Extraction Method	Aggregate Source				Total NS	% NS
	Hard Limestone	Soft Limestone	Rhyolite	Granodiorite		
Virgin	2	2	2	2	8	100
Centrifuge	1	0	1	0	2	25
Reflux	1	0	1	0	2	25
Ignition	0	0	1	1	2	25
Total NS	2	0	3	1		
% NS	33	0	50	17		

Summary of Statistically Non-Significant BSG Results

– The virgin & mechanical breakdown specific gravity results are statistically similar – 100% occurrence.

– The other three extraction methods lead to the same probability of statistically similar results – 25%.

Summary of Statistically Non-Significant BSG Results

– Results were highly dependent upon aggregate mineralogy.

– None of the soft limestone results were statistically similar to the virgin or mechanical breakdown.

Statistical Outcome by Extraction Method

– All extraction methods have the same probability (25%) of providing significantly similar results to those desired (mechanical breakdown).

Extraction Method	Specific Gravity Statistical Percentages		
	Not Significant	Significantly Lower	Significantly Higher
Centrifuge	25	13	63
Reflux	25	13	63
Ignition	25	50	25

Summary and Conclusions

– There is not one extraction method that consistently resulted in NS difference between the mean recovered & virgin aggregate or the mechanical breakdown properties.

– Test results appear to be highly dependent upon aggregate mineralogy.

– The ignition oven method is more conservative when it comes to VMA calculations (i.e., lower).

Summary and Conclusions

- If binder information is necessary, the centrifuge would be the next best extraction method after the ignition oven.
- Due to the noted dependency on aggregate mineralogy it may be prudent to conduct a similar small scale study within a given region.

Thank you!

Questions?