DEVELOP GUIDELINES AND IMPLEMENTATION RECOMMENDATIONS

by

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0-6855 Validation of RAP and/or RAS in Hydration Cement Concrete

Develop Guidelines and Implementation Recommendations

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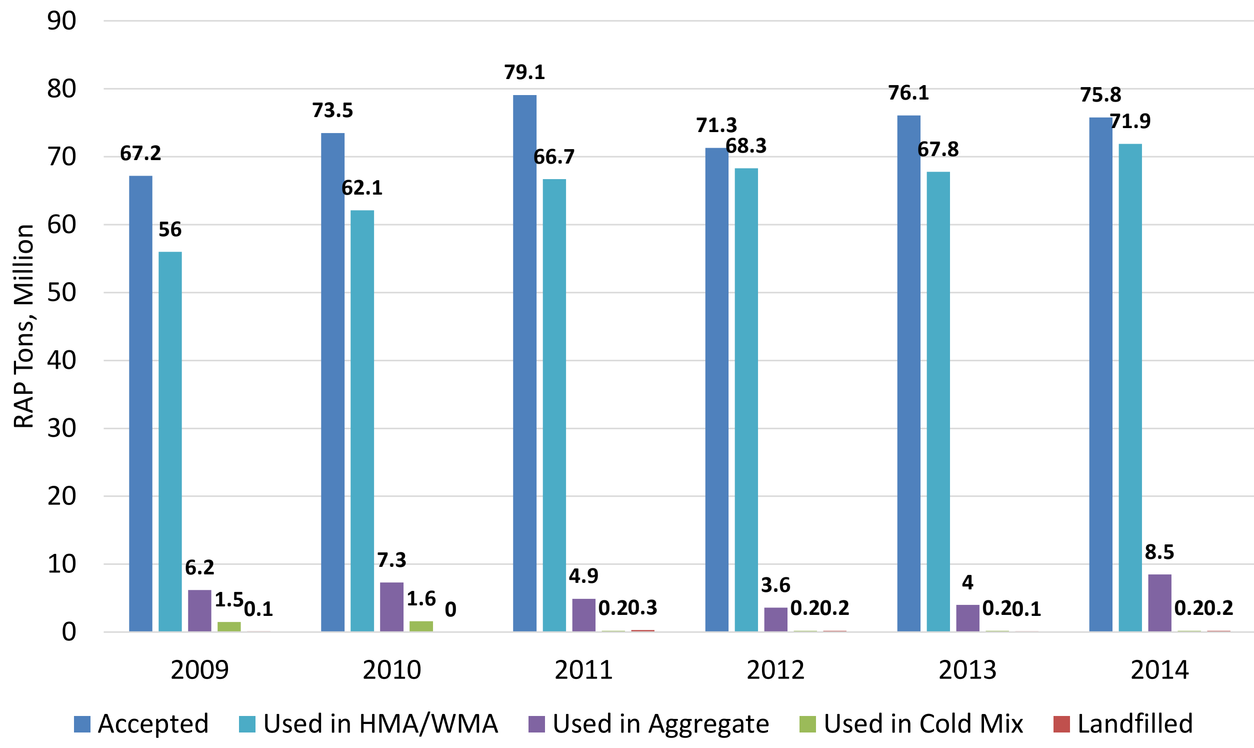
Introduction

- What is RAP?
  - Old materials removed from existing HMA pavement
  - Removal: cold milling & ripping and crushing
- RAP Properties
  - Coarse RAP is finer than conventional CA and Fine RAP is coarser than conventional FA
  - Aged asphalt has higher viscosity
  - Fine RAP has higher asphalt content
  - Properties vary depend on service life and degree of aging

Cold milling

Ripping and crushing

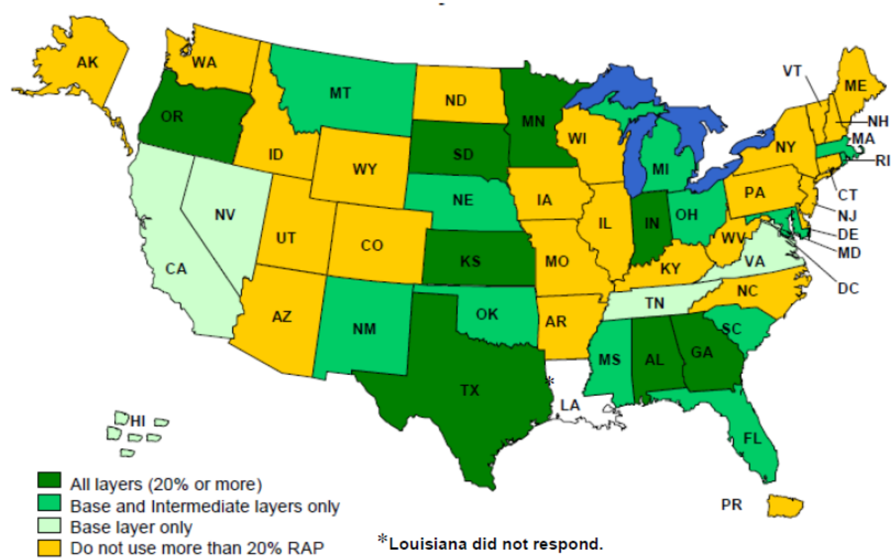
Re-use of RAP



Hanse and Copeland: Annual Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2009–2012, 2013, 2014

Restricted Use of RAP in HMA

- The amount in HMA is limited to 10–30%
  - Aged binder causes reduced cracking resistance
- Texas: unfractionated RAP is limited to 10, 20, and 30 percent by surface, intermediate, and base layers
- Texas is conservative about using RAP in HMA, only had 15% RAP in HMA in average (ranked the 10th low among all the U.S states)
- More than 91% of contractors in US had excess RAP



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Issues: Excess RAP Stockpiles

- Expenses related to stockpiling
  - Fuel costs for truck and loaders
  - Original and maintenance equipment investment
  - Safety violation fines
  - Space costs
- Threaten environment and public safety
  - Dust production
  - Safety accidents

- Use RAP in PCC as aggregate replacement
  - Help reduce sizes of RAP stockpiles
  - Protect environment and public by consuming less virgin aggregates

Effect of RAP on PCC Mechanical Properties: Lab Investigation

Concrete Property	Effect on Property as the Amount of RAP in Concrete Increases	References
Air content	Increase	Delwar et al. 1997; Hossiney et al. 2008
	No Effect	Dumitru et al. 1999; Huang et al. 2005, 2006; Hossiney et al. 2010; Bermel 2011
Unit weight	Decrease	Patankar and Williams 1970; Delwar et al. 1997; Hossiney et al. 2008, 2010; Al-Oraimi et al. 2009; Tia et al. 2012
Slump	Increase	Hossiney et al. 2010
	Decrease	Delwar et al. 1997; Huang et al. 2006; Hossiney et al. 2008; Al-Oraimi et al. 2009; Okafor 2010; Tia et al. 2012
	No effect	Bermel 2011
	No clear trend	Huang et al. 2005
Temperature	Increase	Tia et al. 2012
Compressive strength	Decrease	Patankar and Williams 1970; Kolias 1996a; Delwar et al. 1997; Li et al. 1998; Sommer and Bohrn 1998; Dumitru et al. 1999; Hassan et al 2000; Mathias et al. 2004; Huang et al. 2005, 2006; Katsakou and Kolias 2007; Hossiney et al. 2008, 2010; Al-Oraimi et al. 2009; Okafor 2010; Bermel 2011; Bilodeau et al. 2011; Tia et al. 2012; Brand 2012; Berry et al. 2013
Modulus of elasticity	Decrease	Patankar and Williams 1970; Kolias 1996a,1996b; Delwar et al. 1997; Sommer and Bohrn 1998; Dumitru et al. 1999; Mathias et al. 2004; Huang et al. 2006; Katsakou and Kolias 2007; Hossiney et al. 2008, 2010; Al-Oraimi et al. 2009; Bilodeau et al. 2011; Brand 2012; Berry et al. 2013
Poisson's ratio	Increase	Tia et al. 2012
Splitting tensile strength	Decrease	Patankar and Williams 1970; Kolias 1996a; Sommer and Bohrn 1998; Dumitru et al. 1999; Mathias et al. 2004; Huang et al. 2005, 2006; Hossiney et al. 2008, 2010; Al-Oraimi et al. 2009; Okafor 2010; Bermel 2011; Tia et al. 2012; Brand 2012

Effect of RAP on PCC Mechanical Properties: Lab Investigation (cont'd)

Concrete Property	Effect on Property as the Amount of RAP in Concrete Increases	References
Flexural strength	Decrease	Patankar and Williams 1970; Sommer 1994; Kolias 1996a; Li et al. 1998; Sommer and Bohrn 1998; Dumitru et al. 1999; Hassan et al 2000; Katsakou and Kolias 2007; Hossiney et al. 2008, 2010; Al-Oraimi et al. 2009; Okafor 2010; Bermel 2011; Tia et al. 2012; Brand 2012; Berry et al. 2013
Direct tensile strength	Decrease	Patankar and Williams 1970; Katsakou and Kolias 2007
Complex stiffness modulus	Decrease	Kolias 1996b; Bilodeau et al. 2011
Resilient modulus	Decrease	Li et al. 1998
Creep strains	Increase	Kolias 1996a
Coefficient of thermal expansion	Increase	Tia et al. 2012
	No clear trend	Hossieny et al. 2008, 2010
Toughness	Increase	Huang et al. 2005, 2006; Tia et al. 2012
Fatigue properties	Reduce	Mathias et al. 2004
	Improve	Li et al. 1998
Porosity	Increase	Hassan et al. 2000
Oxygen permeability	Increase	Hassan et al. 2000
Surface absorption	No effect	Al-Oraimi et al. 2009
Frost resistance	Decrease	Sommer 1994; Sommer and Bohrn 1998

Summarized in Brand, A. (2012). "Fractionated reclaimed asphalt pavement as a coarse aggregate replacement in a ternary blended concrete pavement."

Recent U.S. State Funded RAP-PCC Projects

State	Year	Lab Investigations	Field Investigations
Florida DOT	2010-2012	**<u>Experimental</u>** – (1) Four RAPs , mainly limestone with 0%, 20%, 40%, 70% & 100% replacement, use of both coarse and fine RAP, (2) Cementitious content: 490-500 lbs/cy, (3) w/cm=0.5 **<u>Test Results</u>** • Reduction in fc, MOE, ST, MOR. • Increase in toughness • Stress/strength ratio could be lower	None
Illinois State Toll Highway Authority	2012	**<u>Experimental</u>** – (1) Coarse dolomite FRAP with 0%, 20%, 35% and 50% replacement, (2) Ternary blend concrete: cement, slag and fly ash, (3) Cementitous content: 630 lbs/cy and (4) w/cm=0.37 **<u>Test Results</u>** Up to 50% FRAP replacement can satisfy: • Strength requirement (3500 psi fc, and 650 psi MOR at 14 days) • Durability requirements	**<u>Two-lift:</u>** • Ternary blend RAP PCC with 21% FRAP as lower lift (9-11 inch) • A 3 inch conventional PCC top lift • Good performance **<u>Conventional concrete pavement with HMA overlay:</u>** • 9 inch thick concrete with 28% coarse FRAP - 655 lbs/cy cementitious content with 21% fly ash • 2 inch HMA overlay • Good performance
Montana DOT	2013-2015	**<u>Experimental</u>** – (1) Minimally processed RAP (no crushing or washing), (2) HR:50% fine RAP+100% coarse RAP; HS: 25% fine RAP+50% coarse RAP, (3) Paste content: 0.346, and (4) w/cm=0.386 **<u>Test Results</u>** - Meet MDT concrete pavement specifications and exhibit adequate durability	• Two RAP PCC slabs (one HR and one HS) at the WSU/WTI research facility • No issues related to production and construction • No cracking or spalling during 2-year period • No excessive shrinkage or curling

Research Objectives

- Research needs to be conducted to address the following areas / issues in order to promote utilization of RAP to make PCC for TxDOT:
  - Validate the earlier findings on change of mechanical properties
  - Proper utilization of optimized aggregate gradation to improve RAP-PCC performance
  - Acquire better understanding on the RAP-PCC durability
  - Investigate chemical interaction and hydration behavior due to the presence of asphalt in the PCC system (e.g., calorimeter, SEM-EDS)
  - Apply advanced techniques (e.g., X-Ray CT, Petrography) to understand crack propagation and other important mechanisms
  - Apply models to predict RAP-PCC pavement performance
  - Address practical and cost-benefit issues

Materials and Mix Designs

HOU

BRY

AMA

SA

Agglomerated particles in AMA

Fixed parameters	
w/c	0.40
Cementitious content	520 lbs/cy
Class F Fly ash replacement	20%
Varying parameters	
RAP type	4
RAP replacement level (by volume of coarse aggregate)	0, 20% and 40%

w/cm ratio

Coarse RAP Replacement

0.40_520_20HOU

RAP ID

Cementitious content

- Gap-graded: 0.40_520_REF, 0.40_520_HOU, 0.40_520_AMA
- Dense-graded: 0.40_520_BRY, 0.40_520_SA

Specimen Fabrication and Testing

	Fresh concrete properties		Hardened concrete properties			
	Slump	Air content	Compressive strength	Modulus of elasticity	Flexural strength	Splitting tensile strength
Standard	ASTM C143	ASTM C231	ASTM C39/C39M	ASTM C469	ASTM C78/C78M	ASTM C496
Specimen size	-	-	48” Cylinder	48” Cylinder	6620” Beam	48” Cylinder

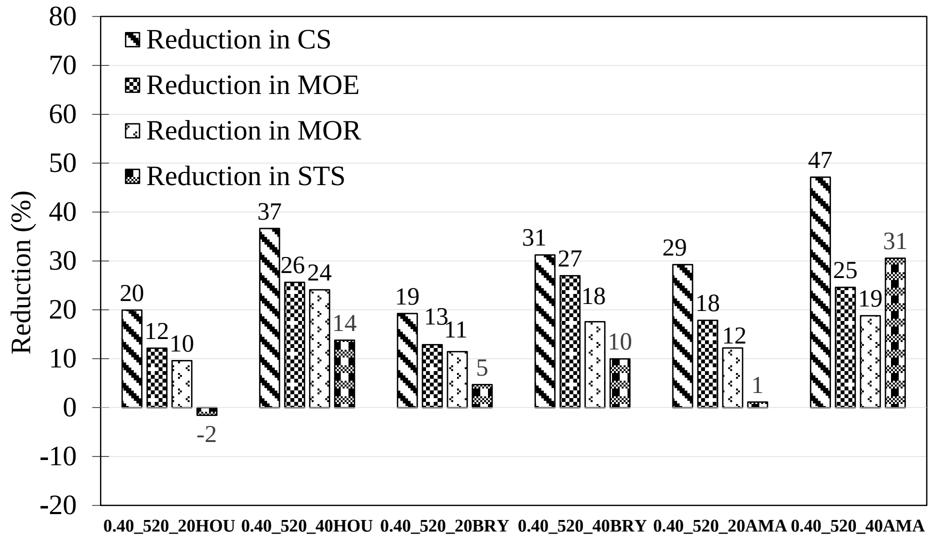
Compressive strength

Modulus of elasticity

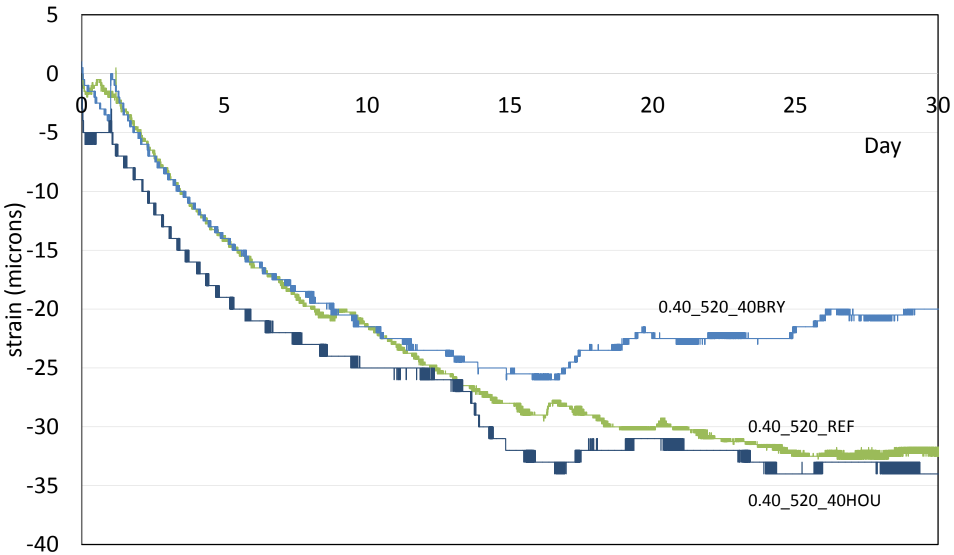
Flexural strength

Splitting tensile strength

Test Results Highlights: RAP-PCC Properties

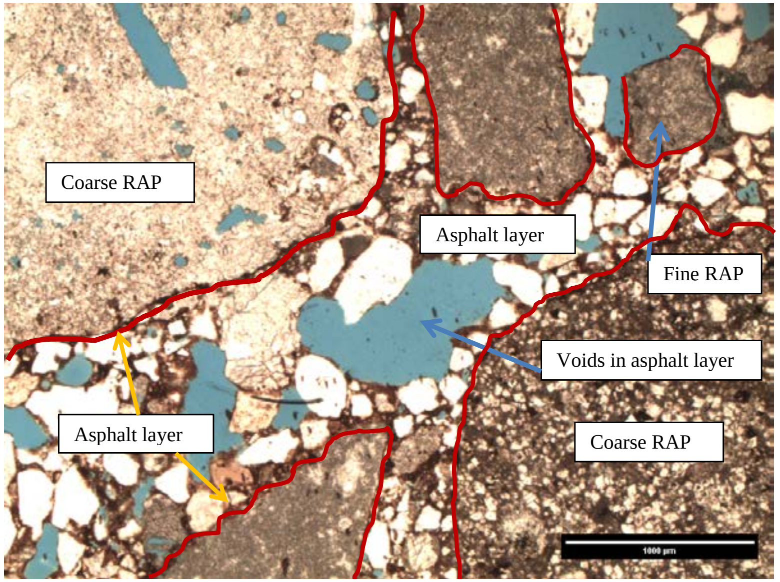


- The order of reduction:
  Compressive Strength > Split Tensile Strength > Modulus of Elasticity > Modulus of Rupture
- BRY RAP showed the best performance
  – Dense gradation
- AMA RAP showed relatively poor performance
  – High amounts of agglomerated particles

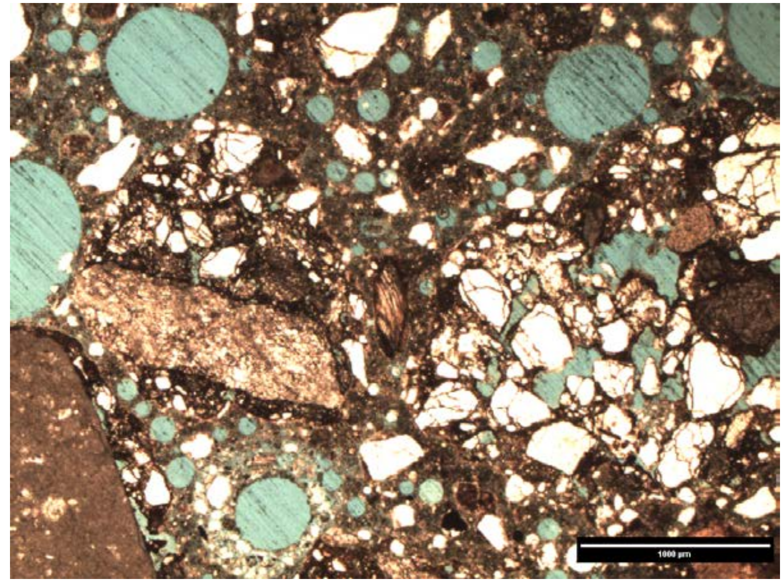


- Ring test (ASTM C1581)
  – No cracking was observed after 28 days
  – It seems dense graded RAP PCC had less shrinkage

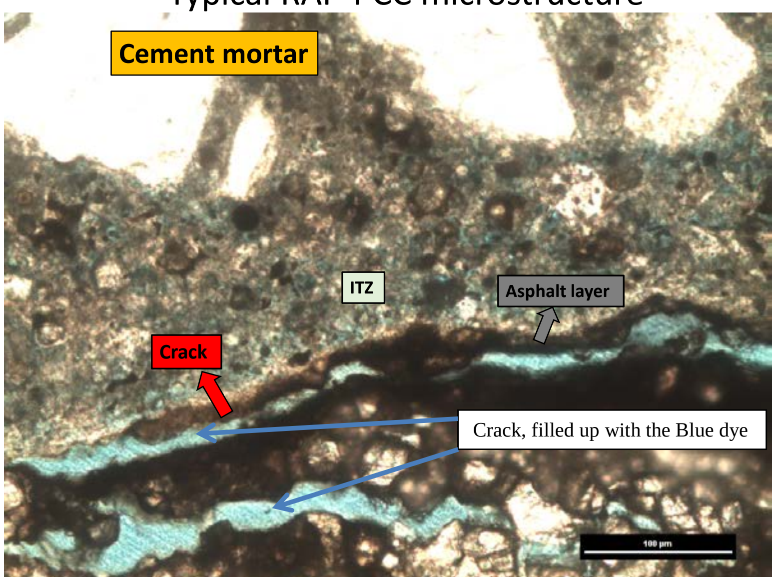
Test Results (Microstructure) Highlights: Crack Propagation



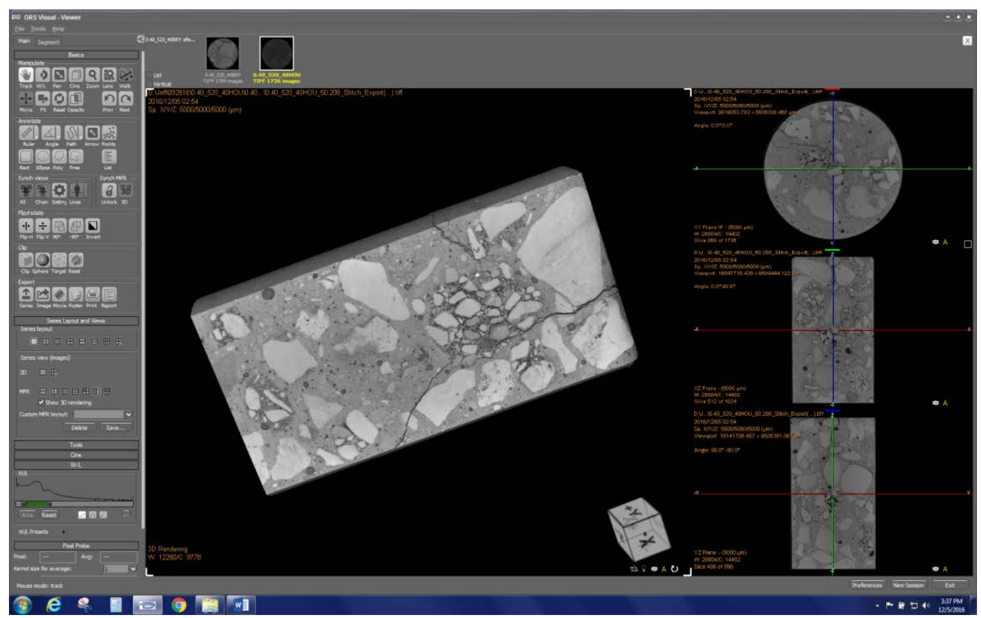
Typical RAP-PCC microstructure



RAP-PCC with higher air void content

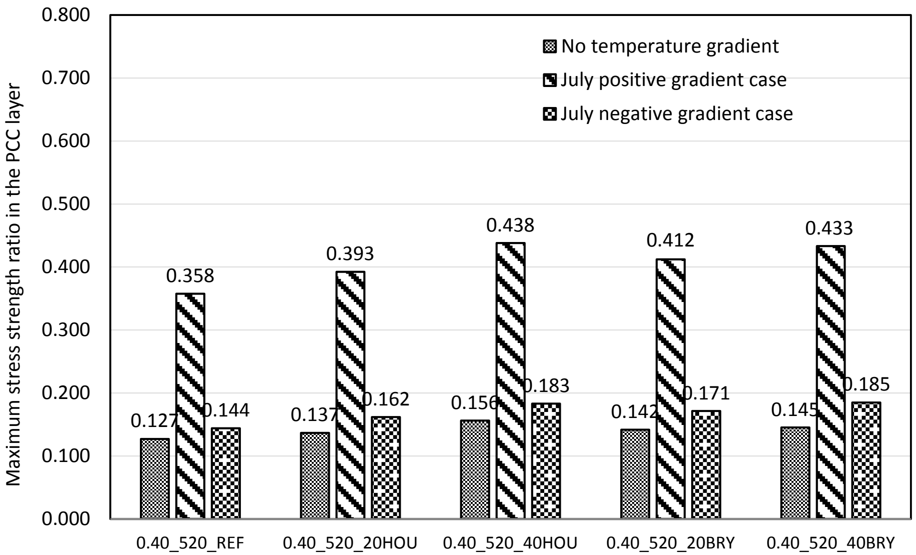


Asphalt cohesive failure (microscope image)



Crack passing agglomerated particles (X-RAY CT 3D image)

Results: Pavement Performance Prediction



- Critical stress analysis by ISLAB 2000
  - RAP-PCC pavement has higher stress/strength ratio
  - This high ratio caused by a higher CoTE and a reduced MOR
- Pavement design
  - RAP-PCC pavement needs slab with slightly higher thickness than the conventional PCC slab (Table below)

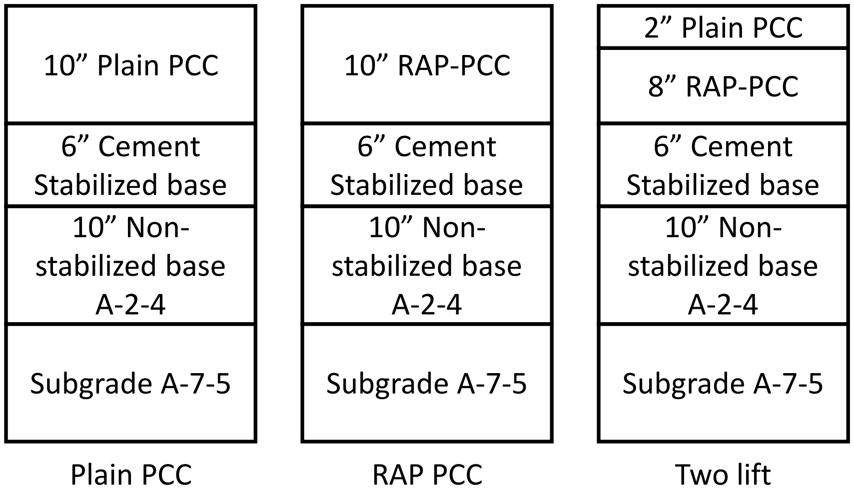
Slab thickness designed by AASHTO 1993 (CPCD)

Mix ID	Calculated thickness	Design thickness
0.40_520_REF	10	10
0.40_520_20HOU	10.305	10.5
0.40_520_40HOU	11.205	11.5
0.40_520_20BRY	10.405	10.5
0.40_520_40BRY	10.705	11

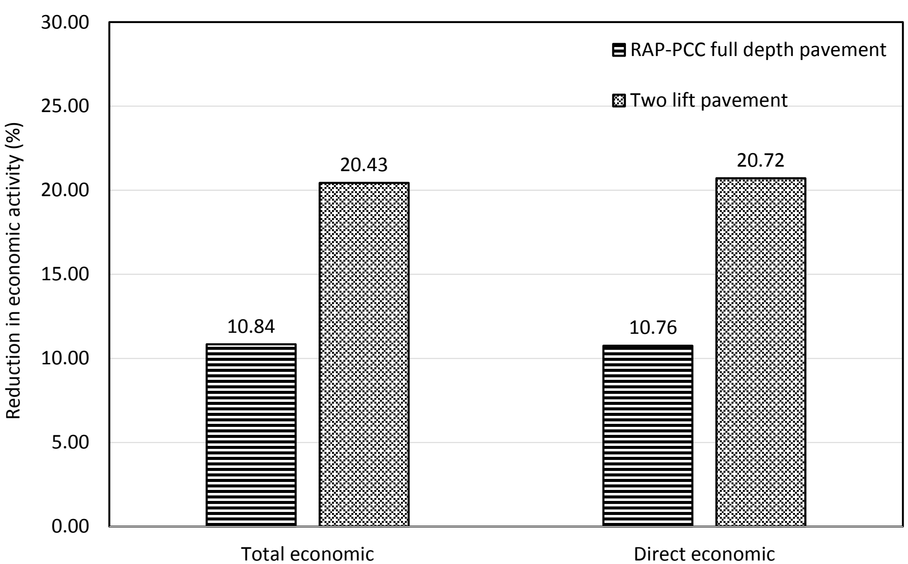
Slab thickness designed by TxCRCP (CRCP)

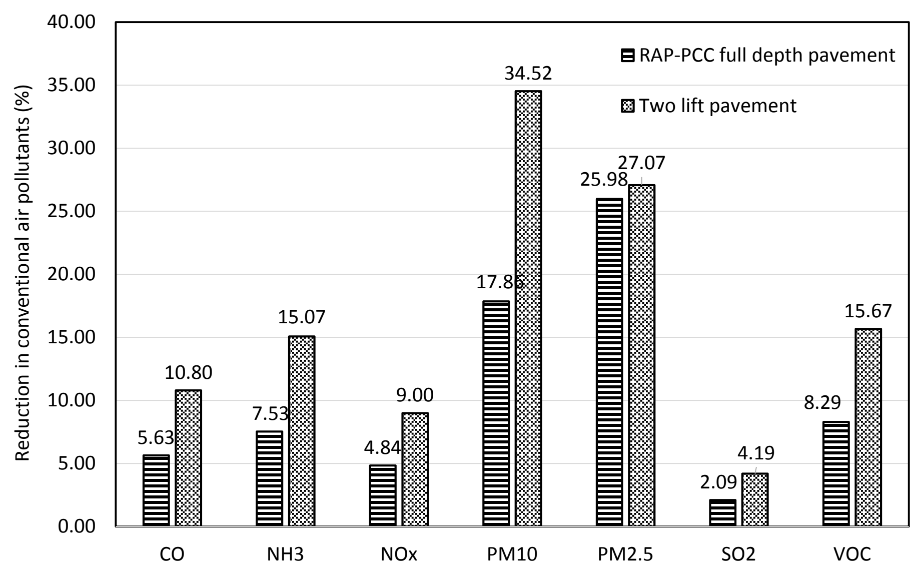
Mix ID	Design thickness (inch)	Punchouts at design thickness (per mile)
0.40_520_REF	10	8.1
0.40_520_20HOU	10.5	9.3
0.40_520_40HOU	12	8.7
0.40_520_20BRY	10.5	9.7
0.40_520_40BRY	11	9.5

Summary Results: Life Cycle Assessment



- Using RAP in PCC consumed less virgin aggregates
  - Save money
  - Less negative impact on environment
- Two lift a good option to maximize RAP use





% reduction is calculated as % difference between the RAP-PCC pavements and the plain PCC full depth pavement

Main Findings

- Replacing virgin coarse aggregate by RAP has caused reduction in CS, MOE, MOR, and STS. The % reduction in MOR turned out to be the lowest.
- The coarse RAP with suitable gradation containing sufficient intermediate size particles can help make dense graded concrete. The dense graded RAP-PCC showed better workability and mechanical properties compared to the other gap graded RAP-PCC.
- The ACI equations were modified. The original equations in the ACI code underestimate the prediction of MOR, MOE, and STS for RAP-PCC.
- Regression relationships were developed to describe RAP-PCC mechanical properties with varying asphalt content. Both CS and MOR have strong linear relationship with global asphalt binder volume fraction (GABVF).
- Based on CS/MOR vs. GABVF relationships equations, approaches to determine the optimum RAP replacement were proposed for both Class P and low strength classes.

Main Findings (cont'd)

- The presence of RAP clump is a common feature. The agglomerated RAP particles appeared to be a single particle in naked eye but their agglomerated nature was clearly visible under microscope.
- The major weak point of the RAP PCC system is the asphalt. Asphalt cohesive failure (i.e., crack easily propagate through the asphalt layer around the RAP particles) is the major failure mechanism.
- The presence of RAP has caused higher amounts of air voids in the studied RAP-PCC mixtures compared to the reference PCC sample.
- At higher replacement level (> 20%), the pavement containing RAP PCC needs slightly higher slab thickness. A slight increase in thickness is largely caused by the increase in CoTE and Poisson's ratio and the reduction in MOR when RAP is added into concrete.

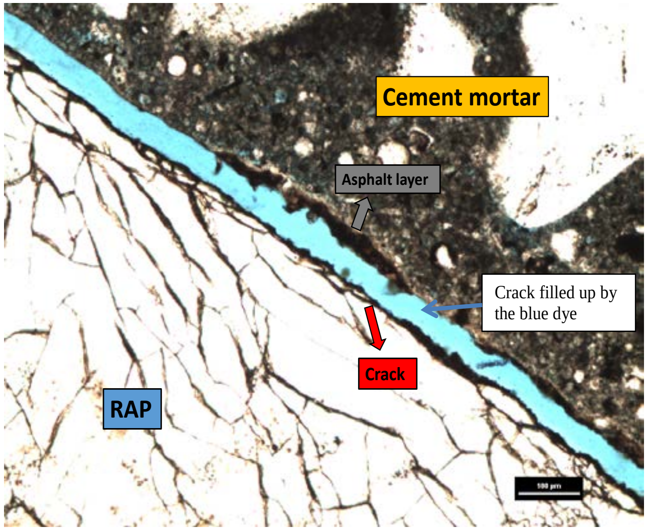
Main Findings (cont'd)

- Compared with the material production for plain PCC pavement, the production of materials for constructing RAP-PCC pavements (either full depth or two lift) yielded lower economic activity (more economical) and consumed less amounts of energy. It released less amounts of air pollutants, greenhouse gases, and toxic materials. It also led to less amounts of land use and water withdrawals.
- The idea of using RAP-PCC as bottom lift in a two lift PCC pavement can maximize the RAP usage without compromising the pavement performance or compromise within the permissible limits. The cost and environmental benefits were obvious for all three pavement types.
- Other than the benefits from material production process, the use of RAP in PCC can reduce the size of the RAP stockpile significantly, which leads to cost savings and protecting environment and public safety.

Guidelines and Implementation Recommendations

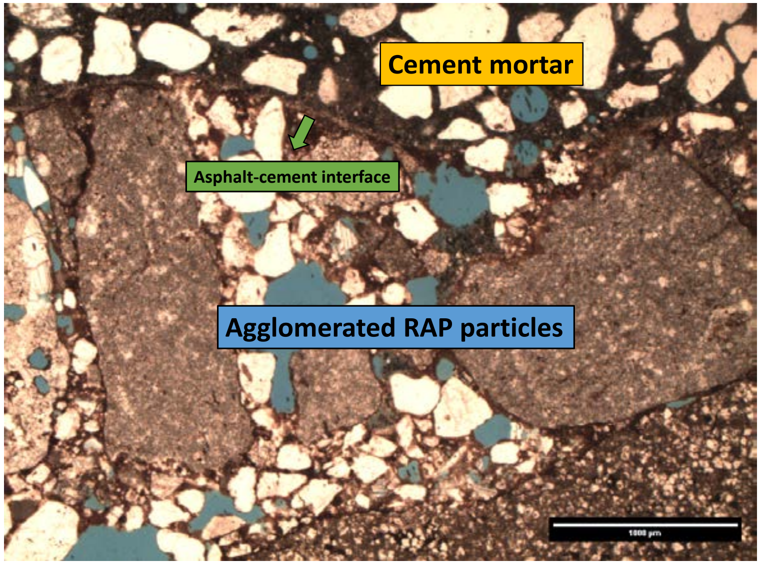
How to Select RAP Material?

- Lower binder content
  - Coarse RAP with gradation similar to virgin aggregate: ≤ 5.0%
  - Coarse RAP with dense aggregate gradation (with intermediate size particles): ≤ 6.5%
  - Class P uses coarse RAP only
- Less amounts of clumps
  - Visual examination
  - Microscope thin section observation



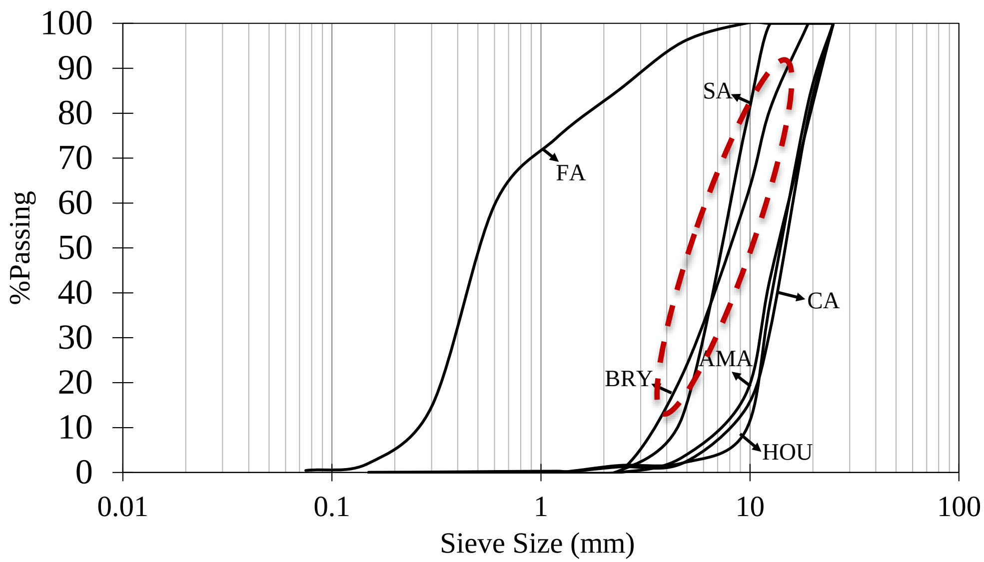
Asphalt the weak point in RAP-PCC system


Agglomerated RAP particles (visual examination)

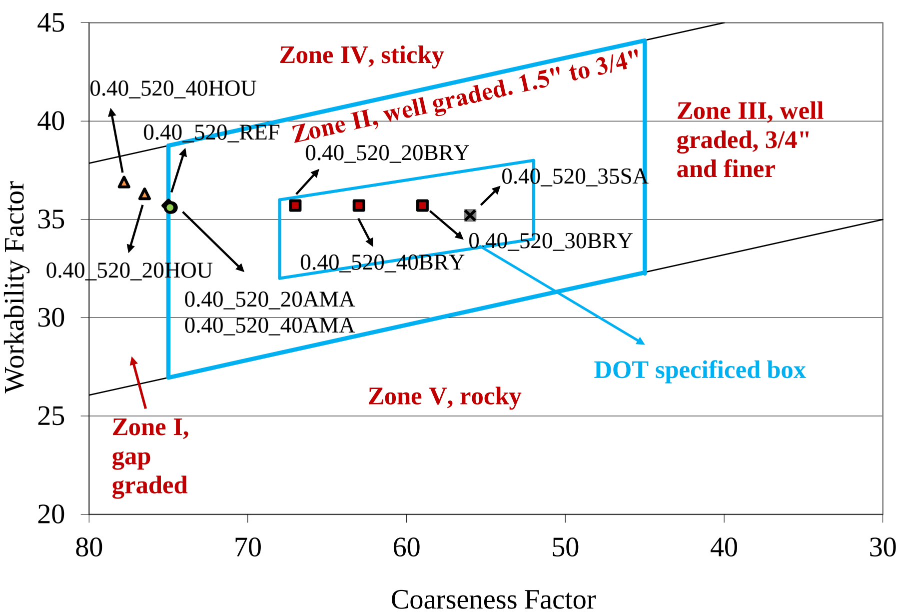


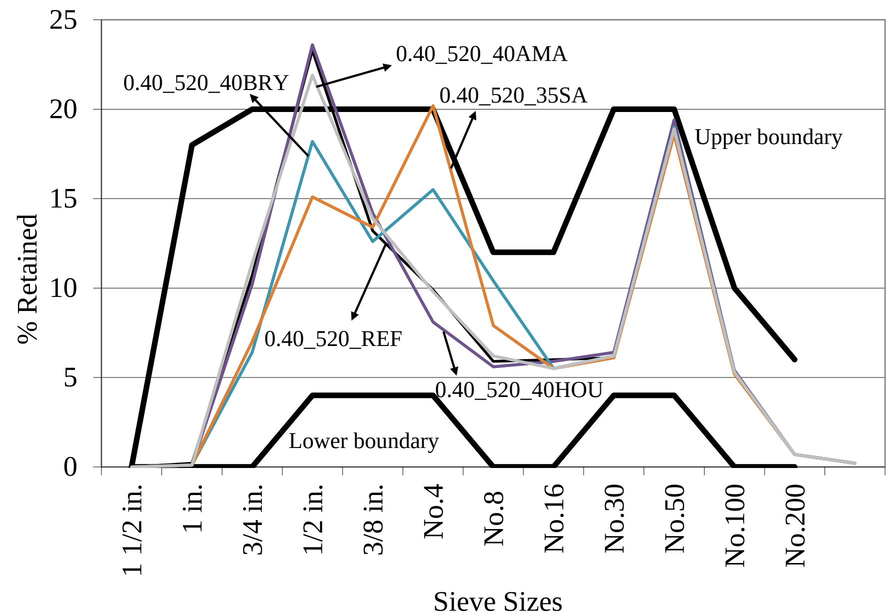
Agglomerated RAP particles (thin section observation)

How to Select RAP Material?



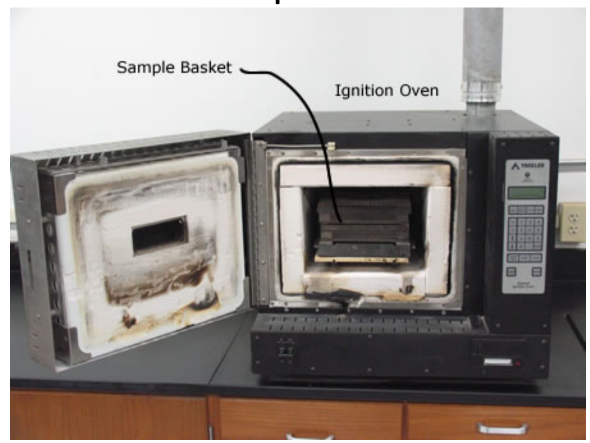
- Adequate gradation
  - Higher amount of intermediate sizes (No.8-3/8”)
  - Optimized aggregate gradation analysis (Tex-470-A, form 2227)





How to Determine the Optimum RAP Replacement Level for Class P Requirement?

1. Select a good quality of coarse RAP and test asphalt binder content



Asphalt binder content: 6.19%

BRY RAP: intermediate size with little agglomeration

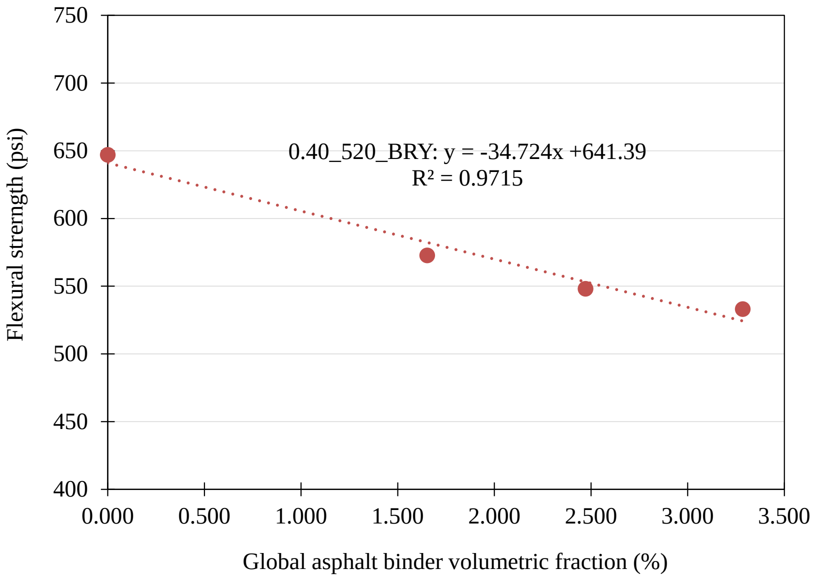
2. Design RAP-PCC mixtures by replacing 20% coarse RAP and 40% coarse RAP, respectively. If possible, adding one more point (30%) is highly recommended.

	0.40_520_REF	0.40_520_20BRY	0.40_520_30BRY	0.40_520_40BRY
Cement (lbs/cy)	416	416	416	416
Fly Ash (lbs/cy)	104	104	104	104
Virgin coarse aggregate (lbs/cy)	1783	1399	1237	1030
RAP (lbs/cy)	0	350	499	687
FA (lbs/cy)	1296	1308	1312	1320
Water Reducer (fl oz/cy)	10.4	10.4	10.4	10.4
Air Entraining Agent (fl oz/cy)	1.563	1.563	1.563	1.563
Water (lbs/cy)	208	208	208	208

How to Determine the Optimum RAP Replacement Level for Class P Requirement?

3. Cast and cure RAP-PCC samples and plain PCC sample. test samples' mechanical properties at 28 days. It is recommended to test 28-day flexural strength. If the flexural strength test is not applicable, testing compressive strength is allowed.
4. Construct regression relationship between the 28-day flexural strength (or compressive strength if it was tested in step 3) and the global asphalt binder volumetric fraction (GABVF).

Flexural strength



GABVF: the volumetric fraction of asphalt binder with respect to the whole aggregate system (RAP+ virgin aggregates)

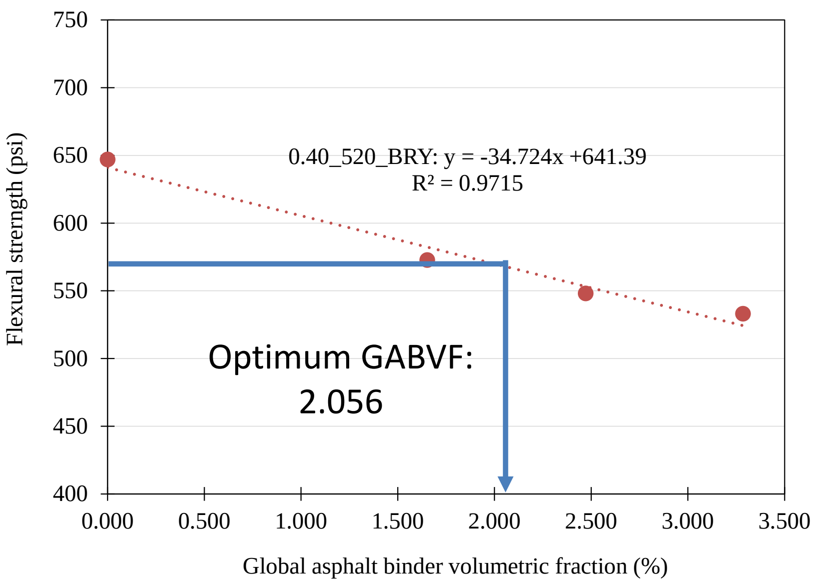
$$\theta_g = \theta_l \times v$$

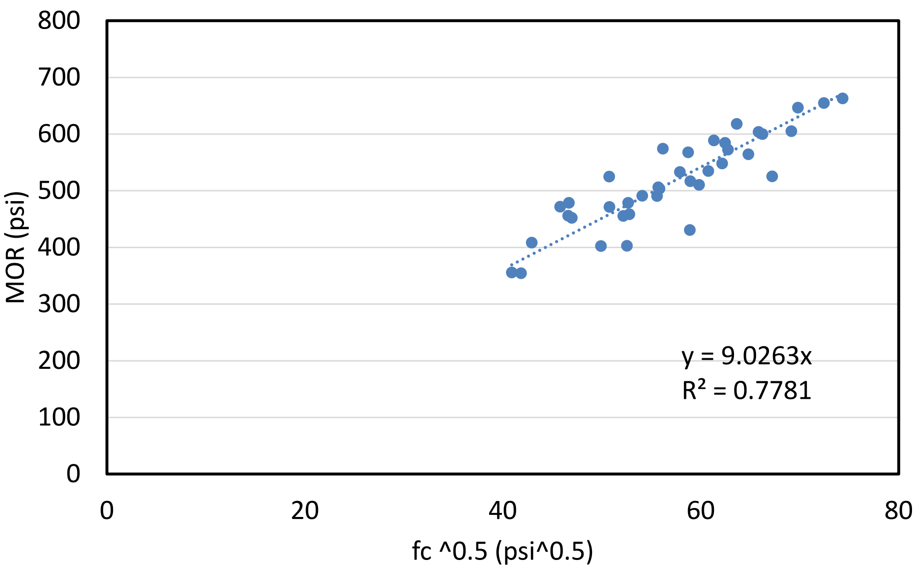
θ_l: the volumetric fraction of asphalt binder with respect to the RAP

v : the volumetric fraction of RAP in the whole aggregate system

How to Determine the Optimum RAP Replacement Level for Class P Requirement?

5. Determine the optimum GABVF in accordance with the target flexural strength. For TxDOT Class P specification, the 28-day flexural strength requirement is 570 psi. If 28-day compressive strength is tested in step 3, the target compressive strength requirement can be set as 3906 psi.
6. Back-calculate the optimum RAP replacement level using mix design information.





2.056 Optimum GABVF = 24% RAP Replacement

$$\mathrm{MOR} = 9.03 \times f_c^{0.5}$$

570 psi

3906 psi

How to Determine the Optimum RAP Replacement Level for Other Classes of Concrete with Low Strength Requirements?

- Fine RAP is allowed to be used for low strength concrete

Strength specification for different concrete class (Item 421)

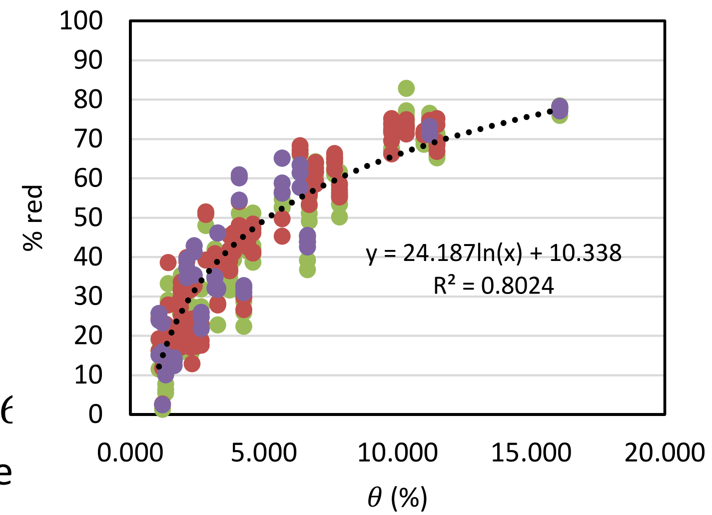
Class	Class B	Class A&E	Class C and SS	Class S
56-day fc	2000 psi	3000 psi	3600 psi	4000 psi

- Less rigorous approach

1. Determine RAP binder content
2. Design and cast reference sample, and test its 56-day fc
3. Calculate $\%red = \frac{fc(REF)-fc(target)}{fc(REF)} \times 100$
4. Determine optimum GABVF (θ) using generalized correlation equation:

$$\%red = 26.455 \times \ln(\theta) + 6.22\text{(}$$

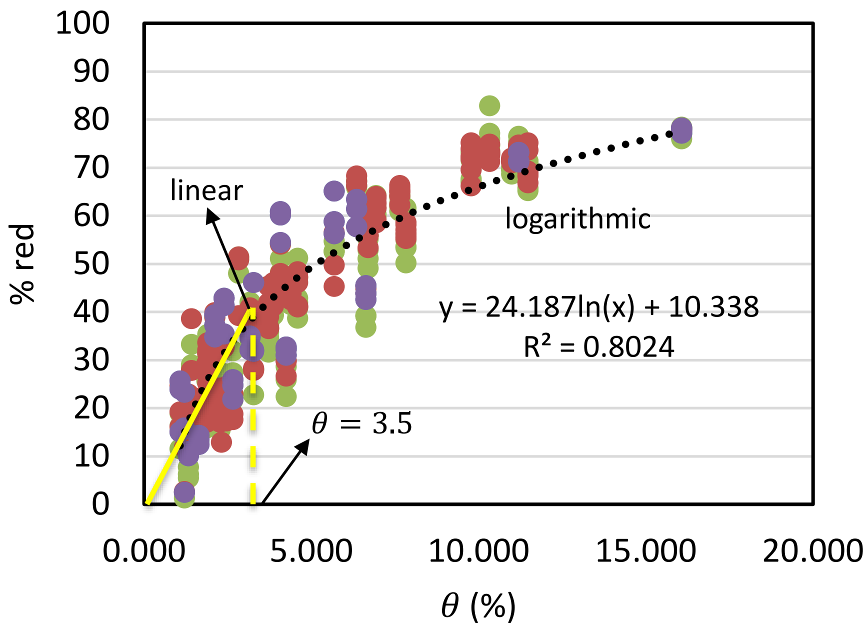
5. Back-calculate the optimum RAP replacement leve



The generalized correlation equation is generated in this project by using both experimental data and data from literature.

How to Determine the Optimum RAP Replacement Level for Other Classes of Concrete with Low Strength Requirements?

- More rigorous approach
  1. Determine RAP binder content
  2. Design and cast reference sample, RAP-PCC samples at various replacement level covering the entire range (e.g., 0, 20%, 40%, 70% and 100%); test their 56-day fc.
  3. Construct regression relationship between the 56-day fc and the global asphalt binder volumetric fraction (GABVF).
  4. Select the best regression equation for describing the fc and GABVF:
     Max GABVF<3.5: linear relationship
     Max AGBVF>3.5: logarithmic relationship
  5. Back-calculate the optimum RAP replacement level



How to Select RAP-PCC Pavement Type?

- If RAP-PCC satisfy the requirements of adequate surface characteristics: a full depth RAP-PCC pavement can be allowed
  - Surface characteristics
    - Abrasion resistance
    - Skid resistance
    - Ride quality
    - Noise reduction
  - Pavement thickness design
    - CRCP: TxDOT CRCP
    - CPCD: ASSHTO 1993

How to Select RAP-PCC Pavement Type?

- If RAP-PCC doesn't have adequate surface characteristics: two lift pavement construction is recommended
  - Top lift: 2-3 inch
  - Bottom lift: 6-10 inch
  - Use RAP-PCC as bottom lift to compensate reduced strength and surface properties

Statistics of existing two lift pavement (summarized by project 0-6749)

	Top lift		Bottom lift	
	Average	Standard deviation	Average	Standard deviation
Thickness	2.6”	0.9”	7.8”	1.5”
Cement content	579 pcy	108 pcy	512 pcy	60 pcy
w/c	0.42	0.03	0.44	0.02
Slump	1.6”	0.9”	1.38”	0.94”
Air	0.06	0.018	0.062	0.01
fc	4600 psi	922 psi	4100 psi	548 psi
MOR	640 psi	NA	371 psi	NA
Aggregate type	High quality aggregate (granite, rhyolite, basalt, etc.)		Local aggregates (limestone sand, river gravel, RCA, RAP, etc.)	

Implementation and Future Work

Testing more materials
- More RAP types and locations
- Ideal RAP gradation for PCC
- Better techniques to predict RAP-PCC properties

Additional mechanical tests
- Creep test
- Fracture toughness
- Fatigue test

Durability tests
- Ring test
- Rapid chloride permeability test
- Chemical durability test
- Pavement surface characteristics

Two-lift pavement specifications
- Material strength
- Design procedure
- Effects of bonding between top and bottom lift
- Other practical issues

Field section
- Full-depth pavement construction
- Two-lift pavement construction

Testing more materials

More RAP types and locations

Ideal RAP gradation for PCC

Better techniques to predict RAP-PCC properties

- More RAP types and locations
  - Increase the database – testing representative RAPs covering all geographic locations under TxDOT
  - Verify the findings in the project
- Ideal RAP gradation for PCC
  - Current project used HMA making stockpiles
  - Work with industry to generate stockpiles with gradation needed to make RAP-PCC with dense gradation
- Better techniques to predict RAP-PCC properties
  - Correlate or interpret the factors that affect the rate of deterioration (k)
  - Degree of RAP agglomeration can be quantified using petrographic methods

Additional mechanical tests

- Creep test
- Fracture toughness
- Fatigue test

- Creep test
  - RAP-PCC shall have more creep due to asphalt viscoelastic nature
  - Effects on pavement performance
- Fracture toughness
  - RAP-PCC might have equivalent fracture properties
  - Fracture properties are more relevant for field applications
- Fatigue test
  - Fatigue test is important in order to address the crack formation and propagation aspects
  - No work has been done yet on RAP-PCC

Durability tests

- Ring test
- Rapid chloride permeability test
- Chemical durability test
- Pavement surface characteristics

- Ring test
  - No cracks were observed using the conventional ring tests
  - Dual ring test under more severe condition is needed
- Rapid chloride permeability test
  - Needs to be performed in order to verify whether RAP-PCC has adequate chloride resistance
- Chemical durability test
  - Alkali silica reaction (ASR) potential needs to be tested
- Pavement surface characteristics
  - Abrasion resistance, skid resistance, ride quality and noise production
  - Directly relates to the feasibility of using RAP-PCC in full depth pavement application

Two-lift pavement specifications

- Material strength
- Design procedure
- Effects of bonding between top and bottom lift
- Other practical issues

- Material strength
  - The material strength requirements for both top and bottom lifts need to be specified
- Design procedure
  - Current practice is to use MEPDG overlay design
  - This design has many problems
- Effects of bonding between top and bottom lift
  - Directly relates to pavement short term and long term performance
- Other practical issues
  - Cost/benefit
  - Construction management

Field section

Full-depth pavement construction

Two-lift pavement construction

- Full-depth pavement construction
  - RAP-PCC full depth pavement with same slab thickness of the reference pavement
  - RAP-PCC full depth pavement with thicker slab
- Two-lift pavement construction
  - Using RAP-PCC as bottom lift

THANK YOU