Rejuvenators: Industry update and Path to Implementation

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March 2023

Cargill® Helping the world thrive

Global Supplier of Asphalt Chemistries

Cargill® Helping the world thrive

To empower a more sustainable life and keeping people safe on the road through high-performance and advanced bio-based asphalt additives.

- Rejuvenation
- Warm Mix
- Cold Mix
- Emulsions
- Rheology
- Stabilizers

State-of-the-art Asphalt Lab

- Customer custom formulation services
- Compositional and analytical evaluation
- Advanced rheology and thermal analysis

155,000 employees

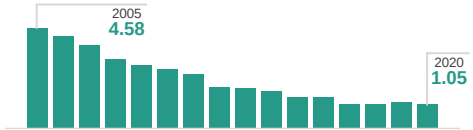
155 years of experience

Working in **70** countries

$114,6 billion in annual revenue

Our commitments

Safe
We relentlessly work to improve the safety of our people. Reduction in injuries per 200,000 hours worked over 15 years.



Responsible
We strive to strengthen the communities where we live and work.

$115 million
Total charitable contributions last year across 56 countries

Attendance at our farmer trainings for sustainable agricultural practices totaled 860,000 last year

Sustainable
- Agriculture is how we will protect the planet and our shared future.
- Climate change: Reducing supply chain emissions per ton of product 30% by 2030, and absolute operational emissions 10% by 2025
- Water resources: Achieving sustainable water management in all priority watersheds by 2030
- Land use: Eliminating deforestation in our supply chains by 2030

Agenda

- Recycling Agents: What? Why? How?
- RA Implementation: Best Practices
- RA-BMD Spec. Implementation Examples
- Why This Matters

Recycling Agents

“Rejuvenation” is an inaccurate, but popular term for Recycling Agents.

- Rejuvenators do not undo oxidative aging!!!

A Recycling Agent reverses the impact of aging on asphalt, reactivating the asphalt, to restore performance, and durability.

A “Rejuvenating” Recycling Agent reverses the impact of aging by:

- Restoring cracking resistance, maintain rutting performance
- Improving workability, compaction, and appearance
- Improving aging susceptibility of the pavement
- Providing predictable and reliable results

How are Rejuvenators Added to Asphalt?

Typically, **0.3-3% wt. of the binder or 0.015-0.15% wt. of the mix**, added via:

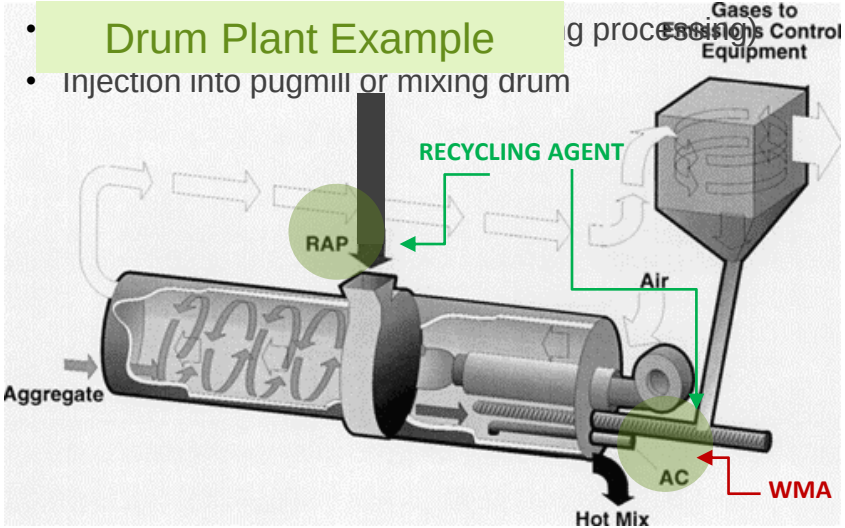
For both RA and WMA:

- In-line into virgin binder using additive pump
- Pre-blended into virgin binder (mostly for WMA)

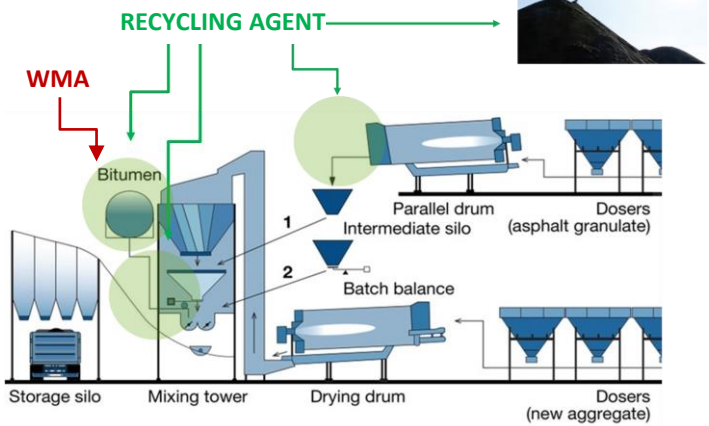
Only for RA:

- [illegible]g processing)
- Injection into pugmill or mixing drum

Drum Plant Example

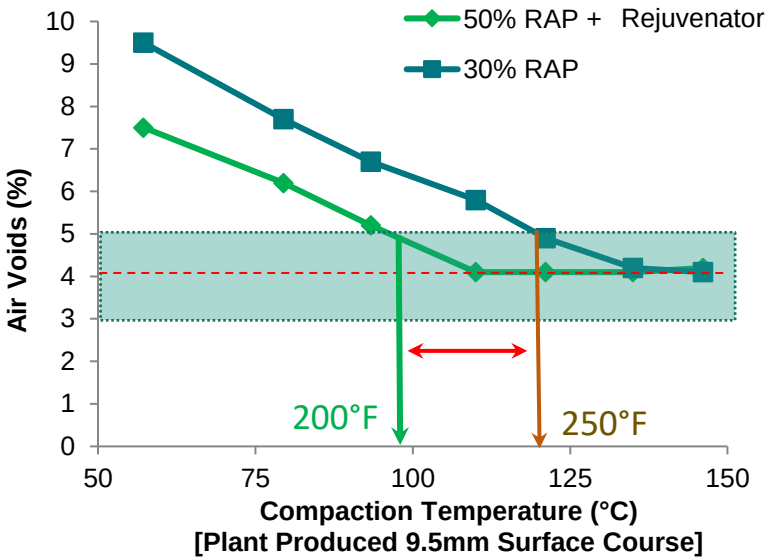


Batch Plant Example



First Impressions: Improved workability

- Rejuvenation significantly improved the Compactability, even after a 20% increase in RAP content.
  - A large improvement in compaction temperatures achieved
  - No over-compaction at hot mix temperatures.



Role of Recycling Agents in Mix Design

- Recycling agents have been used to modify performance attributes in a mix.
- The following general impact trends can be expected:

Mix Parameter	Expected RA Impact
Cracking Resistance	Improve
High Temperature Stiffness	Decrease
Moisture Resistance	Typically, None

RA Implementation:
Best Practices

What is the process for producing High-RAP mixes?

1. **Check and meet the fundamentals:**
   - Can the plant reliably handle more RAP? (Capacity, belts, flights, dryers, etc.)
   - Do I have a way to introduce rejuvenators into my mix at the plant? (e.g., a liquid antistrip system or similar additive setups)
   - Do I have enough RAP?

2. **Implementation:**
   A. For implementation in commercial mixes: Work with rejuvenator supplier on the appropriate dosage to produce higher RAP mixes with quality consistent with normally supplied mix designs. Step up RAP QC frequency.

   B. For implementation in agency “spec” mixes: Fundamentally the same, but also requires a framework that provides **transparency and reliability for all stakeholders**.

Step 1- RA Properties via ASTM D4552-20 (By Supplier)

(Published July 2020)

This step ensures that rejuvenator meets basic requirements for safety, thermal stability, storage stability, and compatibility to be used in Hot Mix Asphalt production.

Most Bio-oils

Most Petro. oils

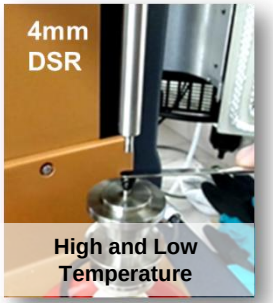
Test	ASTM Test Method	RA 0		RA 1		RA 5		RA 25		RA 75		RA 250		RA 500		Example Bio-based Rejuvenator
		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	
Viscosity • 60 °C [140 °F], mm²/s	D2170	10	49	50	175	176	900	901	4500	4501	12500	12501	37500	37501	60000	30
Flash Point, COC, °C [°F]	D92	219 [425]	...	219 [425]	...	219 [425]	...	219 [425]	...	219 [425]	...	219 [425]	...	219 [425]	...	>290°C
Saturates, wt. %[A]	D2007	...	30	...	30	...	30	...	30	...	30	...	30	...	30	~ 0% (Iatroscan)
Tests on Residue from RTFO 163 °C [325 °F]	D2872															
Viscosity Ratio[E]	"	...	3	...	3	...	3	...	3	...	3	...	3	...	3	1.05
Wt Change, ±, %	"	...	4	...	4	...	4	...	3	...	3	...	3	...	3	<0.5%
Specific Gravity at 25 °C [77 °F]	D70 or D1298	0.900	1.100	0.900	1.100	0.900	1.100	0.900	1.100	0.900	1.100	0.900	1.100	0.900	1.100	0.94

$$ViscosityRatio = \frac{Viscosity\ of\ Residue\ from\ RTFO\ Test\ at\ 60°C\ [140°F]}{Original\ Viscosity\ at\ 60°C\ [140°F]}$$

Step 2: Initial RA Dosage Determination (By Supplier)

- RAP samples are extracted, graded and rheologically fingerprinted for initial dosage determination.

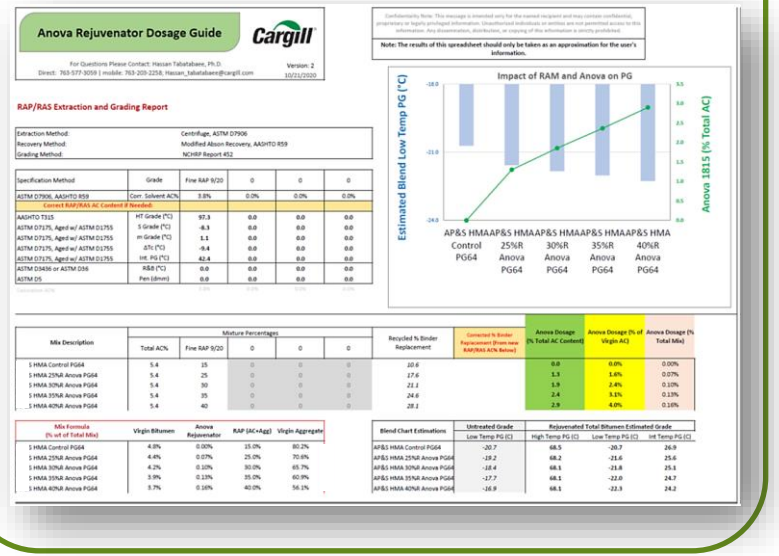
Extraction & Recovery



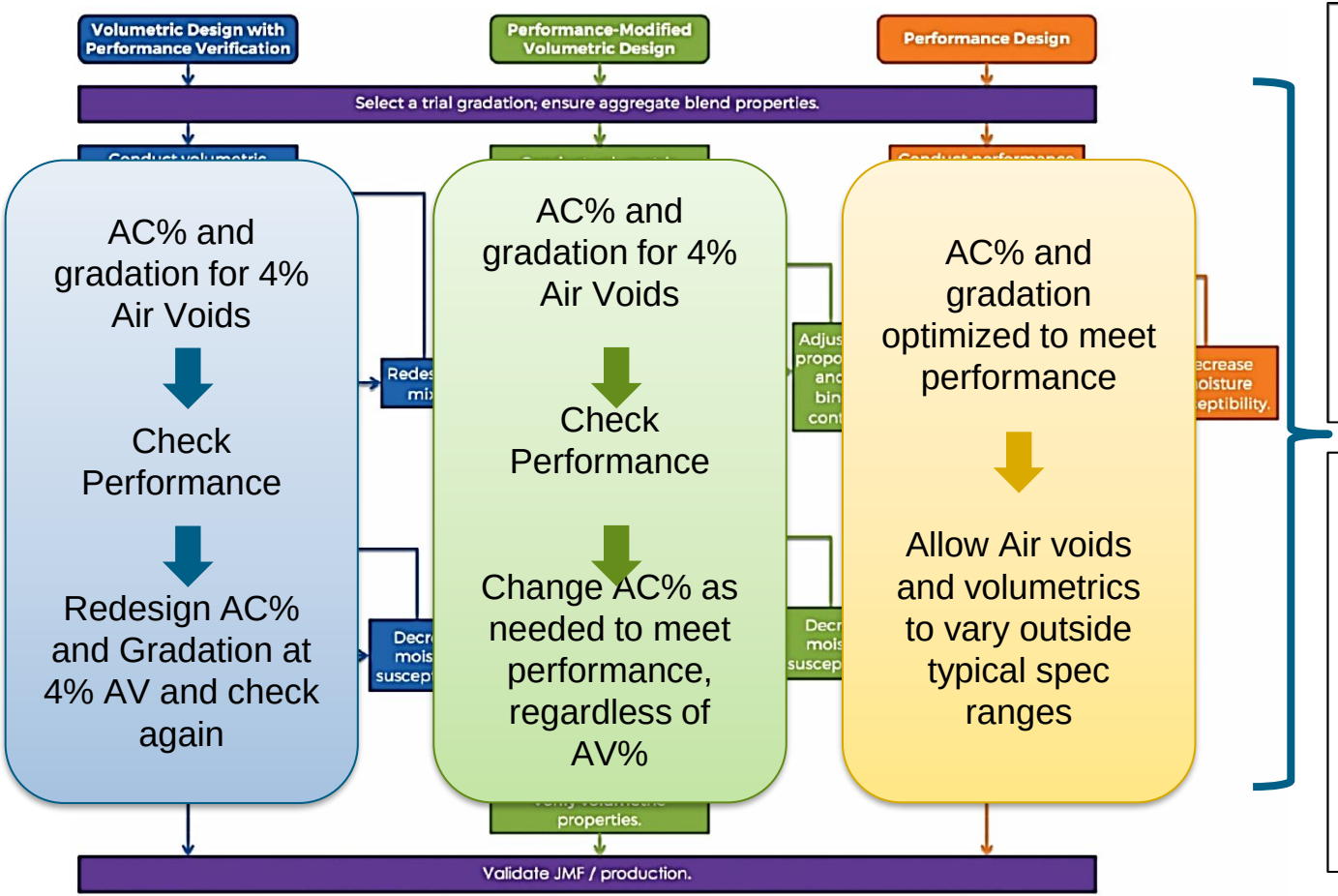
Low Temperature
Cracking Resistance

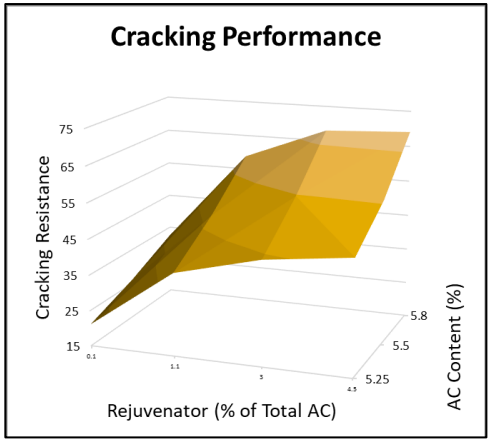
Grading and Analysis

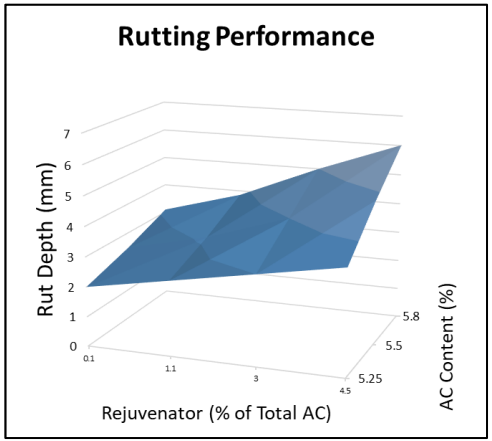
Dosage Determination Report for Target Mix Designs



Step 3: Balanced Mix Design (By Producer)







Quality Management Support

Well-established process for Commercial Mixes

Supplier:

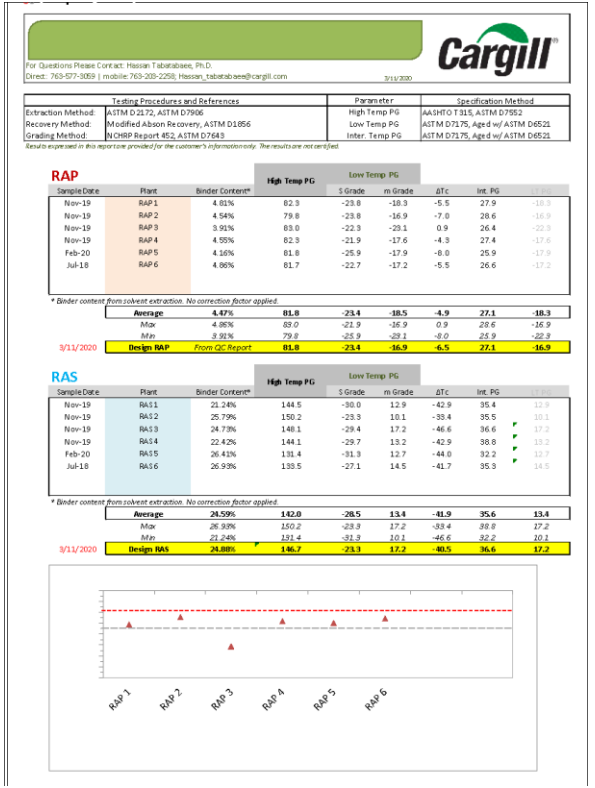
- Product delivered with verifiable Certificate of Analysis
- Support producer with periodic material sampling and verification throughout season.

Producer:

- Maintain appropriate frequency of RAP analysis (often binder content and gradation control.)
- Maintain RAM processing protocols and consistency
- Mix performance verification as needed.

Owner/Agency (in development across country):

- Per agency specification
- Frequent Quality verification of mix composition/volumetrics
- Full mix design performance verification on first plant production of a specific design
- Periodic simple/surrogate mix performance verification



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1/17/2023

RAP

				High Temp PG	Low Temp PG			
	Jun-20	Sample 1	4.50%	88.9	-19.7	-15.3	-4.4	31.0	-15.3
	Jun-20	Sample 2	4.91%	86.5	-23.0	-15.9	-7.0	27.0	-15.9
	Sep-20	Sample 3	4.47%	90.3	-21.0	-16.6	-4.3	30.0	-16.6
	Feb-21	Sample 4	4.39%	91.5	-20.0	-15.9	-4.1	31.6	-15.9
	Feb-21	Sample 5	3.63%	89.3	-21.6	-16.8	-4.8	29.6	-16.8
	Feb-21	Sample 6	5.22%	86.7	-21.6	-17.8	-3.8	29.0	-17.8
	Feb-21	Sample 7	4.04%	86.1	-21.0	-17.2	-3.8	30.3	-17.2
	Feb-21	Sample 8	4.77%	83.4	-22.8	-19.6	-3.2	27.0	-19.6
	Feb-21	Sample 9	4.08%	85.3	-22.9	-18.4	-4.5	27.9	-18.4
	Feb-21	Sample 10	4.11%	75.1	-24.0	-21.6	2.4	26.5	-21.6
	May-21	Sample 11	4.38%	88.7	-20.7	-17.1	-3.6	29.5	-17.1
	May-22	Sample 12	4.91%	89.8	-22.3	-18.0	-4.4	29.1	-18.0
	May-22	Sample 13	5.53%	90.1	-22.1	-21.0	-1.1	27.7	-21.0
	May-22	Sample 14	4.69%	89.8	-21.9	-16.1	-5.7	29.9	-16.1
	Jun-22	Sample 15	5.65%	84.8	-23.6	-21.8	-1.8	25.3	-21.8
	Aug-22	Sample 16	4.35%	85.6	-20.7	-19.0	-1.7	29.9	-19.0
	Oct-22	Sample 17	5.88%	76.2	-27.7	-26.6	-1.1	20.3	-26.6
	Oct-22	Sample 18	3.08%	80.7	-27.1	-26.4	-0.7	21.3	-26.4
New	Jul-22	Sample 19	4.84%	82.5	-24.7	-21.0	-3.7	25.7	-21.0
New	Sep-22	Sample 20	5.20%	92.1	-20.8	-13.2	-7.6	33.2	-13.2

*Binder content from solvent extraction. No correction factor applied.

Average	**4.59%**	**86.1**	**-22.0**	**-18.8**	**-3.0**	**28.1**	**-18.8**
Max	*5.88%*	*91.5*	*-19.3*	*-15.3*	*4.2*	*31.6*	*-15.3*
Min	*3.08%*	*75.1*	*-27.7*	*-26.6*	*-7.0*	*20.3*	*-26.6*
1/17/2023 **Design RAP**	*From QC Report*	**85.7**	**-20.7**	**-16.1**	**-4.6**	**26.9**	**-16.1**

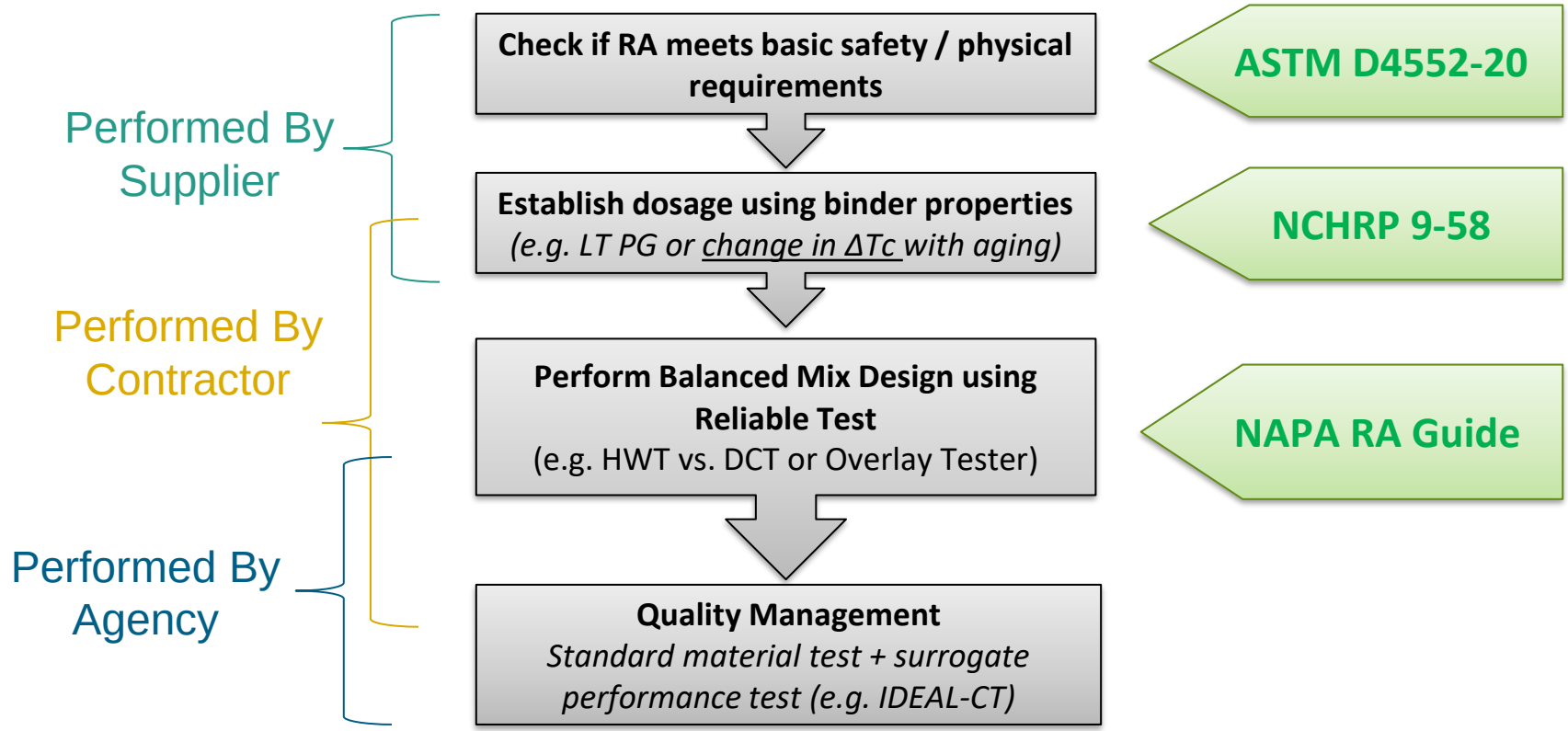
HMA

				High Temp PG	Low Temp PG				
	Sample Date	Plant	Binder Content*		S Grade	m Grade	ΔTc	Int. PG	LTPG
	Jun-20	HMA - 50%	5.22%	72.2	-24.2	-22.3	-1.8	22.0	-22.3
	Sep-20	HMA - 50%	4.98%	75.9	-27.1	-22.3	-4.8	21.7	-22.3
	Nov-20	HMA - 40%	5.46%	73.9	-25.8	-23.6	-2.3	21.9	-23.6
	Dec-20	HMA - 40%	5.56%	67.4	-23.2	-24.1	0.9	23.4	-23.2
	Apr-21	HMA - 50%	4.91%	75.0	-24.1	-23.3	-0.9	23.5	-23.3
	May-21	HMA - 40%	5.40%	64.6	-24.7	-24.2	-0.5	21.8	-24.2
	May-21	HMA - 50%	5.11%	76.1	-22.5	-21.0	-1.5	25.6	-21.0
	Aug-21	HMA - 45/5	5.05%	79.2	-27.9	-25.4	-2.5	20.0	-25.4
	Sep-21	HMA - 30S	5.58%	67.3	-22.9	-23.8	0.9	22.2	-22.9
	Sep-21	HMA - 40%	5.22%	66.7	-23.6	-24.5	0.9	21.8	-23.6
	Sep-21	HMA - 40%	5.29%	69.1	-24.0	-23.6	-0.5	22.3	-23.6
	Sep-21	HMA - 50%	3.99%	73.3	-22.8	-22.8	0.1	24.1	-22.8
	Oct-21	HMA - 30%	4.75%	69.6	-23.6	-23.9	0.3	21.1	-23.6
	Nov-21	HMA - 40%	4.80%	73.3	-25.9	-23.9	-2.0	22.6	-23.9
	Nov-21	HMA - 30%	5.37%	72.7	-28.3	-24.5	-3.8	19.9	-24.5
	May-22	HMA - 40%	5.41%	77.3	-26.2	-24.0	-2.2	21.8	-24.0
	May-22	HMA - 60%	4.47%	85.9	-24.4	-21.3	-3.2	25.9	-21.3
	May-22	HMA - 30%	6.01%	73.4	-25.5	-22.8	-2.7	22.6	-22.8
	Jun-22	HMA - 50%	5.21%	74.4	-22.9	-21.2	-1.6	24.7	-21.2
	Jul-22	HMA - 40%	5.43%	67.0	-25.6	-23.8	-1.8	21.9	-23.8
New	Jul-22	HMA - 30%	5.33%	70.1	-27.8	-24.7	-3.1	20.0	-24.7
New	Sep-22	HMA - 40%	5.55%	74.5	-25.5	-24.1	-1.4	23.0	-24.1

*Binder content from solvent extraction. No correction factor applied.

Average	**5.16%**	**72.7**	**-24.9**	**-23.4**	**-1.5**	**22.5**	**-23.3**
Max	*6.01%*	*85.9*	*-22.5*	*-21.0*	*0.9*	*25.9*	*-21.0*
Min	*3.99%*	*64.6*	*-28.3*	*-25.4*	*-4.8*	*19.9*	*-25.4*

Summary: BMD High RAP-Rejuvenated Design



Field Implementation
NCAT & Other Examples

Examples of Current or Considered BMD Systems

Agency:	New Jersey DOT	Chicago DOT	Illinois Tollway	Illinois DOT	City of Janesville	Virginia DOT	City of Columbus	ODOT (Trial)	City of Phoenix (Trial)
Cracking Test	Overlay Tester	DCT	DCT + IFIT	IFIT	DCT + IFIT	IDEAL-CT	IDEAL-CT	IDEAL-CT	IFIT
Rutting Test	APA	Hamburg	Hamburg	Hamburg	Hamburg	APA	HWT	HWT	HWT to approve RA
Binder Specification	None	Extracted pass PG XX-22, ΔTc > 5	None	None	Extracted pass PG XX-16	None	Extracted pass climate PG + 6	Extracted pass climate PG + 6	Meet virgin grade of 70-28
QC Process	Trial Strip + performance test	Extracted PG	Trial Strip + Performanc e test	TBD	Performance test	Surrogate tests, TBD	IDEAL-CT	IDEAL-CT	Basic VMD QC
State of Implementation	Active as of 2018	Active as of 2018	Active as of 2018	Active as of 2019	Active as of 2017	Trial spec as of 2019	Implement ation in 2022	Trial in 2021	Trials in 2021

Field Evaluation Projects

NCAT: Warm Climate

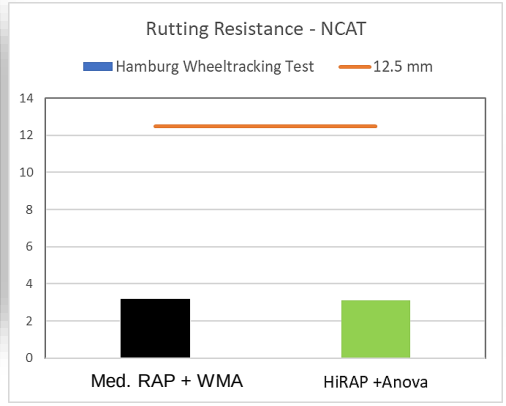
- 30% RAP (24% ABR); PG64-22 Binder + Warm Mix Additive
- 45% RAP (38% ABR); PG64-22 Binder + Rejuvenator
- Aggregates and RAP were shipped in from Virginia for the project

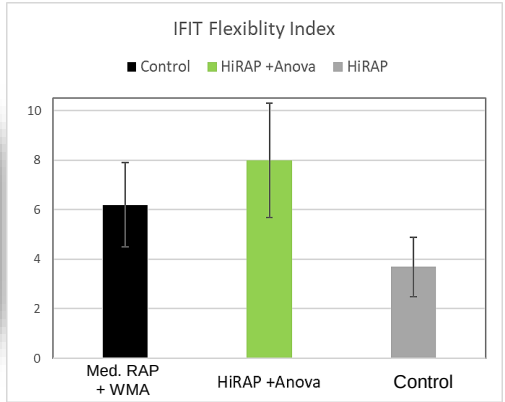
MNROAD: Cold Climate

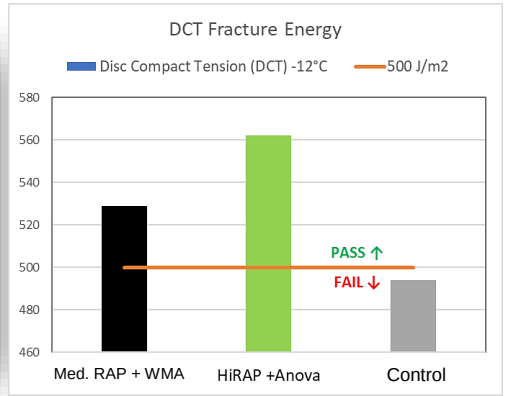
- 25% RAP (20% ABR); PG58-28 Binder
- 45% RAP (31% ABR); PG5828 Binder + Rejuvenator
- Aggregates and RAP were supplied locally in Minnesota for the project

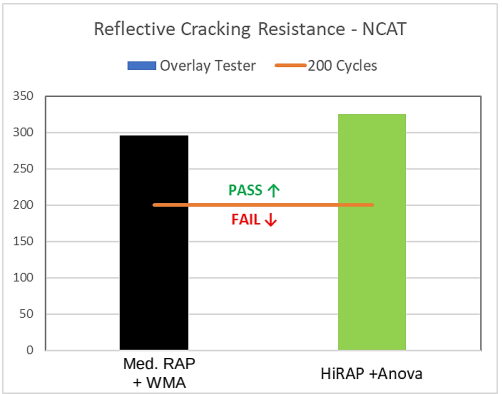
NCAT High RAP and WMA Project

- Designs were done using BMD system under consideration by VADOT at the time (IDEAL vs. APA)
- Rejuvenation of the high RAP mix achieved comparable passing performance compared to the WMA mix.
- Both the RA and WMA mix outperform the high-RAP control mix.







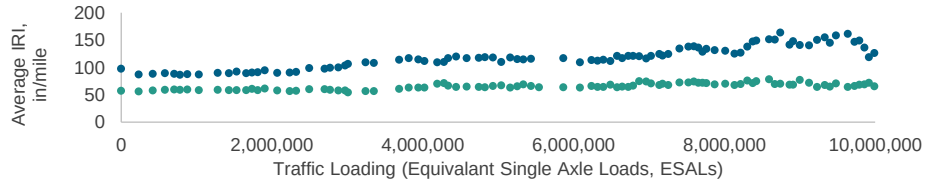


NCAT Field Performance

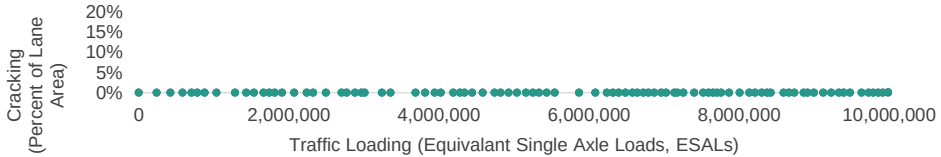
To demonstrate performance Cargill built a test section on the NCAT track using the typical 30% RAP mix with Cargill Anova® WMA, and 45% RAP with Cargill Anova® Rejuvenator.

After 10 million loadings, zero cracks appeared in the test section

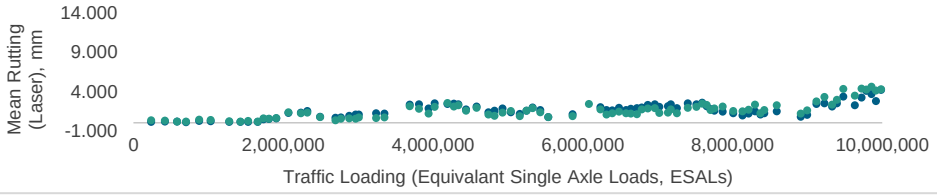
Maintaining Smooth Ride



0 Cracking



No Rutting



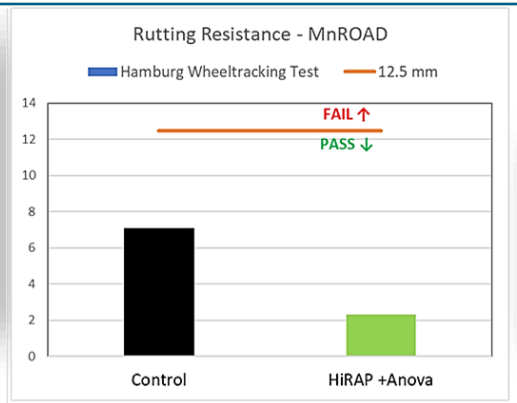
30% RAP + WMA 45% RAP + RA

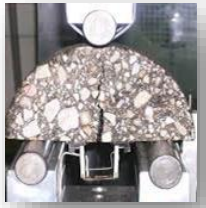
* Data provided and measured by NCAT using plant produced mix.

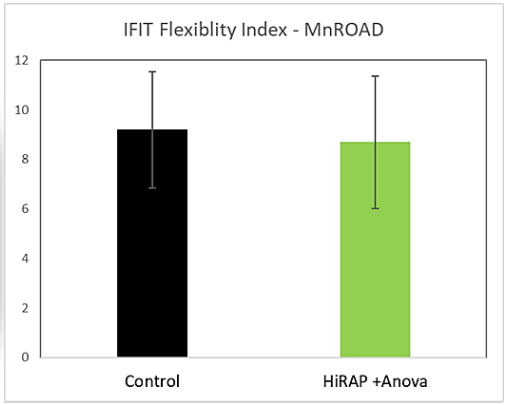
MNROAD High RAP Rejuvenated Project

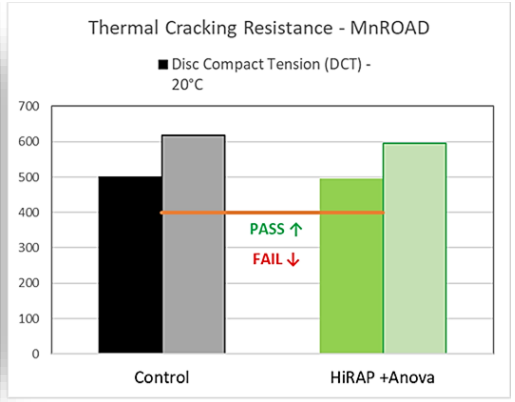
Designs were done using BMD system under consideration by MNDOT at the time (DCT vs. Hamburg)

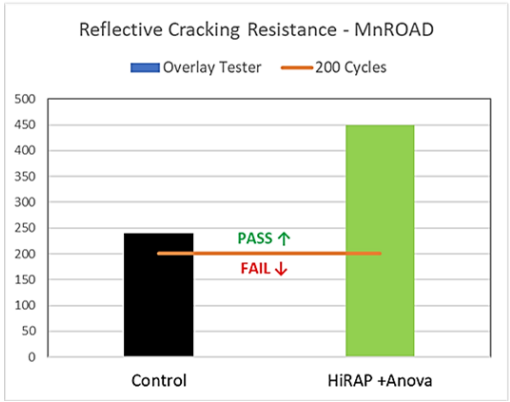
Rejuvenation of the high RAP mix achieved comparable passing performance compared to the Low RAP control mix.











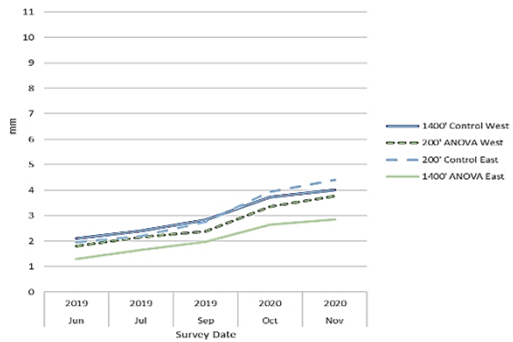
MNROAD Field Performance

To demonstrate performance against the typical 25% RAP mix, Cargill built a test section on the MNROAD track using 45% RAP and Cargill Anova® Rejuvenator.

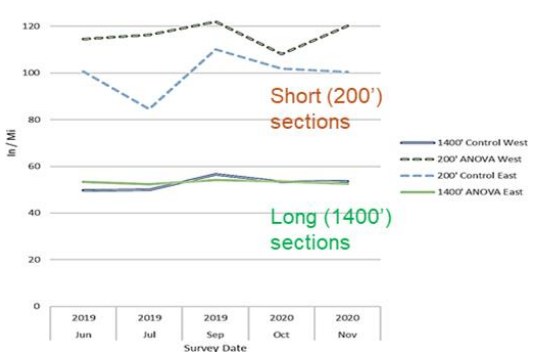
After 2.5 million loadings, fully meeting performance expectations

- About 800,000 ESALs of loading per year since 2018.
- No cracking beyond expected reflective cracking from base course observed, equivalent to control.
- Sections showing good rutting performance. Cargill Anova sections have slightly lower permanent deformation.
- Smoothness has remained consistent since construction. This especially clear on the sufficiently long sections.

No Rutting



Maintaining Smooth Ride

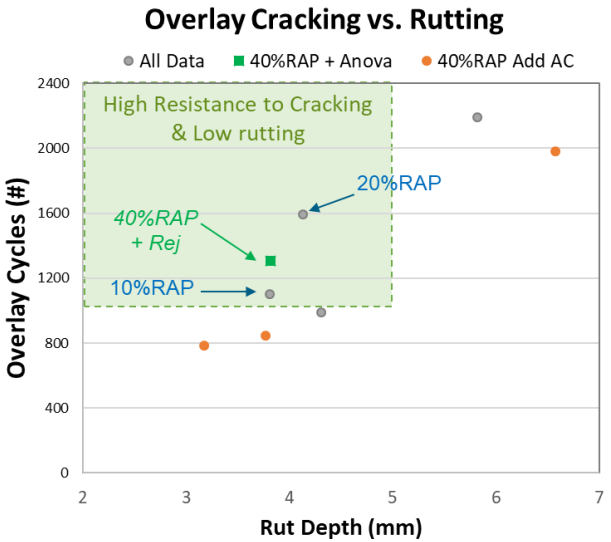


Balanced Mix Design for Delaware:
DelDOT Approved Mix

1. Plant samples were prepared based on Cargill dosage recommendations and HMA producer's mix design.
2. DOT directly sampled plants and carried out Laboratory performance tests.
3. Binder extraction tests were conducted on lab samples by Cargill.

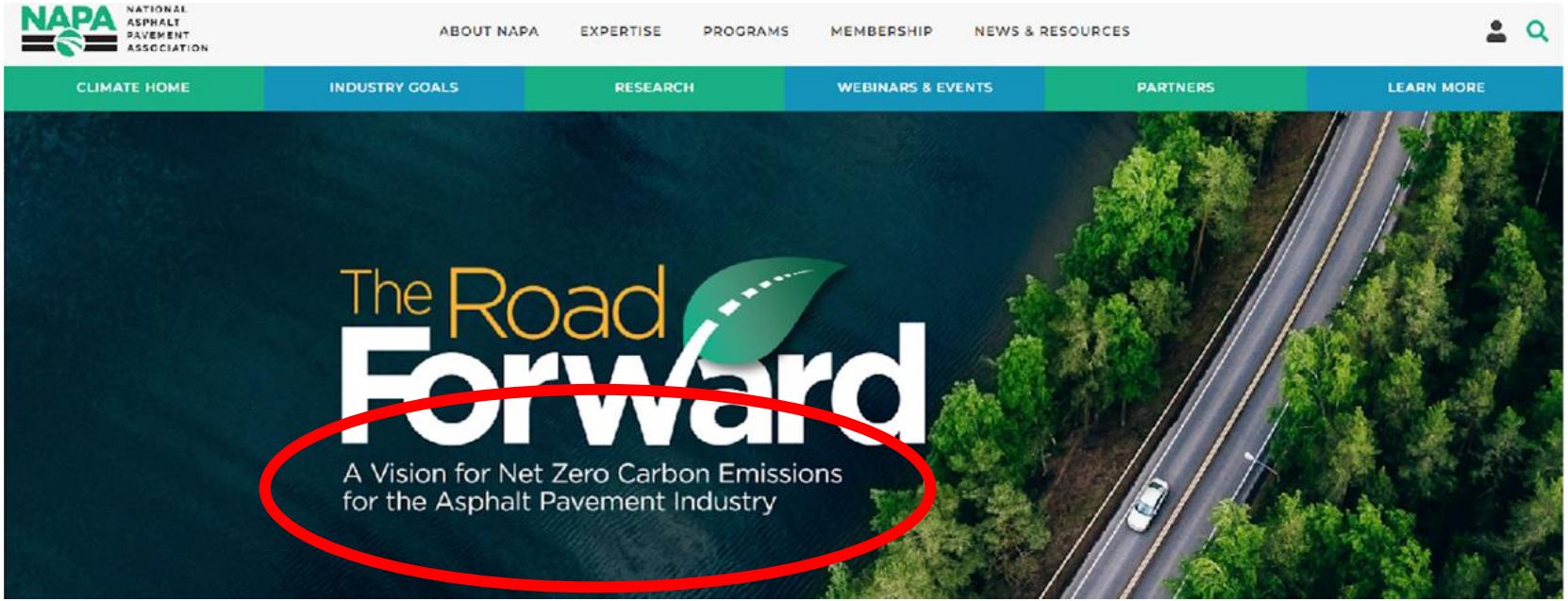
- 25% RAP + 4%RAS + Rejuvenator vs. Control: 25% RAP
- 40%RAP + Rejuvenator vs. Control: 25% RAP
  - AC% optimized by VMD, standard densities
  - Performance checked with Overlay Tester, IdealCT and Hamburg

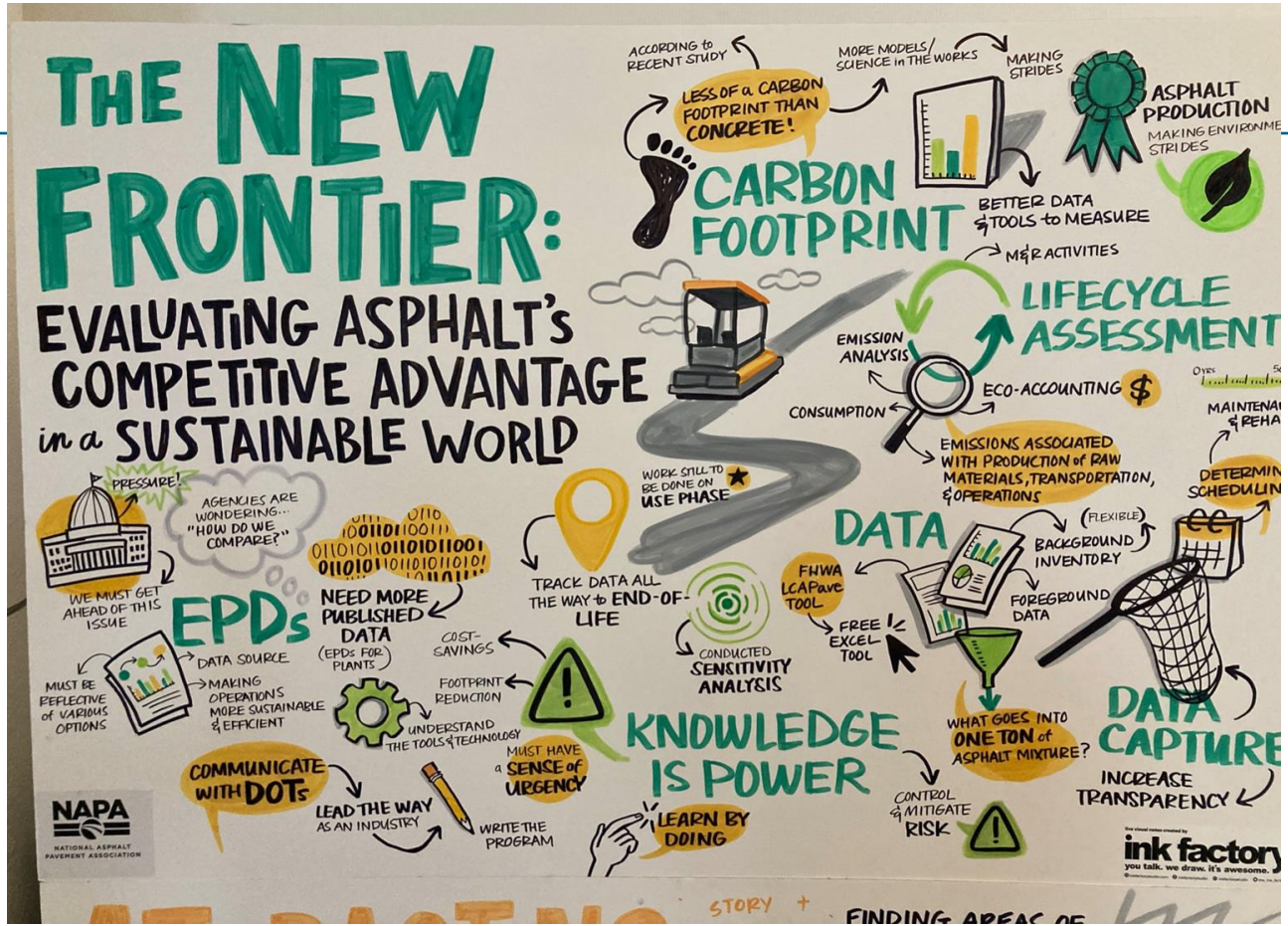
Description	Extract AC %	HT PG	LT S PG	LT m PG	ΔTc
25%RAP + 4%RAS Rej	5.58%	82.5	-22.4	-22.2	-0.2
35%RAP + 5%RAS Rej	5.91%	73. 9	-23.6	-26.6	2.9



Why this Matters!

https://www.asphaltpavement.org/climate





Conclusions and Summary

- Today rejuvenation technology has been used successfully for years in millions of tons of HMA.

- Implementation of High RAP + Rejuvenators in both “non-spec” commercial mixes and spec’d Agency mixes can be highly practical and feasible today:
  - Work with rejuvenator supplier on the appropriate dosage to produce higher RAP mixes with quality consistent with normally supplied mix designs.

- The NCAT and MNROAD studies demonstrated that even for high-performance and high-service pavements a framework can be used that provides **transparency and reliability for all stakeholders**:
  - Step 1: Recycling Agent Property Certification (e.g. through ASTM D4552-20) - by supplier
  - Step 2: Initial dosage determination based on rheology, led by supplier
  - Step 3: Balanced Mix Design (BMD) process, led by producers
  - Step 4: Robust quality management practices by all parties