Effect of Silo Storage Time on the Characteristics of Virgin and RAP HMA Mixtures

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Acknowledgements

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- Research Partners
  - Dr. Bennert, Rutgers University
  - Dr. Kim, North Carolina State University
  - Dr. Mogawer, University of Massachusetts Dartmouth
  - Gerry Reinke, Mathy Construction
- Cindy LaFleur, Callanan Industries

Silo Storage Study

- HMA stored in silos before delivery to site
- High temperatures to maintain workability
- Short-term aging?
- Storage time not controlled

Source: www.hotmixmag.com

TPF 5(230)

- Phase I
  - Different RAP contents, PG grades
- Phase II
  - Silo storage study
  - PG 64-28 Virgin and RAP mixtures
  - Virgin contaminated with PG 76

Source: www.jfallenco.com

Objectives

- Measure effect of storage time on Virgin, RAP
- Determine if changes are due to aging from silo and/or blending

Source: www.srwestend.com

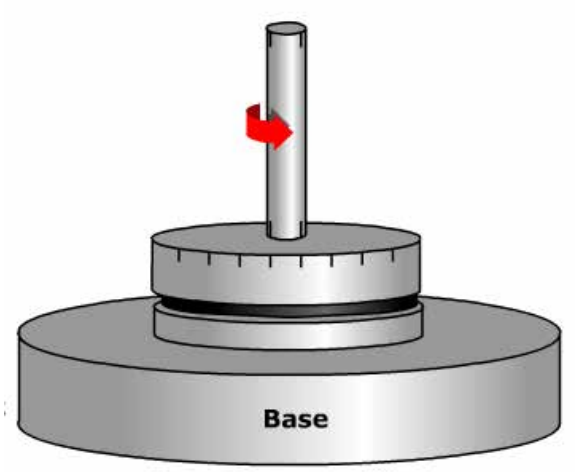
Materials

- Virgin mixture
  - PG 64-22
  - 12.5 mm NMAS
  - 7.0 ± 0.5% air voids
  - 0, 2.5, 5, 7.5 hour storage times
- 25% RAP mixture
  - PG 64-28
  - 12.5 mm NMAS
  - 6.0 ± 0.5% air voids
  - 0, 2.5, 5, 7.5, 10 hour storage times
- Mixture discharge temperatures: ~175º C (350º F)

Source: www.hellotrade.com

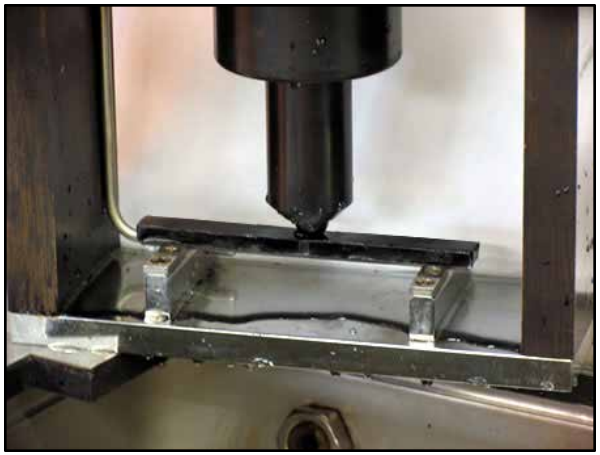
Binder Testing Methods

- Dynamic Shear Rheometer
- Bending Beam Rheometer
- Rolling Thin Film Oven aging on virgin binder



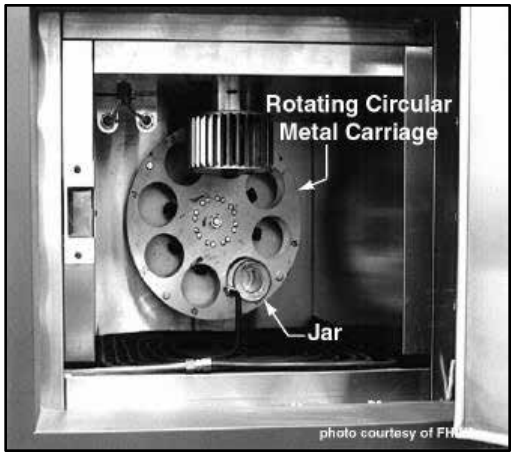
DSR

Source: www.pavementinteractive.org



BBR

Source: www.pavementinteractive.org



RTFO

Source: www.pavementinteractive.org

Mixture Testing Methods

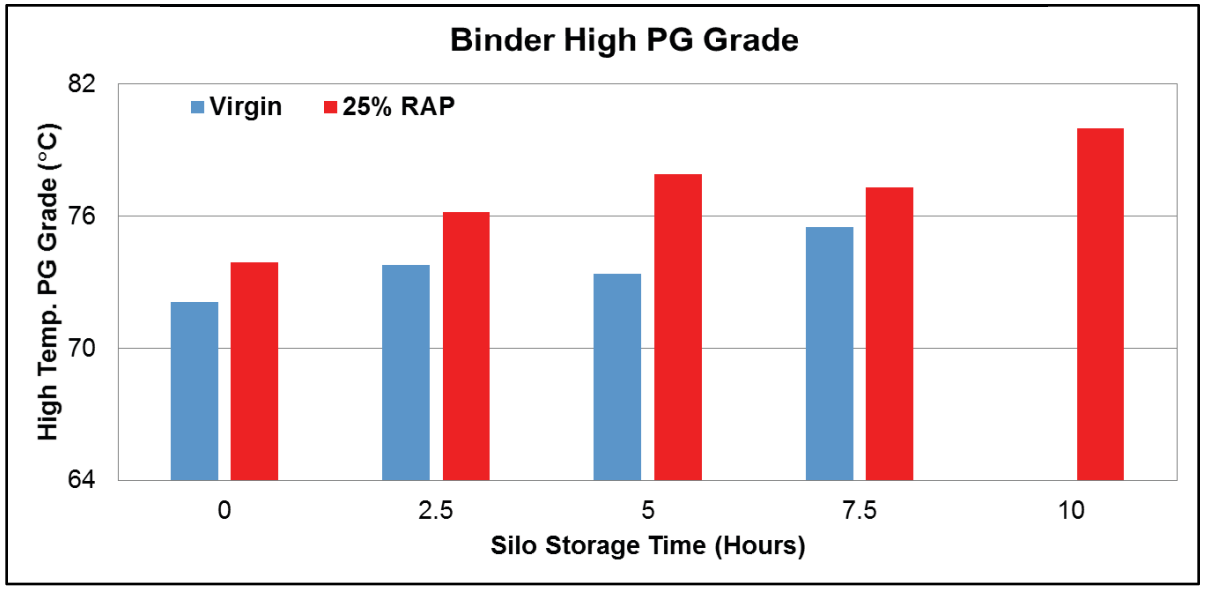
- Dynamic Modulus
- S-VECD Fatigue
- LVECD (Layered ViscoElastic Critical Distresses)
- DCT (Disk-Shaped Compact Tension) Test
- TSRST (Thermal Stress Restrained Specimen Test)

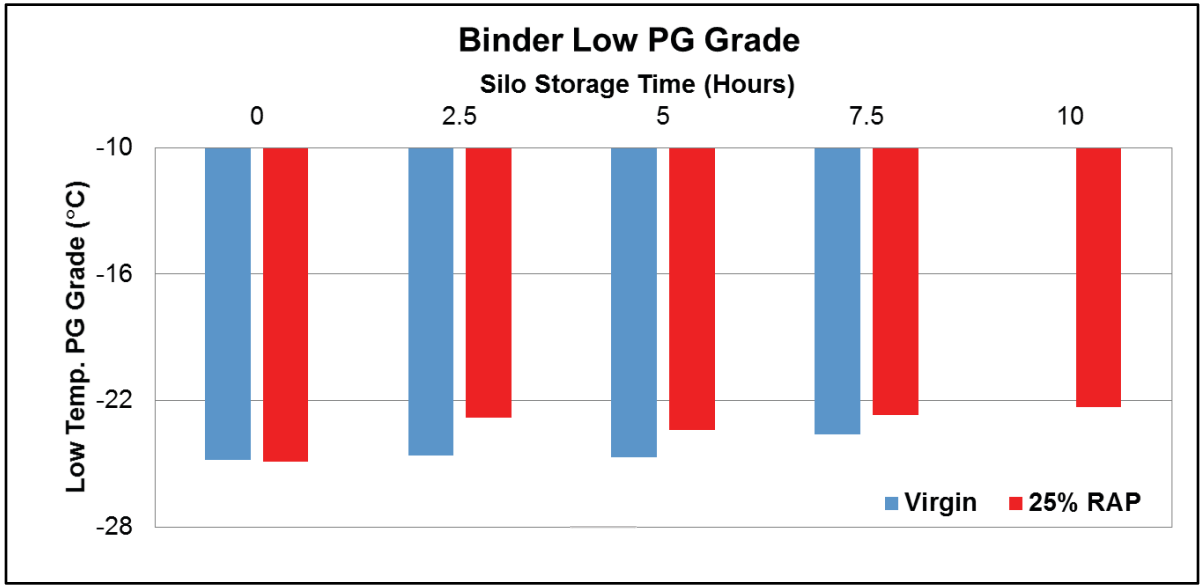
S-VECD

DCT

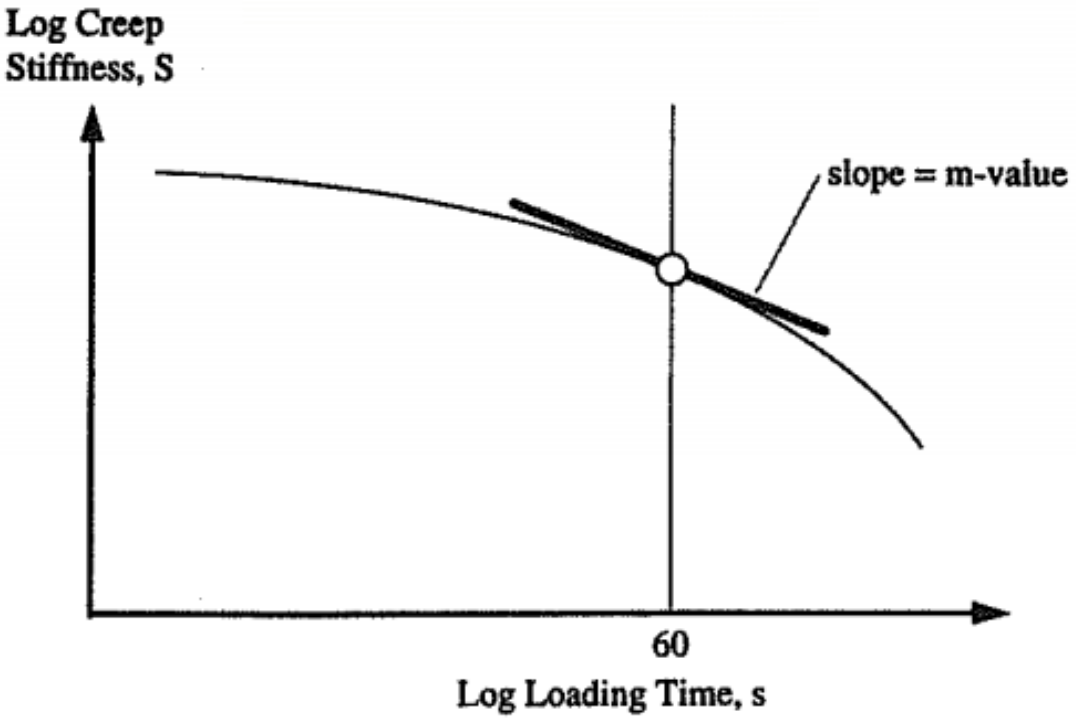
TSRST

Binder: PG Grading





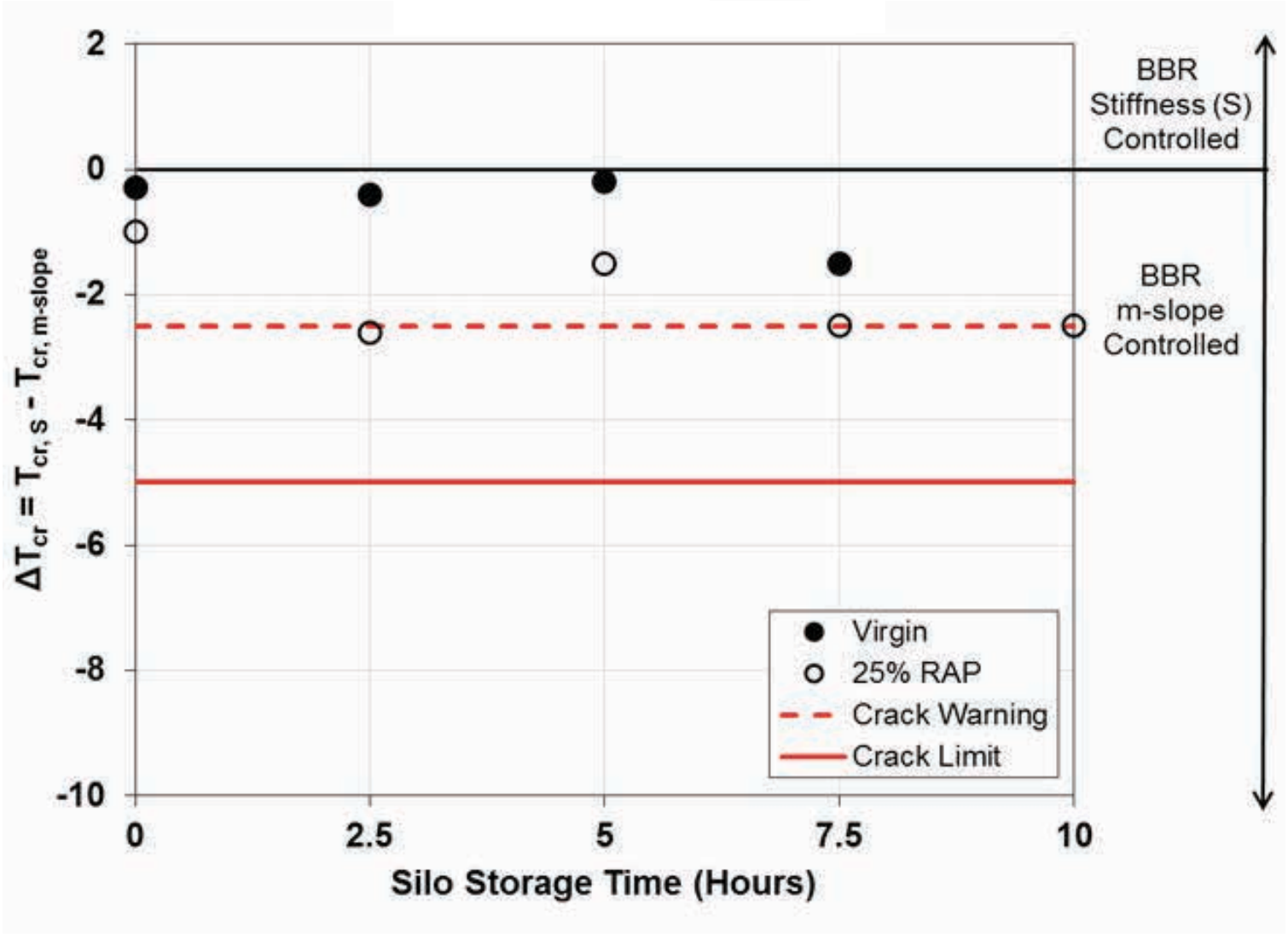
Binder: ΔT_{cr}



Source: Brown, Kandhal, et al., 2009

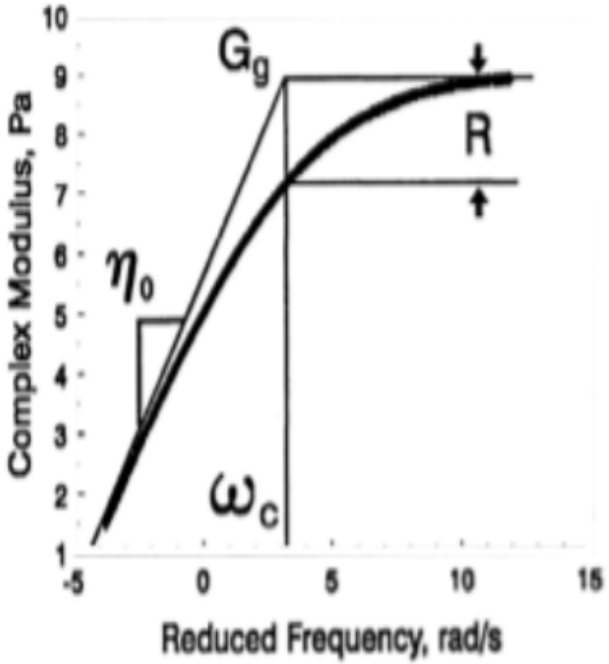
- $T_{cr\ (Stiffness)}$ = Critical low temp. where S(60) = 300
- $T_{cr\ (m\text{-}value)}$ = Critical low temp. where m(60) = 0.3
- $\Delta T_{cr} = T_{cr\ (Stiffness)} - T_{cr\ (m\text{-}value)}$

Binder: ΔT_{cr}



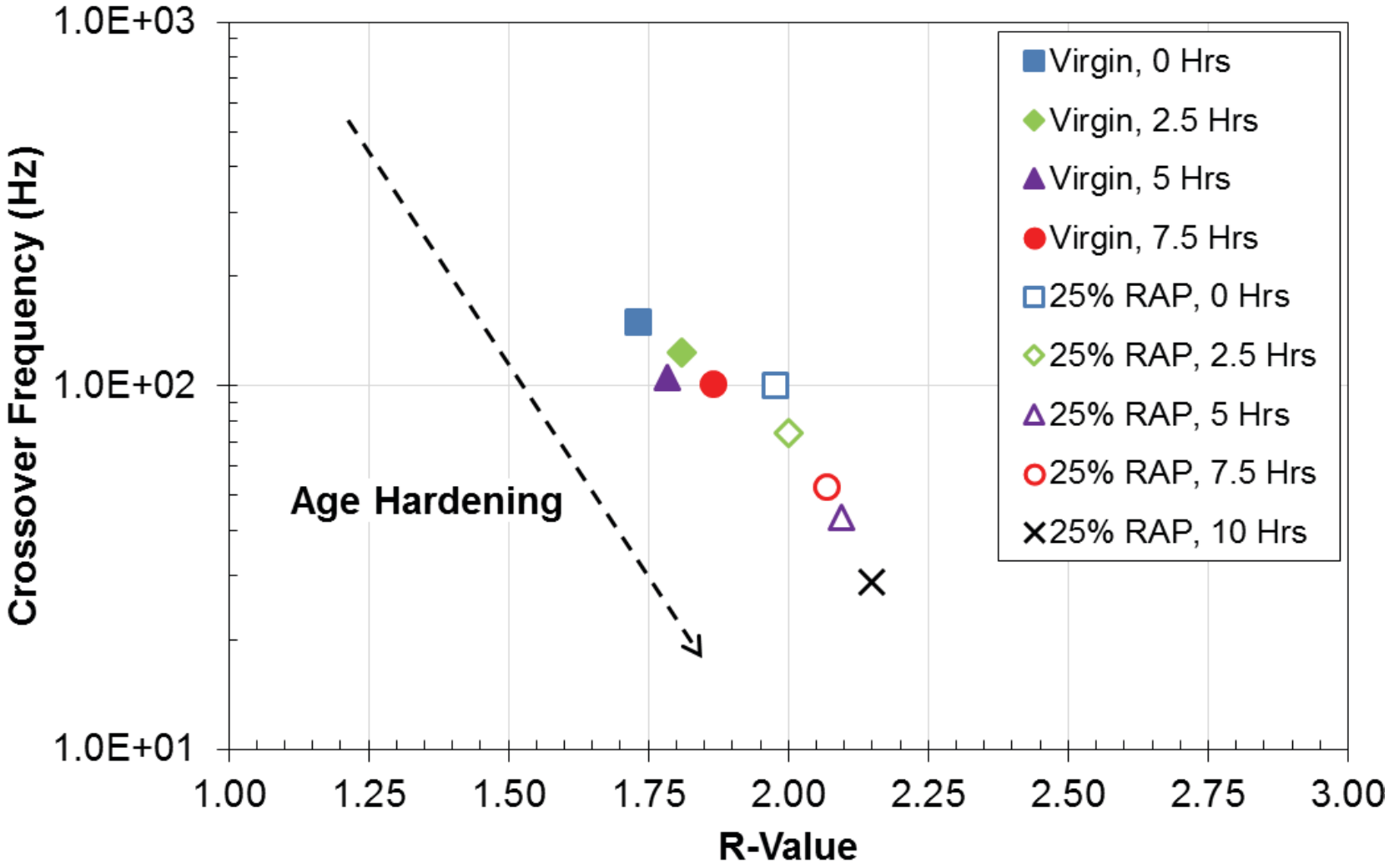
Binder: Rheological Indices

- CAM master curve parameters ω, R
- Crossover frequency, ω
- Rheological index, R-value

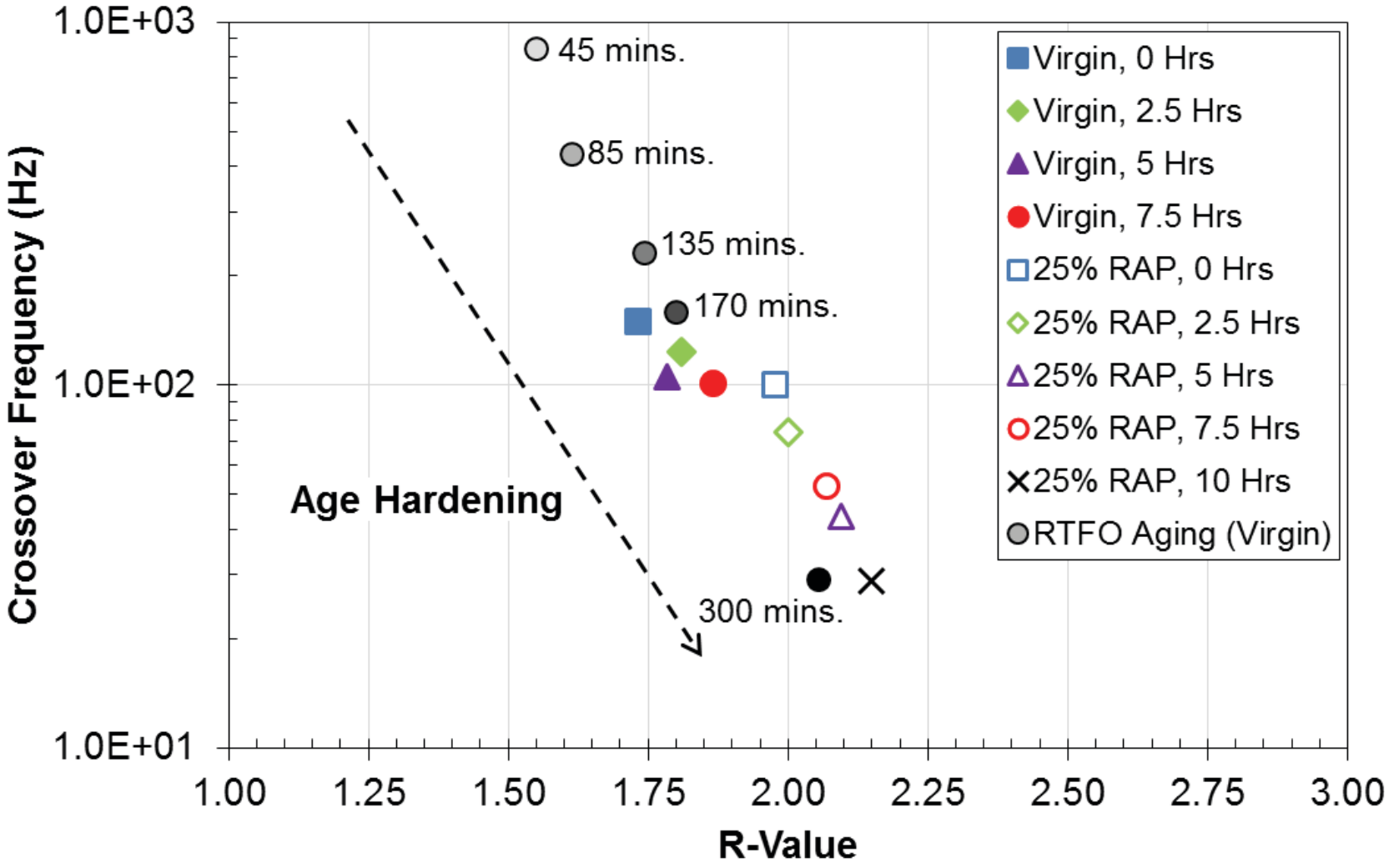


Source: Anderson, Rowe, and Christen, 2008

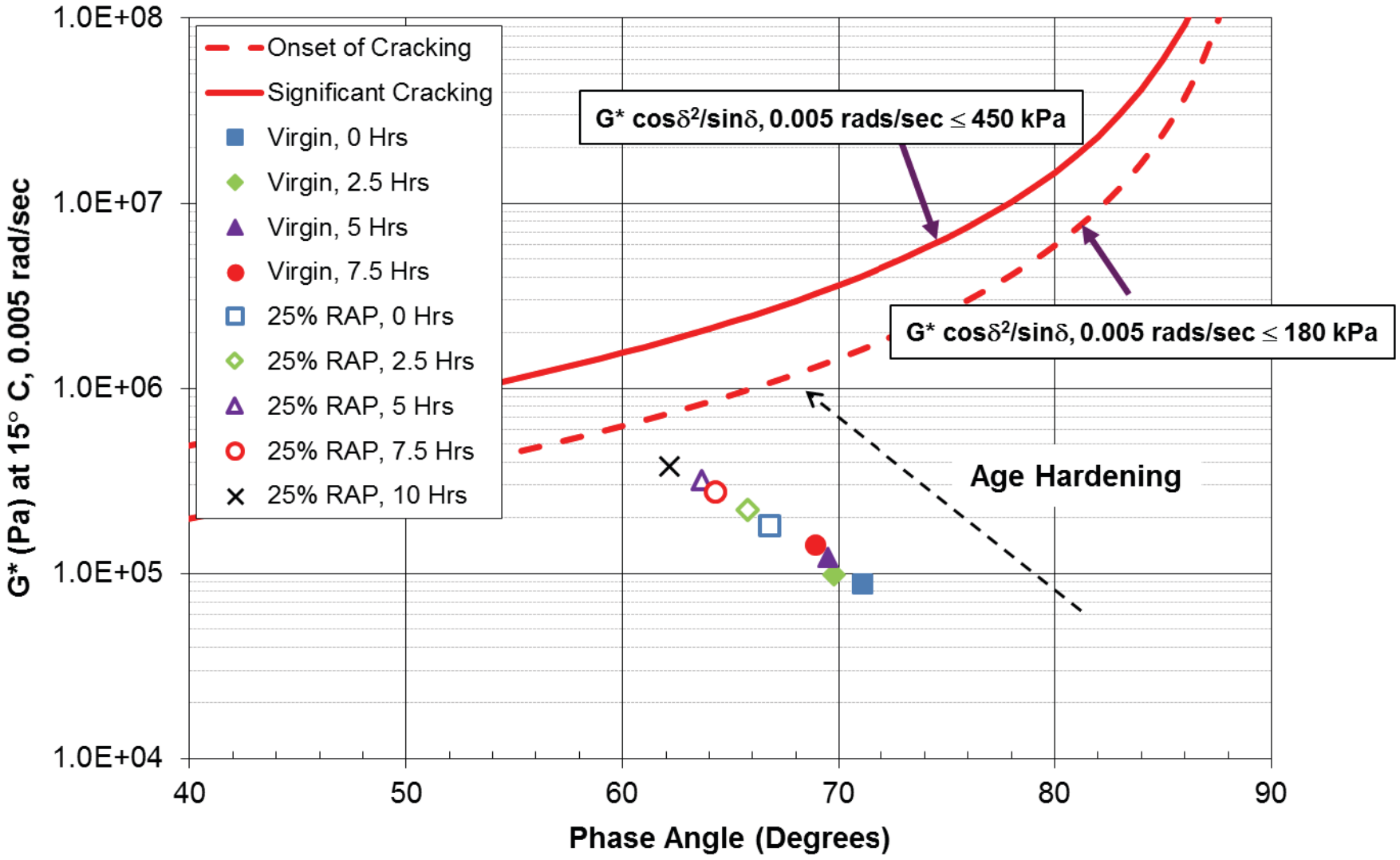
Binder: Rheological Indices



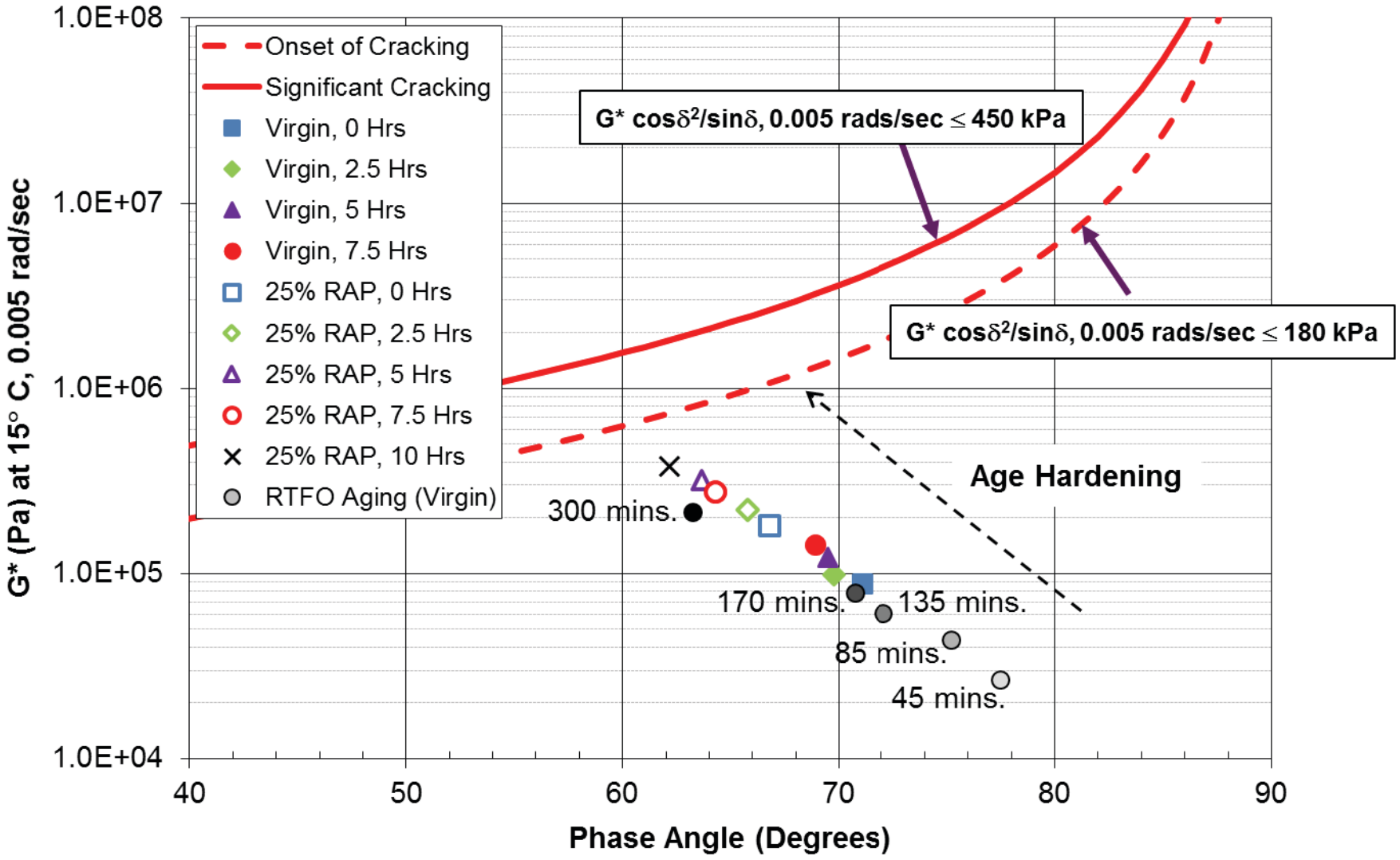
Binder: Rheological Indices



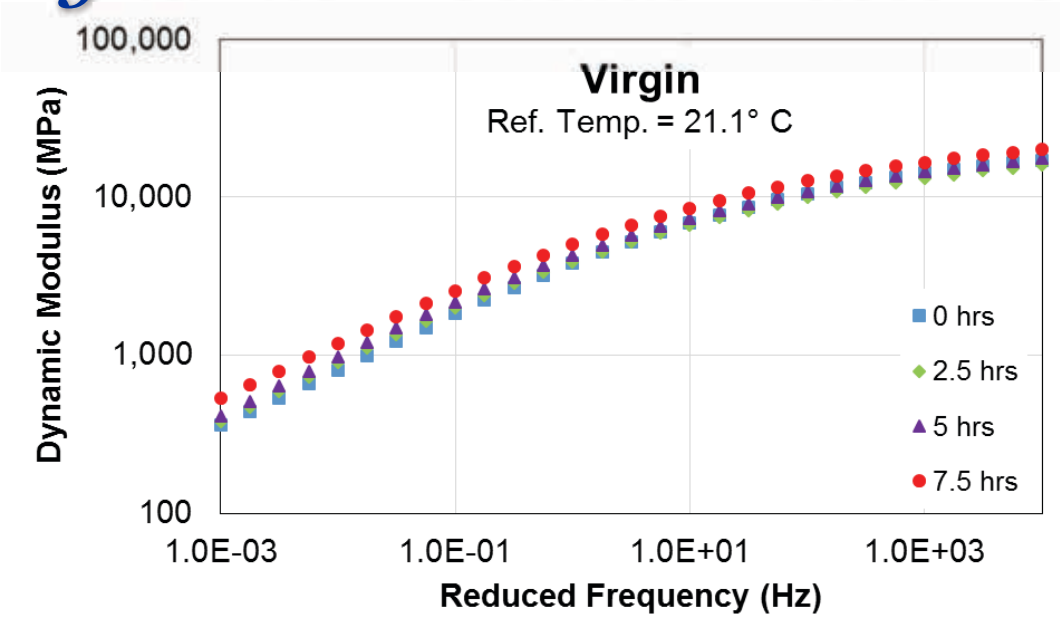
Binder: Glover-Rowe Parameter

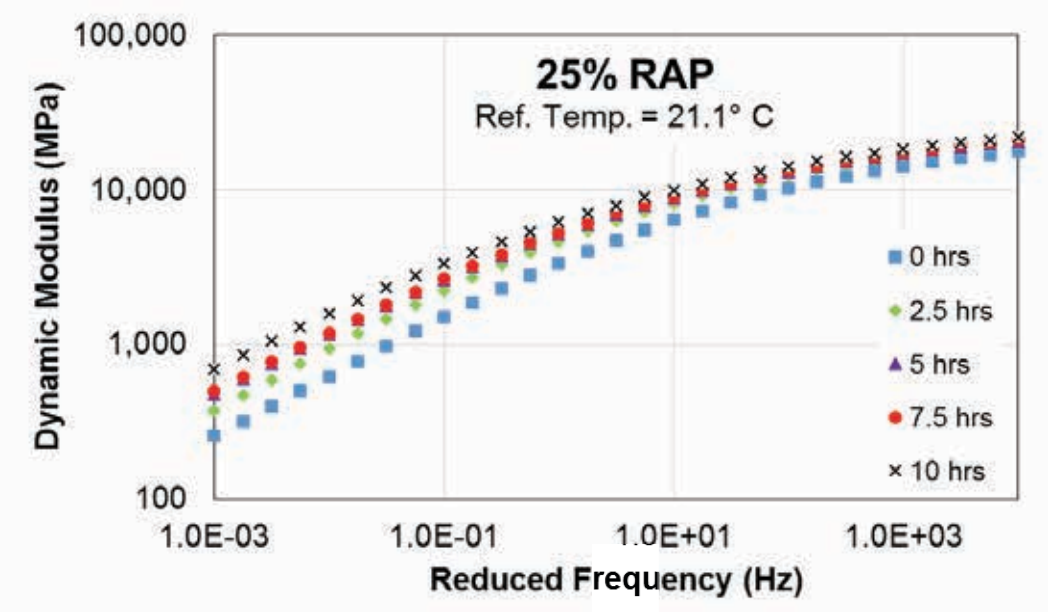


Binder: Glover-Rowe Parameter

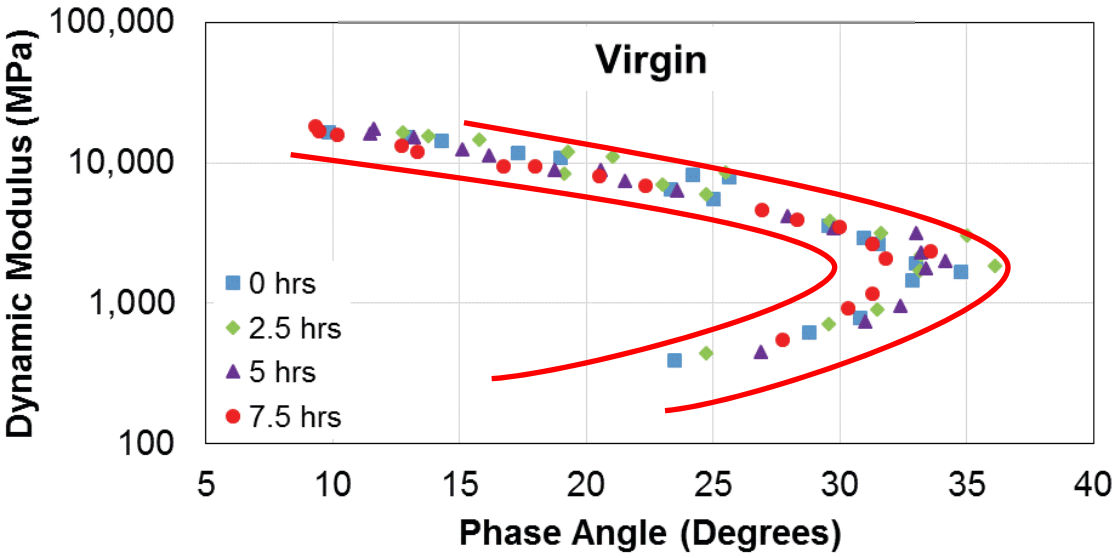


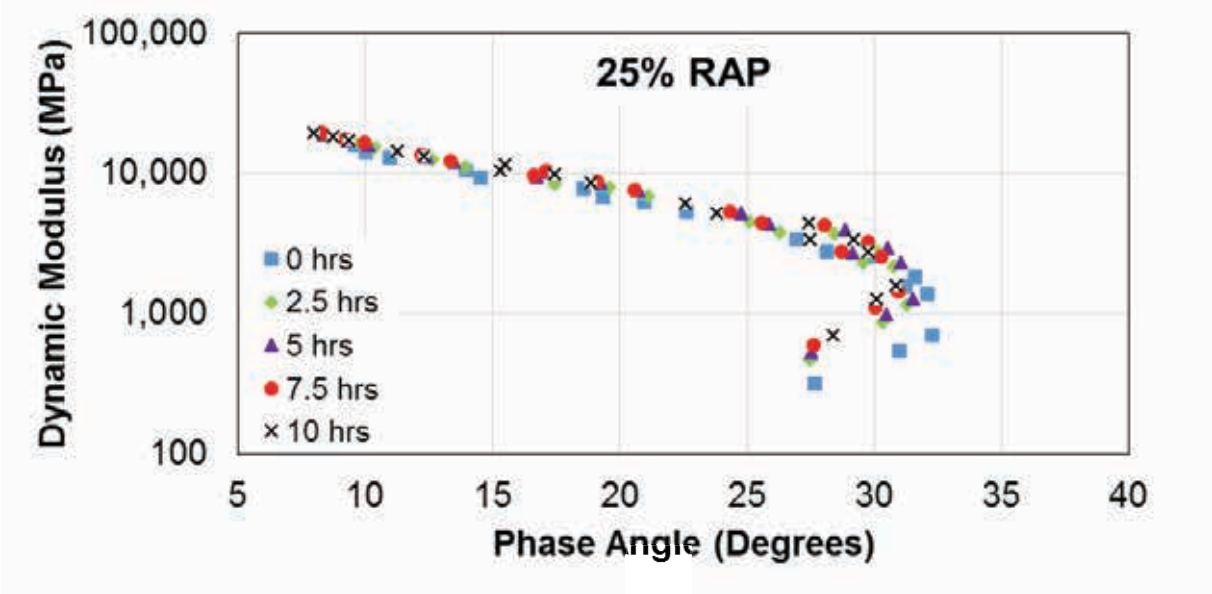
Dynamic Modulus Master Curves



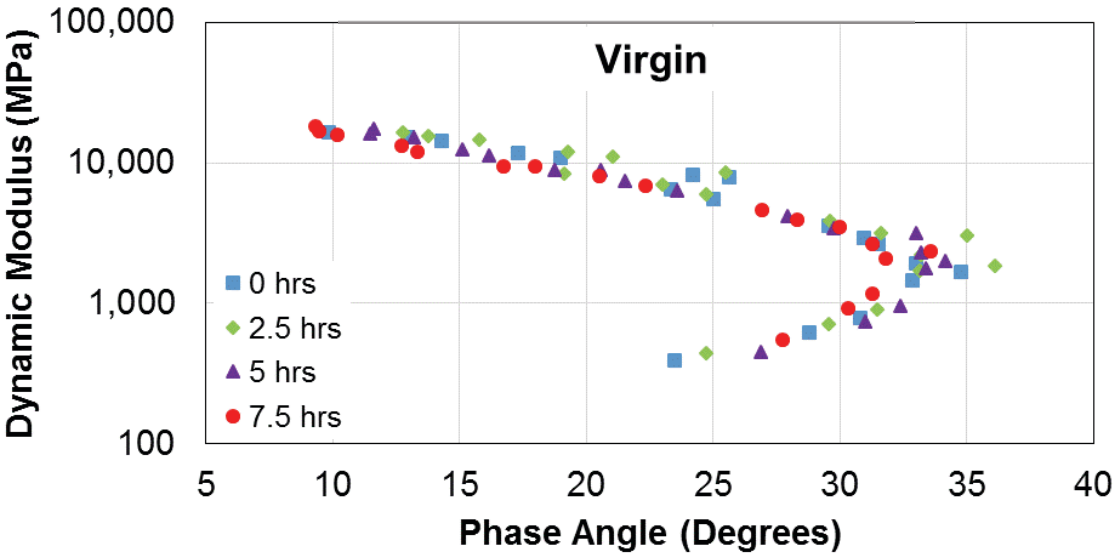


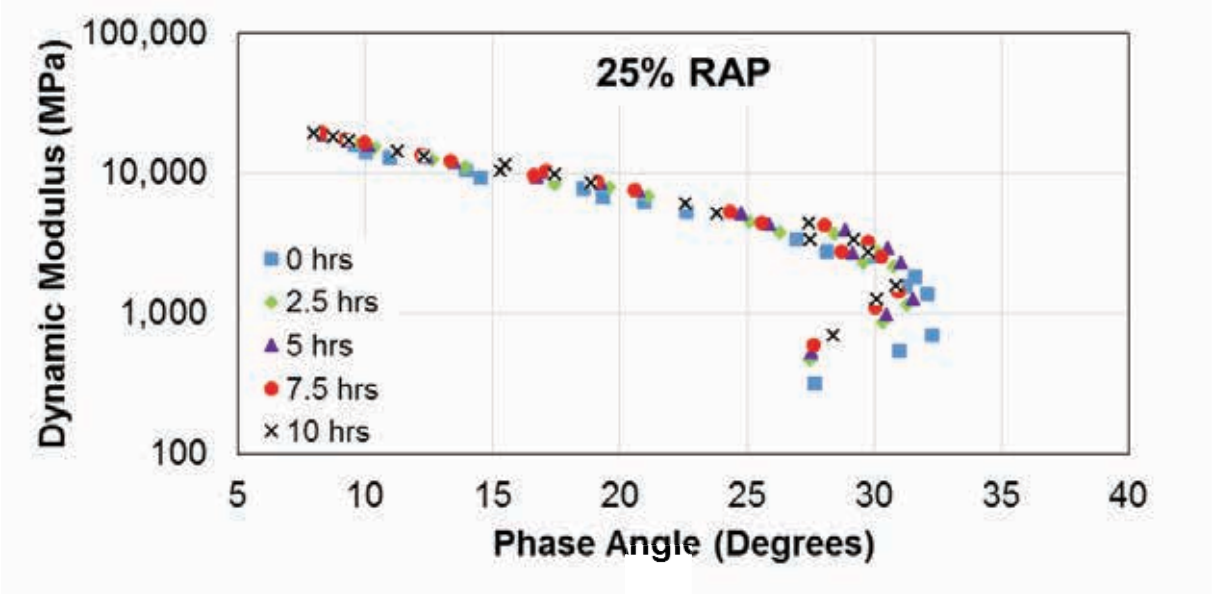
Black Space


Virgin
Dynamic Modulus (MPa)
100,000
10,000
1,000
100
0 hrs
2.5 hrs
5 hrs
7.5 hrs
5
10
15
20
25
30
35
40
Phase Angle (Degrees)

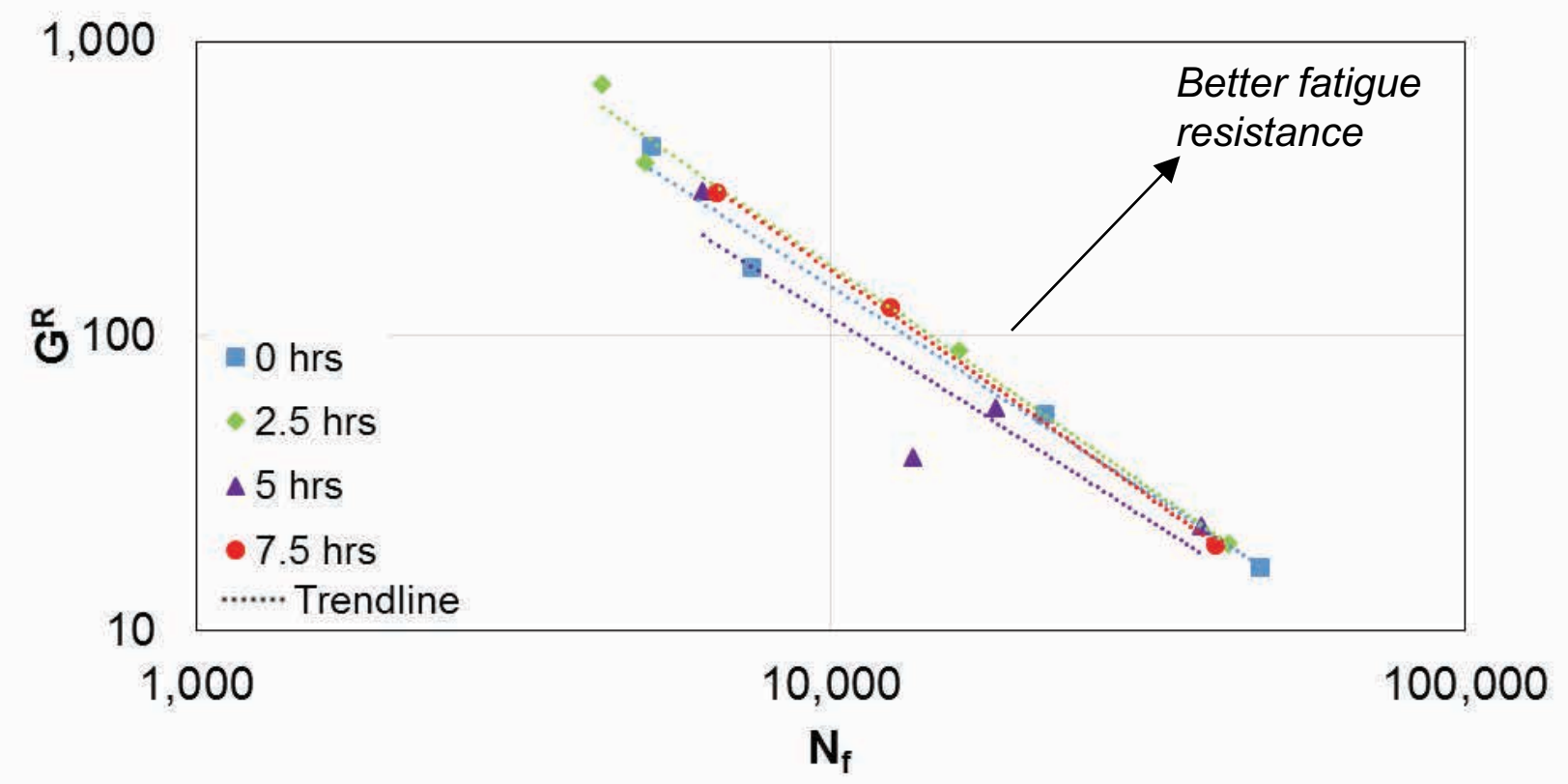

25% RAP
Dynamic Modulus (MPa)
100,000
10,000
1,000
100
0 hrs
2.5 hrs
5 hrs
7.5 hrs
10 hrs
5
10
15
20
25
30
35
40
Phase Angle (Degrees)

Black Space


Virgin
Dynamic Modulus (MPa)
100,000
10,000
1,000
100
0 hrs
2.5 hrs
5 hrs
7.5 hrs
5
10
15
20
25
30
35
40
Phase Angle (Degrees)


25% RAP
Dynamic Modulus (MPa)
100,000
10,000
1,000
100
0 hrs
2.5 hrs
5 hrs
7.5 hrs
10 hrs
5
10
15
20
25
30
35
40
Phase Angle (Degrees)

Fatigue: G^R-N_f



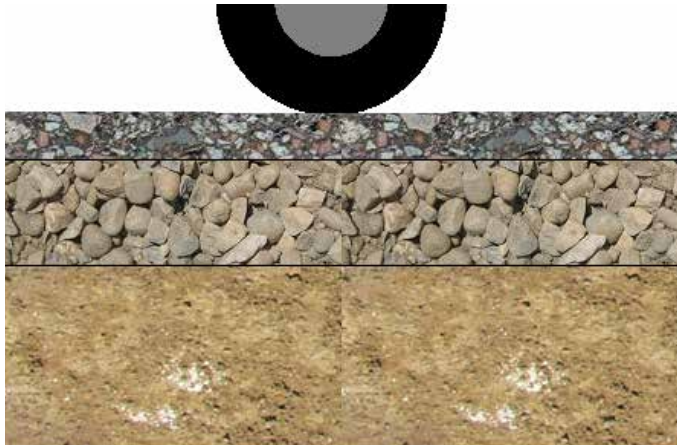
Virgin mix only

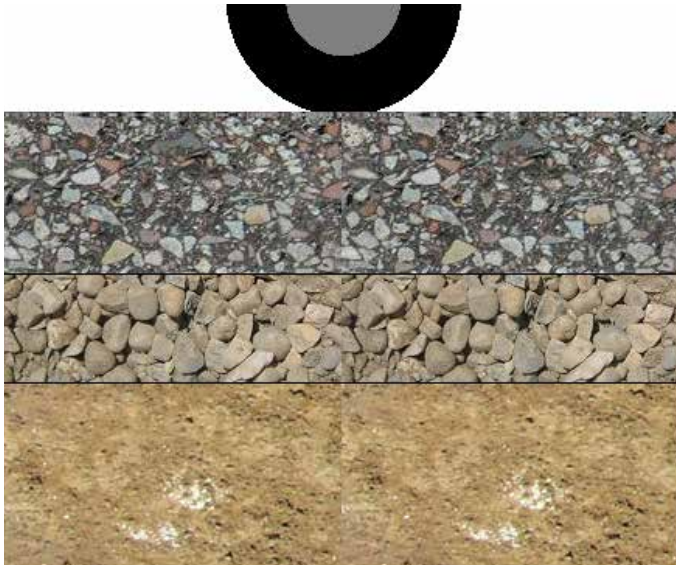
G^R: Fatigue failure criterion; characterizes damage accumulation

N_f: Number of cycles to failure

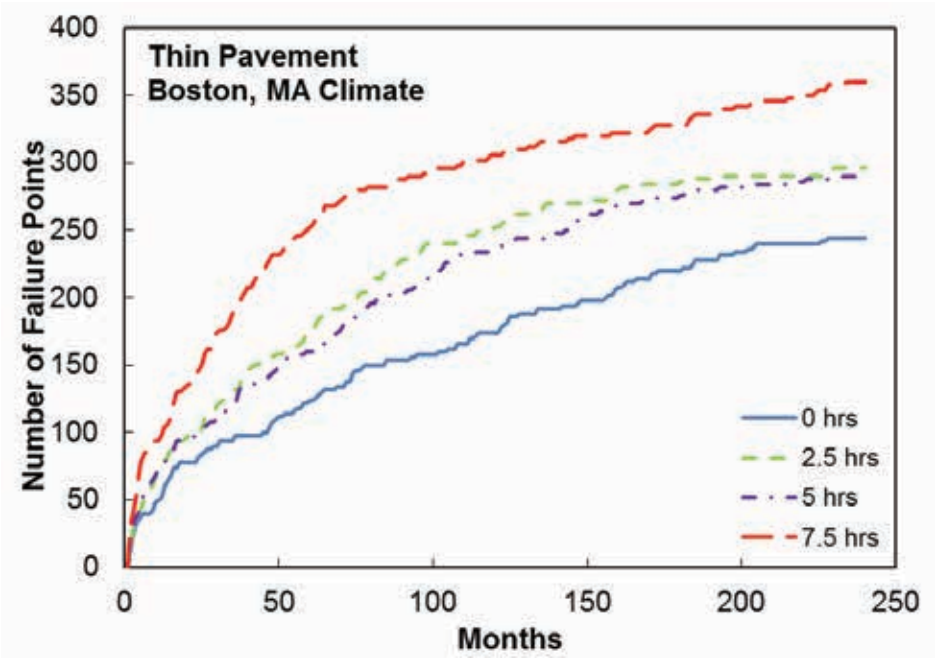
LVECD Pavement Life Evaluation

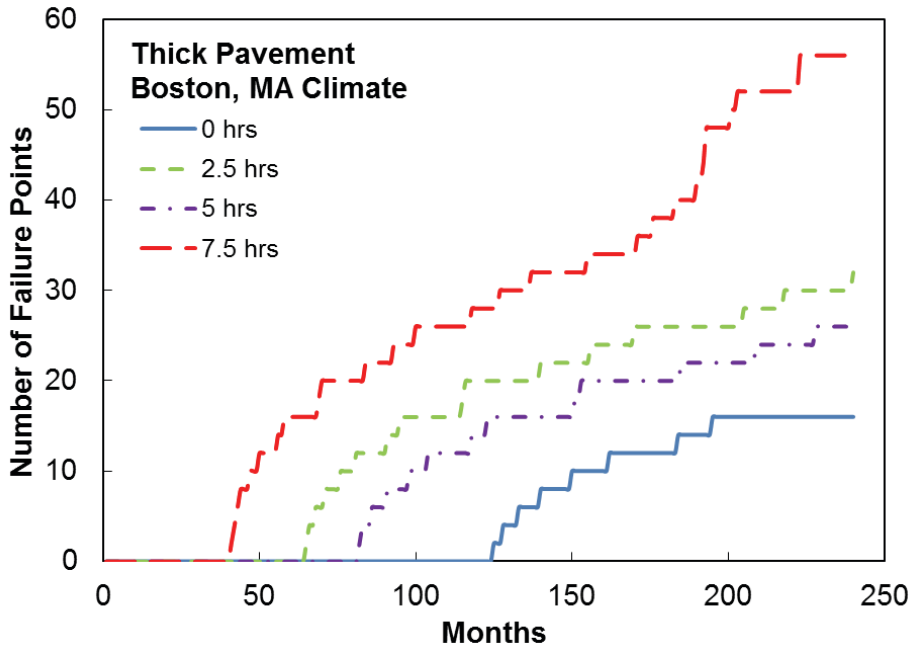
- Layered Viscoelastic Critical Distresses
- Uses Dynamic modulus & S-VECD fatigue results
- Pavement structure:
  - Asphalt layer: 100 mm (thin), 300 mm (thick)
  - Aggregate base: 200 mm, 350 MPa
  - Subgrade: 100 MPa





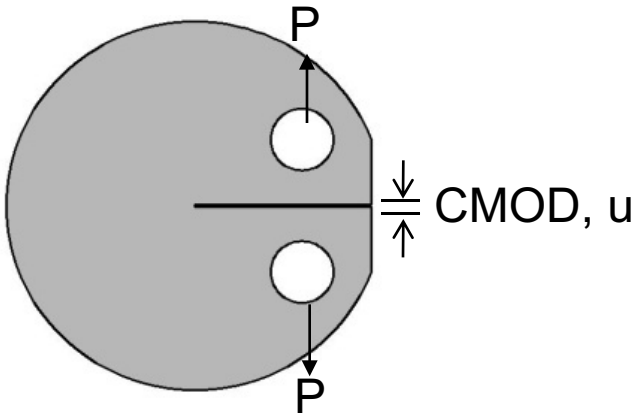
LVECD Pavement Life Evaluation

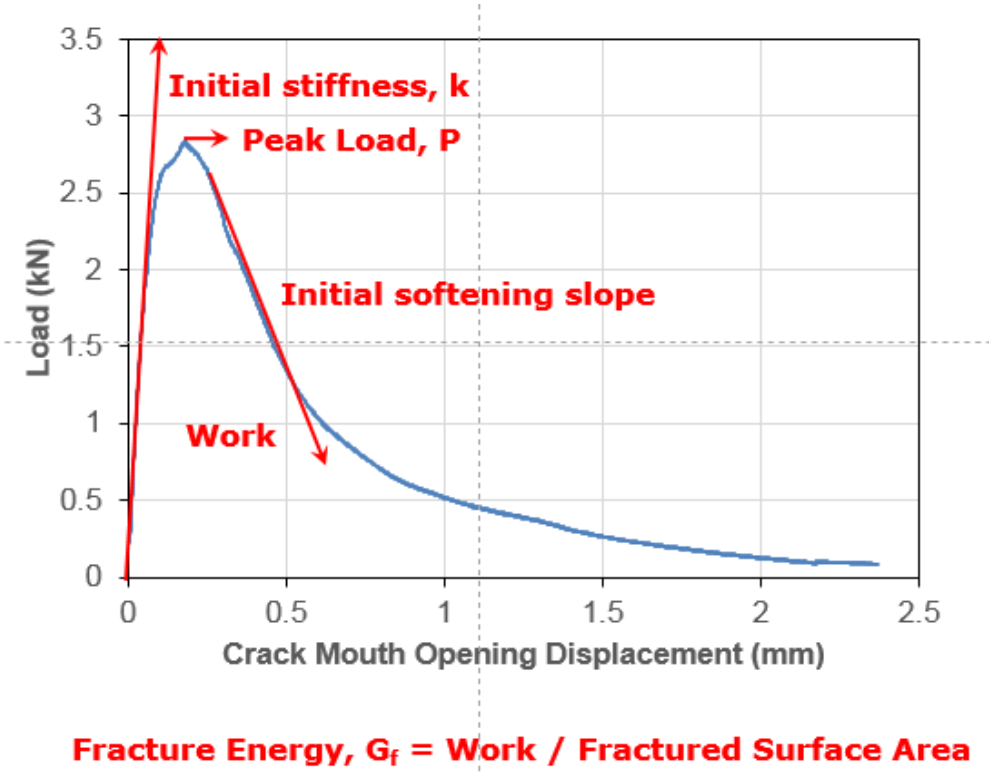




DCT Testing

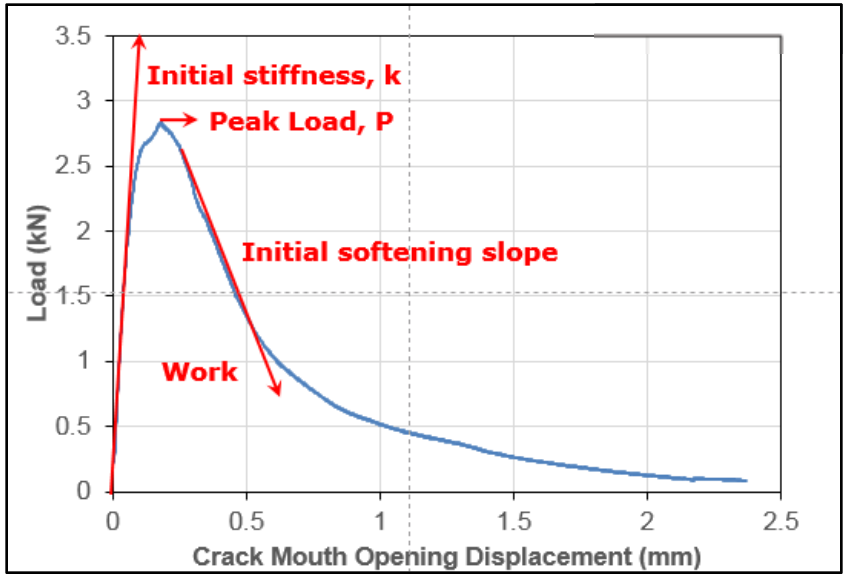
- Disk-Shaped Compact Tension Test
- Loading Rate:
  - Crack Mouth Opening Displacement
  - CMOD = 1.0 mm/min

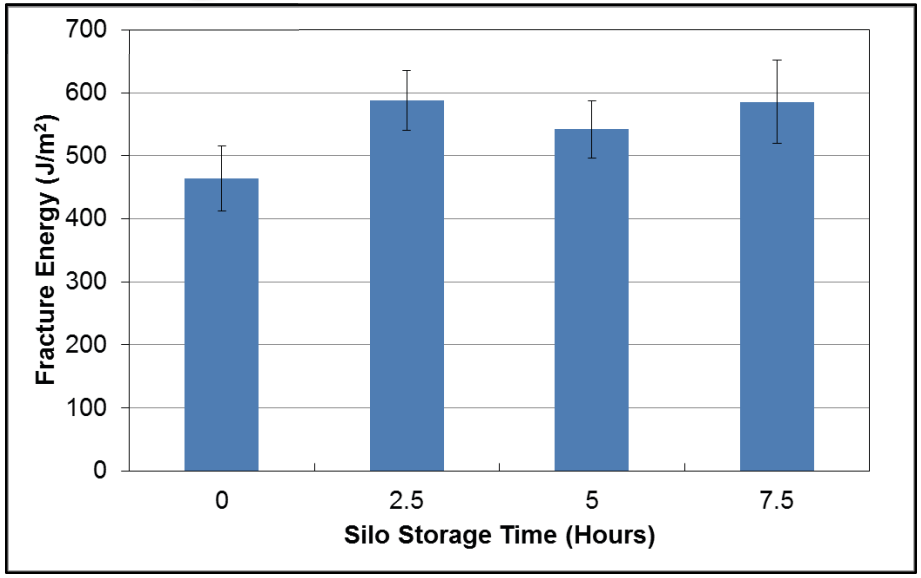


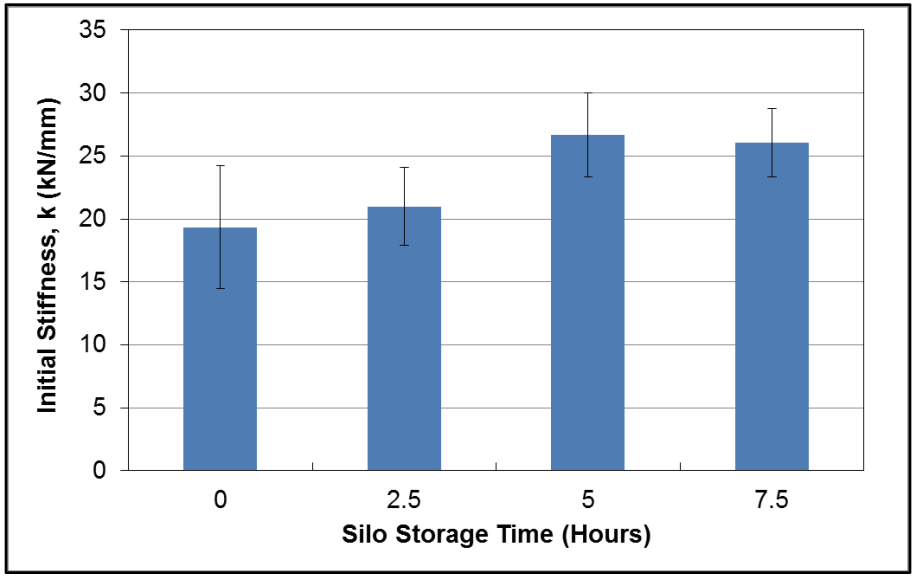


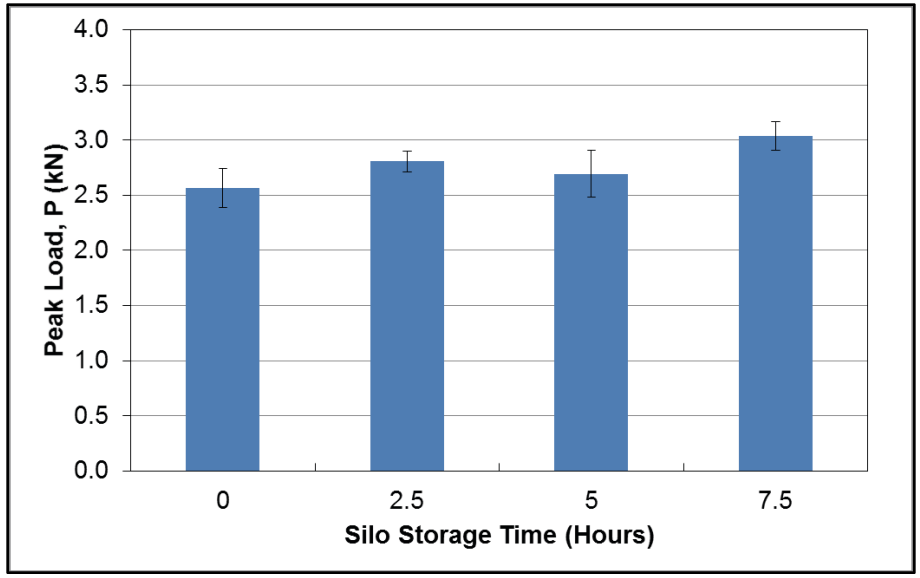
Fracture Energy, G_f = Work / Fractured Surface Area

DCT Testing


Initial stiffness, k
Peak Load, P
Initial softening slope
Work
Load (kN)
Crack Mouth Opening Displacement (mm)
0
0.5
1
1.5
2
2.5
3
3.5

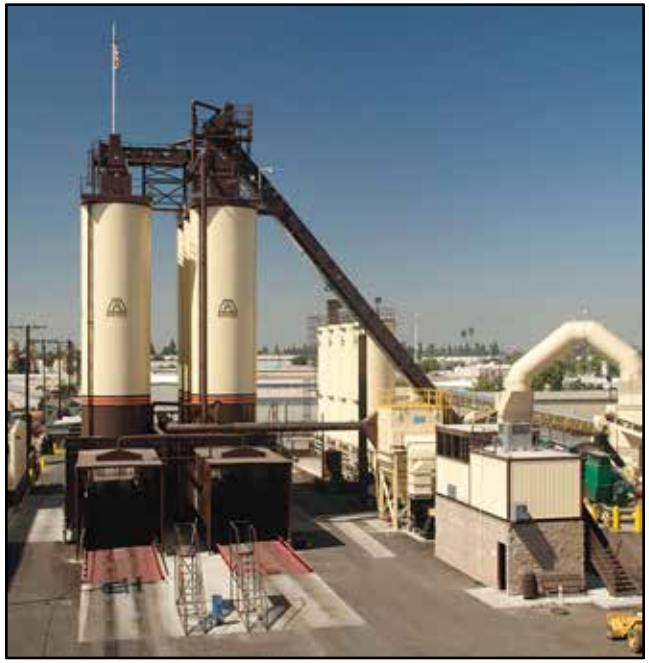

Fracture Energy (J/m²)
Silo Storage Time (Hours)
0
100
200
300
400
500
600
700
0
2.5
5
7.5


Initial Stiffness, k (kN/mm)
Silo Storage Time (Hours)
0
5
10
15
20
25
30
35
0
2.5
5
7.5


Peak Load, P (kN)
Silo Storage Time (Hours)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
0
2.5
5
7.5

Summary

- Testing clearly indicated aging with storage time
- RAP experienced larger changes
- Short-term aging and blending/diffusion
- Lab conditioning methods vs. plant production
- Important to understand effect of plant production parameters



Source: www.hotmixmag.com

Thank you for attention!

Questions/Comments?

Source: www.huffingtonpost.com

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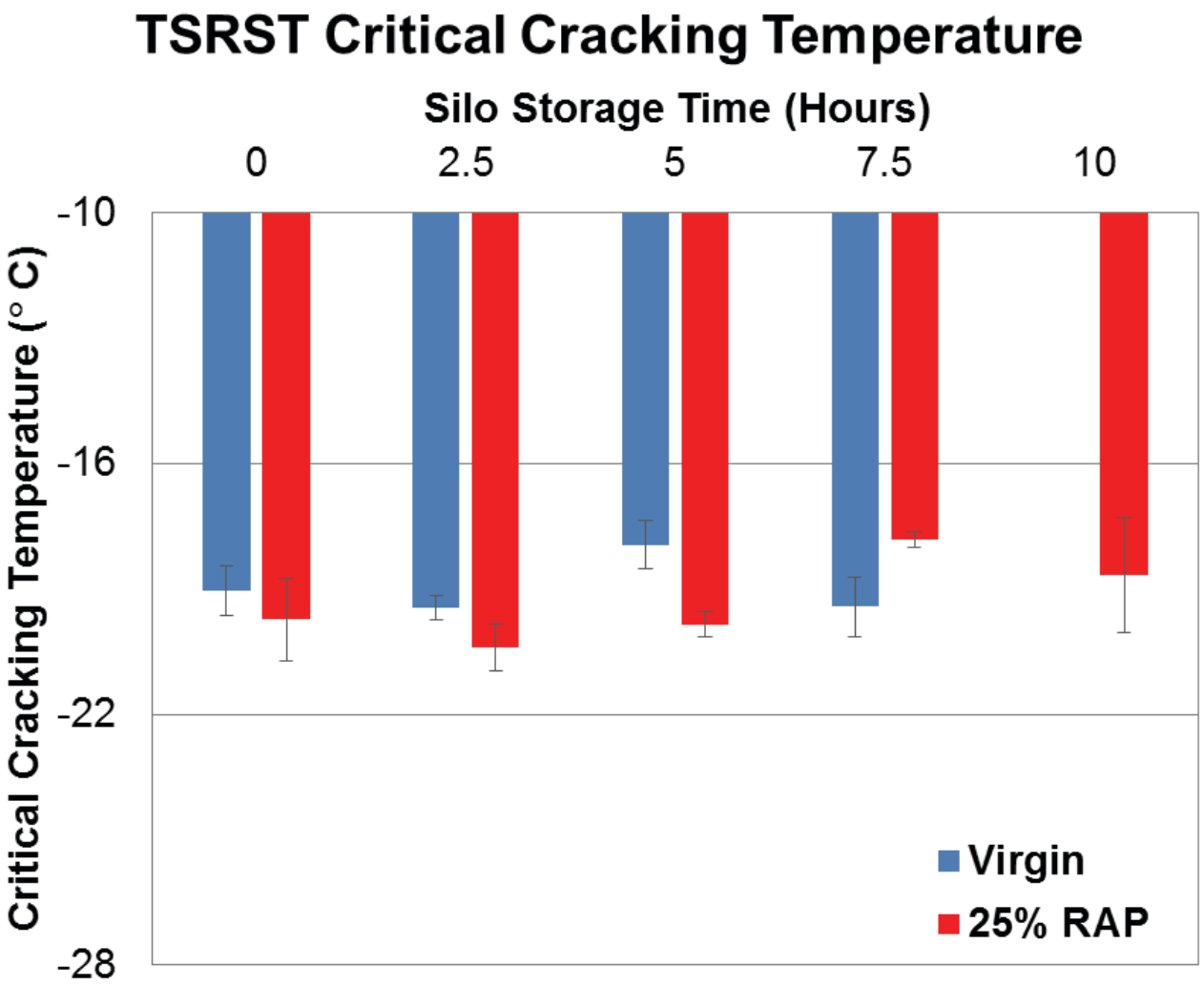
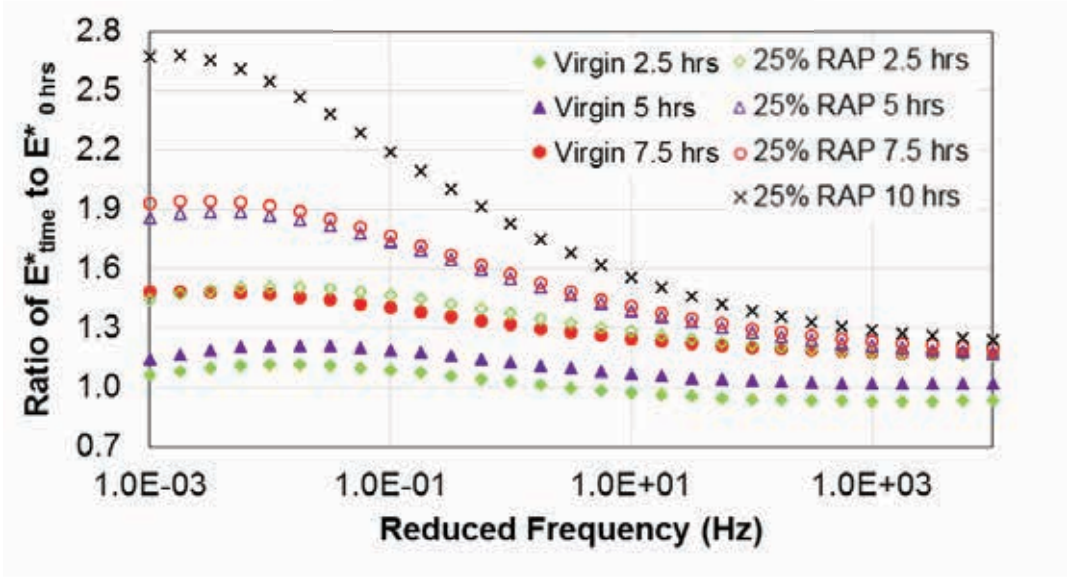
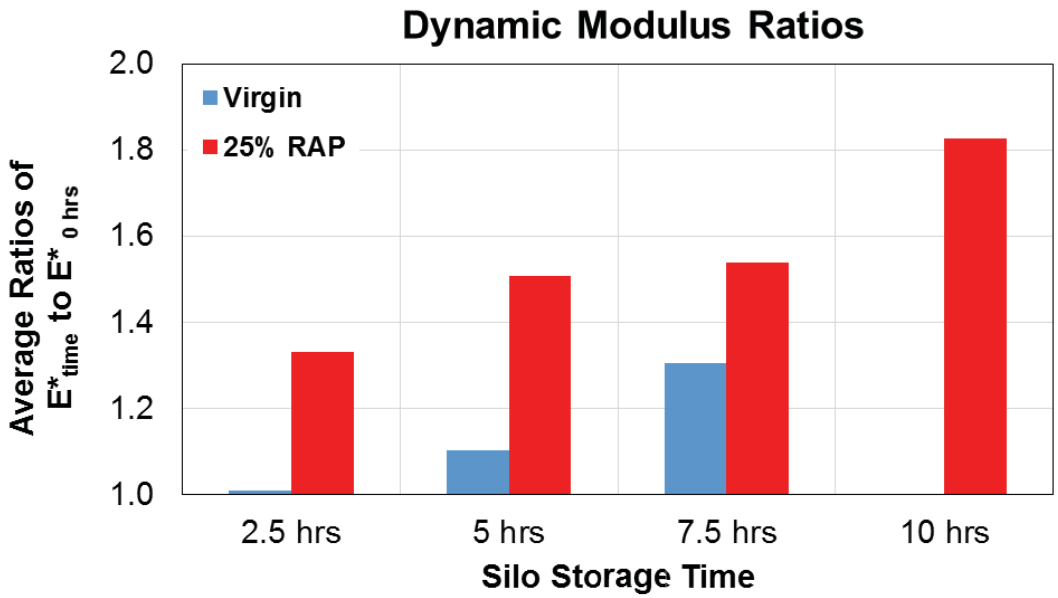
TSRST


TSRST Critical Cracking Temperature
Silo Storage Time (Hours)
0
2.5
5
7.5
10
-10
-16
-22
-28
Critical Cracking Temperature (° C)
Virgin
25% RAP

E* Ratios


Ratio of E*time to E* 0 hrs
2.8
2.5
2.2
1.9
1.6
1.3
1.0
0.7
1.0E-03
1.0E-01
1.0E+01
1.0E+03
Reduced Frequency (Hz)
Virgin 2.5 hrs
Virgin 5 hrs
Virgin 7.5 hrs
25% RAP 2.5 hrs
25% RAP 5 hrs
25% RAP 7.5 hrs
25% RAP 10 hrs


Dynamic Modulus Ratios
Average Ratios of E*time to E* 0 hrs
2.0
1.8
1.6
1.4
1.2
1.0
Virgin
25% RAP
2.5 hrs
5 hrs
7.5 hrs
10 hrs
Silo Storage Time

Virgin T-Test Results

Dynamic Modulus																		
Comparison Group: 0 hrs (A)																		
T-Test #	Comparison Group 2	4.4° C (±)						21.1° C (±)						37.8° C (±)					
		25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
AvB	2.5 hrs	0.850	0.474	0.272	0.190	0.166	0.405	0.145	0.159	0.155	0.168	0.148	0.168	0.106	0.098	0.116	0.147	0.152	0.225
AvC	5 hrs	0.213	0.265	0.336	0.390	0.413	0.422	0.046	0.049	0.052	0.069	0.064	0.083	0.056	0.044	0.041	0.050	0.044	0.091
AvD	7.5 hrs	0.044	0.063	0.091	0.103	0.098	0.092	0.001	0.001	0.000	0.001	0.001	0.000	0.003	0.002	0.002	0.001	0.001	0.002
Comparison Group: 7.5 hrs (D)																			
T-Test #	Comparison Group 2	4.4° C (±)						21.1° C (±)						37.8° C (±)					
		25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
DvA	0 hrs	0.044	0.063	0.091	0.103	0.098	0.092	0.001	0.001	0.000	0.001	0.001	0.000	0.003	0.002	0.002	0.001	0.001	0.002
DvB	2.5 hrs	0.034	0.074	0.119	0.156	0.158	0.120	0.021	0.016	0.014	0.010	0.009	0.007	0.031	0.020	0.015	0.012	0.038	0.024
DvC	5 hrs	0.456	0.525	0.537	0.502	0.512	0.494	0.184	0.135	0.116	0.104	0.084	0.073	0.043	0.023	0.013	0.010	0.007	0.010

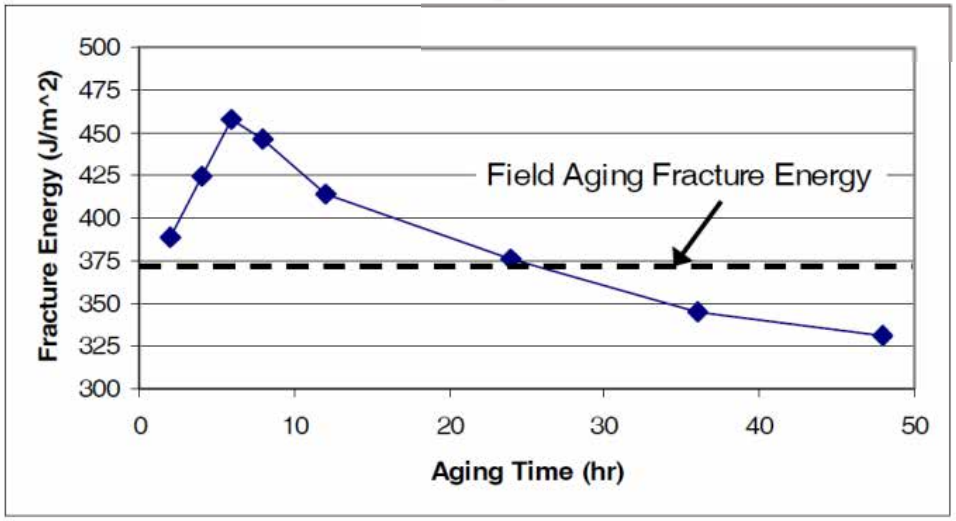
Phase Angle																			
Comparison Group: 0 hrs (A)																			
T-Test #	Comparison Group 2	4.4° C (±)						21.1° C (±)						37.8° C (±)					
		25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
AvB	2.5 hrs	0.227	0.784	0.649	0.590	0.596	0.751	0.004	0.714	0.745	0.968	0.501	0.296	0.256	0.696	0.602	0.420	0.394	0.360
AvC	5 hrs	0.545	0.657	0.772	0.600	0.540	0.461	0.004	0.111	0.181	0.174	0.295	0.665	0.725	0.824	0.374	0.135	0.012	0.035
AvD	7.5 hrs	0.810	0.248	0.213	0.213	0.162	0.099	0.001	0.182	0.239	0.254	0.261	0.662	0.656	0.034	0.116	0.622	0.033	0.010
Comparison Group: 7.5 hrs (D)																			
T-Test #	Comparison Group 2	4.4° C (±)						21.1° C (±)						37.8° C (±)					
		25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
DvA	0 hrs	0.810	0.248	0.213	0.213	0.162	0.099	0.001	0.182	0.239	0.254	0.261	0.662	0.656	0.034	0.116	0.622	0.033	0.010
DvB	2.5 hrs	0.013	0.019	0.016	0.006	0.010	0.014	0.163	0.248	0.304	0.282	0.203	0.369	0.050	0.003	0.019	0.808	0.372	0.074
DvC	5 hrs	0.306	0.355	0.260	0.381	0.348	0.268	0.423	0.586	0.551	0.634	0.512	0.830	0.435	0.064	0.021	0.268	0.289	0.477

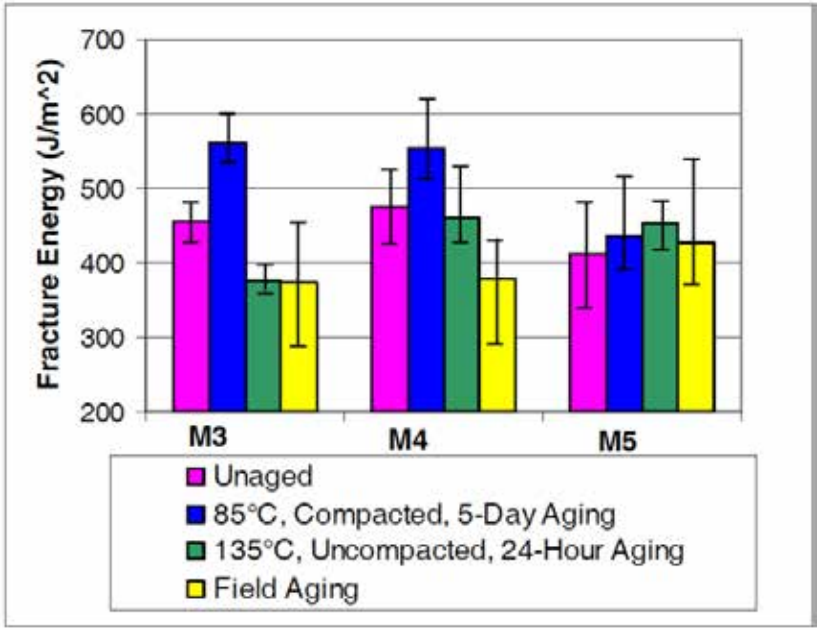
25% RAP T-Test Results

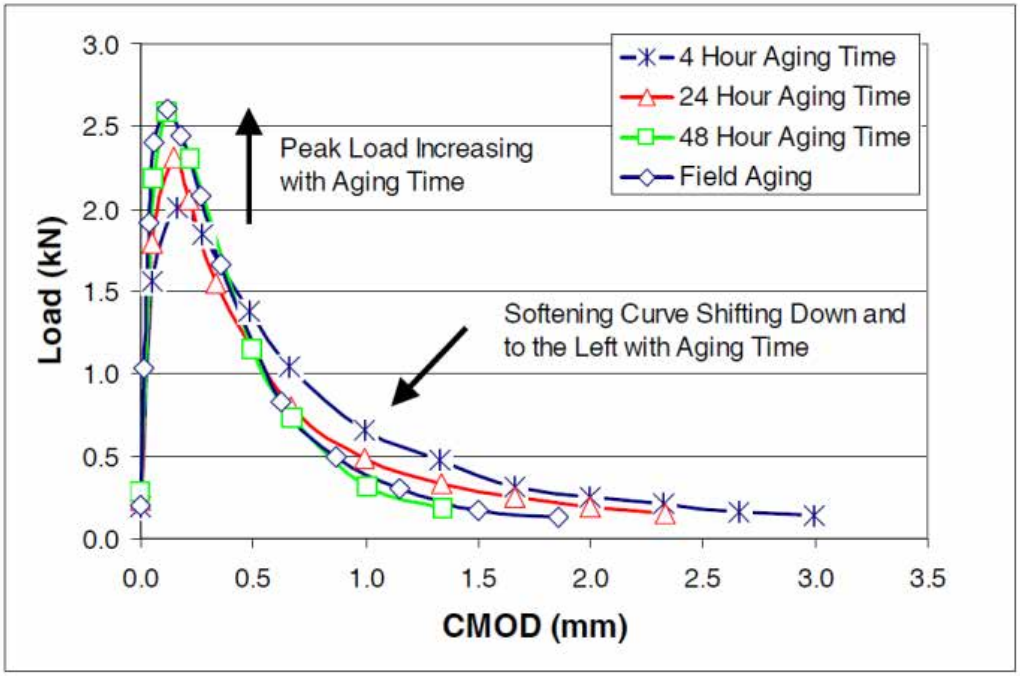
Dynamic Modulus																		
Comparison Group: 0 hrs (A)																		
T-Test #	Comparison Group 2	4.4° C						21.1° C						37.8° C					
		25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
AvB	2.5 hrs	0.154	0.130	0.131	0.153	0.173	0.152	0.149	0.164	0.173	0.170	0.164	0.097	0.143	0.134	0.079	0.080	0.084	0.101
AvC	5 hrs	0.093	0.070	0.063	0.061	0.124	0.098	0.093	0.096	0.093	0.038	0.037	0.035	0.061	0.059	0.058	0.058	0.060	0.066
AvD	7.5 hrs	0.052	0.044	0.041	0.044	0.104	0.087	0.079	0.086	0.087	0.078	0.074	0.024	0.076	0.070	0.064	0.018	0.017	0.015
AvE	10 hrs	0.038	0.025	0.057	0.057	0.063	0.052	0.043	0.046	0.047	0.039	0.008	0.007	0.066	0.055	0.046	0.010	0.008	0.008
Comparison Group: 10 hrs (E)																			
T-Test #	Comparison Group 2	4.4° C						21.1° C						37.8° C					
		25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
EvA	0 hrs	0.038	0.025	0.057	0.057	0.063	0.052	0.043	0.046	0.047	0.039	0.008	0.007	0.066	0.055	0.046	0.010	0.008	0.008
EvB	2.5 hrs	0.181	0.060	0.020	0.013	0.010	0.033	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.005	0.006	0.007	0.008	0.009
EvC	5 hrs	0.542	0.298	0.104	0.014	0.004	0.001	0.000	0.000	0.001	0.007	0.013	0.028	0.057	0.071	0.070	0.071	0.071	0.071
EvD	7.5 hrs	0.849	0.383	0.141	0.040	0.016	0.003	0.004	0.001	0.001	0.002	0.003	0.010	0.083	0.115	0.108	0.093	0.092	0.092

Phase Angle																			
Comparison Group: 0 hrs (A)																			
T-Test #	Comparison Group 2	4.4° C						21.1° C						37.8° C					
		25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
AvB	2.5 hrs	0.051	0.595	0.456	0.118	0.602	0.145	0.179	0.199	0.191	0.131	0.139	0.202	0.180	0.152	0.145	0.105	0.189	0.857
AvC	5 hrs	0.008	0.389	0.296	0.044	0.378	0.060	0.051	0.057	0.049	0.056	0.047	0.046	0.254	0.205	0.155	0.077	0.277	0.895
AvD	7.5 hrs	0.008	0.346	0.228	0.052	0.268	0.074	0.010	0.004	0.002	0.002	0.003	0.000	0.015	0.011	0.006	0.039	0.155	0.974
AvE	10 hrs	0.003	0.160	0.084	0.005	0.079	0.011	0.001	0.001	0.001	0.002	0.002	0.003	0.005	0.004	0.002	0.037	0.175	0.535
Comparison Group: 10 hrs (E)																			
T-Test #	Comparison Group 2	4.4° C						21.1° C						37.8° C					
		25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
EvA	0 hrs	0.003	0.160	0.084	0.005	0.079	0.011	0.001	0.001	0.001	0.002	0.002	0.003	0.005	0.004	0.002	0.037	0.175	0.535
EvB	2.5 hrs	0.104	0.070	0.046	0.050	0.046	0.040	0.050	0.063	0.071	0.083	0.092	0.131	0.289	0.310	0.250	0.486	0.614	0.378
EvC	5 hrs	0.033	0.043	0.028	0.043	0.057	0.088	0.048	0.070	0.078	0.084	0.098	0.144	0.129	0.118	0.103	0.175	0.457	0.433
EvD	7.5 hrs	0.134	0.028	0.015	0.015	0.018	0.025	0.021	0.024	0.026	0.040	0.053	0.104	0.128	0.169	0.158	0.950	0.959	0.496

Effects of Aging on Fracture (Braham et al., 2009)







Literature Review

- Interaction between RAP and virgin mixtures
- "Blending and Diffusion of Reclaimed Asphalt Pavement and Virgin Asphalt Binders," Kriz et al., AAPT 2014
- Two major processes: mixing or contact between the binders and blending/diffusion after contact
- DSR testing to test degree of blending in thick, thin binder layers

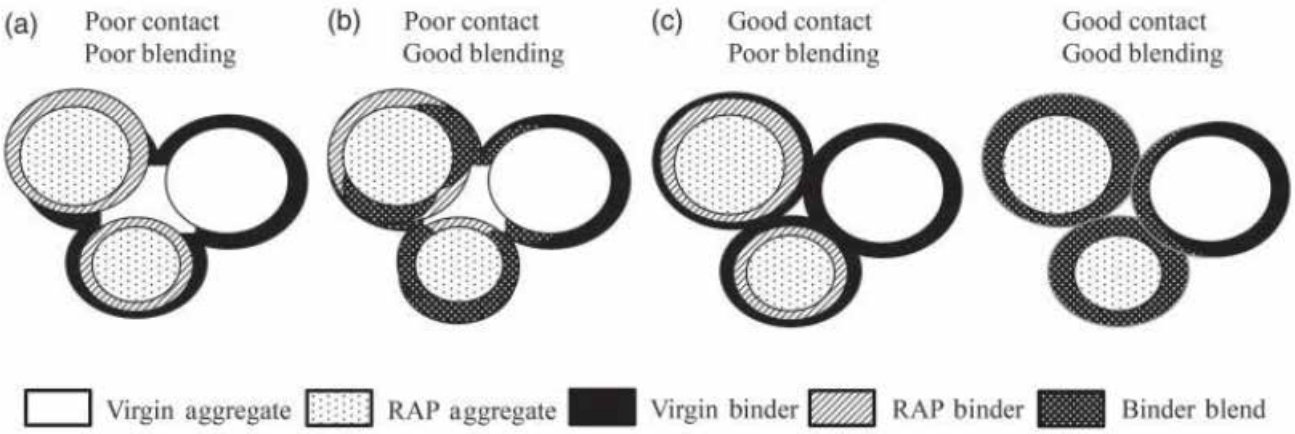
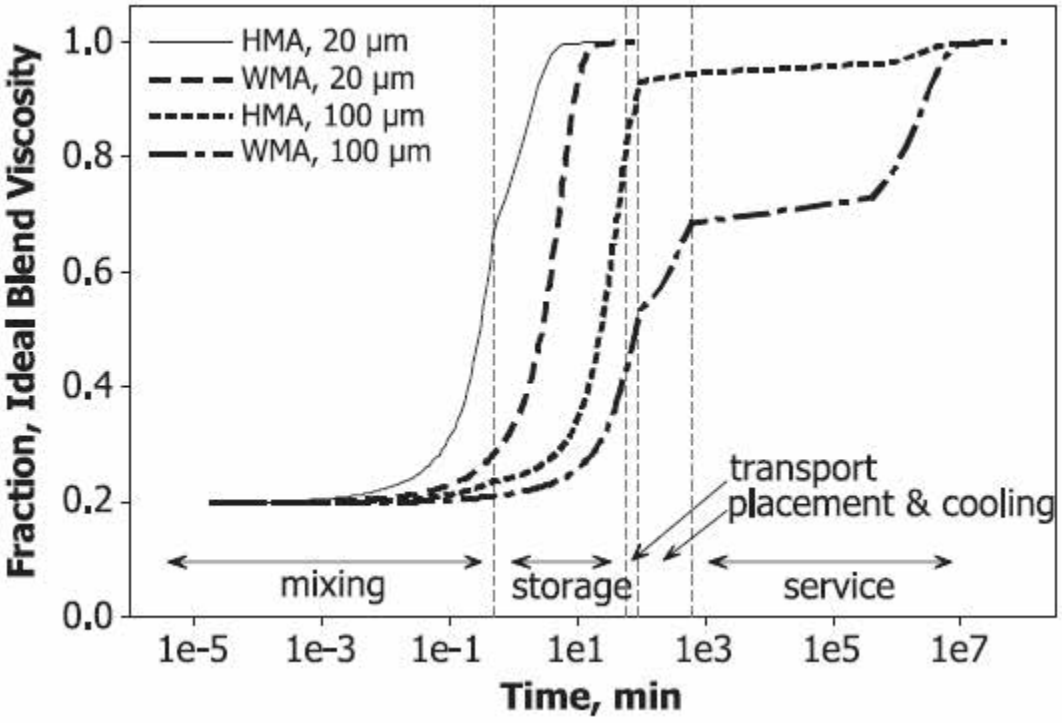


Figure 1. RAP–virgin binder contact and blending due to diffusion. Schematic representation of possible options.

Source: Kriz et al., AAPT 2014, p. 227

Literature Review

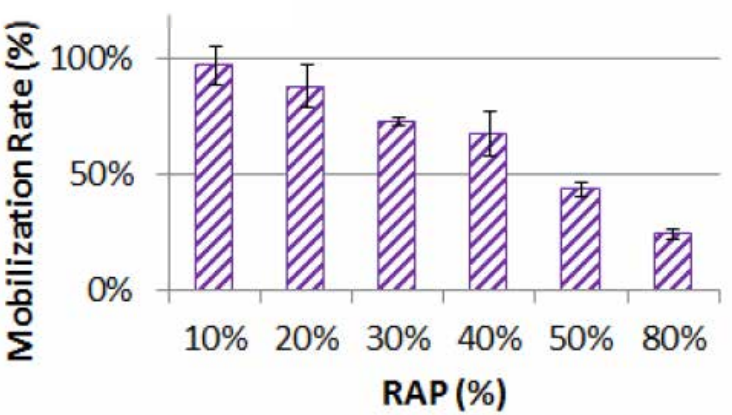
- Thinner layers: 100% blending within minutes of mixing
- Thicker layers: ~90% blending after typical production stages
- Diffusion, blending could potentially continue to occur



Source: Kriz et al., AAPT 2014, p. 254

Literature Review

- Zhao et al. (2015) investigated mobilization rate of virgin and RAP binders
- Under-asphalted mixtures → more prone to cracking



(a) Mobilization rates for RAP mixes

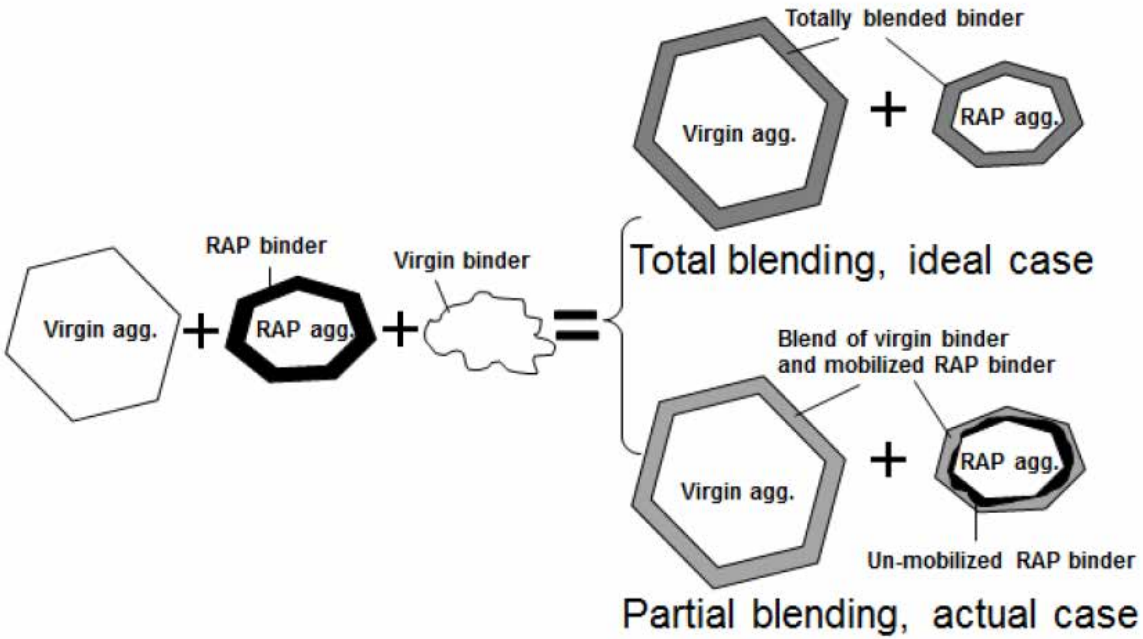


Figure 1. Two possible blending scenarios