OHIO ASPHALT PAVING CONFERENCE

Aging Analysis Approach for Warm Mix Asphalt

Everett Crews, Craig Reynolds, & Trey Wurst

3 February 2021

Flexible Pavements of Ohio

ingevity

Outline of Presentation

What History Has Taught Us about Aging Impacts on Binder Rheology

Aging Analyses Today Are Patterned on the Preceding Studies

High Failure Temperatures Vary According to Laws of Binder Aging

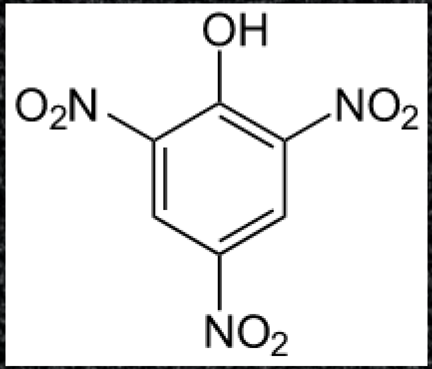
Aging Evaluations Using Glover-Rowe Damage Parameter

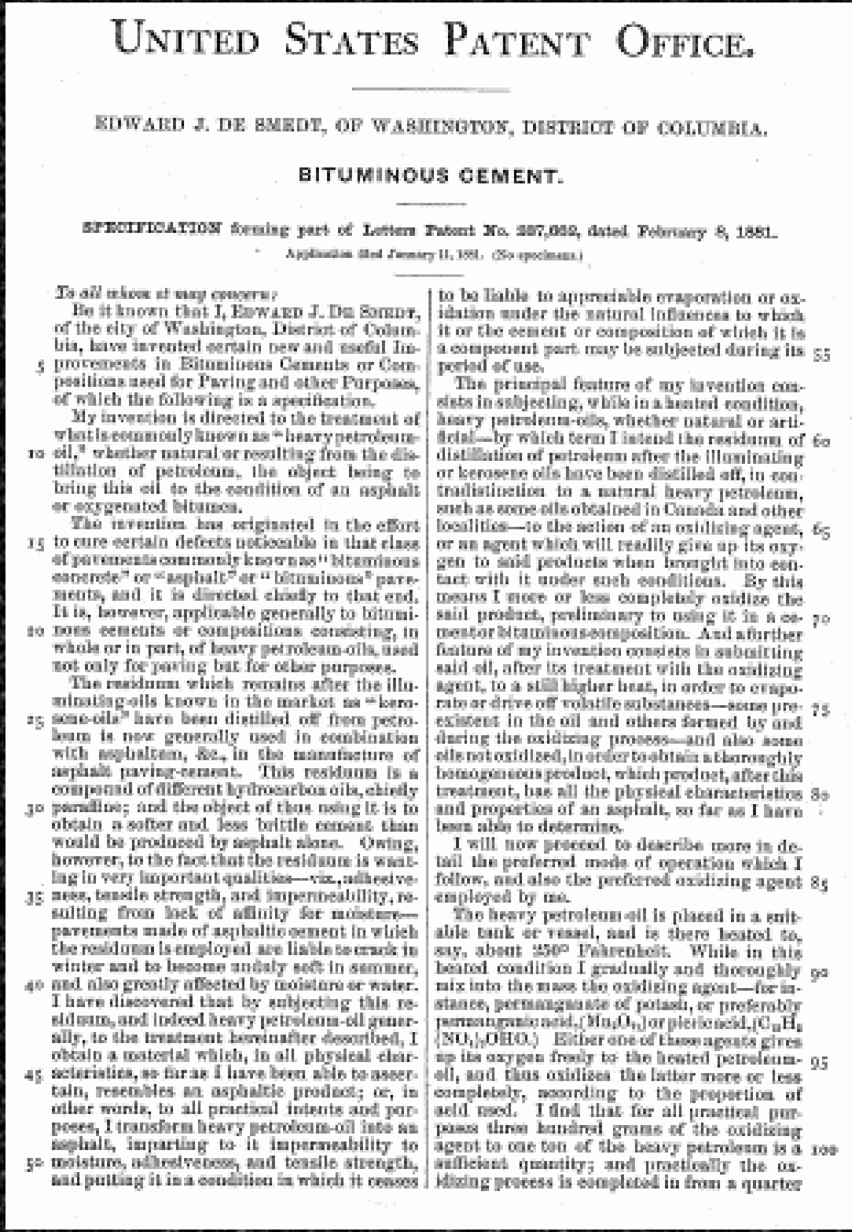
Performance Design

Why Warm Mix Temperatures Are a Crucial Sustainability Benefit

Temperature (& Time) Effects on Binder Stiffening were Long-ago Studied to Stiffen Asphalt

In the 19th century, temperature (& time) were understood to be key variables in oxidation of heavy petroleum bottoms. The chemist, E.J. De Smedt, in his U.S.Patent 237,662 (1881), taught oxidation of heavy petroleum oils with 0.033% picric acid at ~250°F followed by heating to ~500°F (further oxidation and light-ends vaporization). (Ref 1).





UNITED STATES PATENT OFFICE.

EDWARD J. DE SMEDT, OF WASHINGTON, DISTRICT OF COLUMBIA.

BITUMINOUS CEMENT.

SPECIFICATION forming part of Letters Patent No. 237,662, dated February 8, 1881.

Application filed January 11, 1881. (No specimens.)

To all whom it may concern:

Be it known that I, EDWARD J. DE SMEDT, of the city of Washington, District of Columbia, have invented certain new and useful Improvements in Bituminous Cements or Compositions used for Paving and other Purposes, of which the following is a specification.

My invention is directed to the treatment of what is commonly known as "heavy petroleum-oil," whether natural or resulting from the distillation of petroleum, the object being to bring this oil to the condition of an asphalt or oxygenated bitumen.

The invention has originated in the effort to cure certain defects noticeable in that class of pavements commonly known as "bituminous concrete" or "asphalt" or "bituminous" pavements, and it is directed chiefly to that end. It is, however, applicable generally to bituminous cements or compositions consisting, in whole or in part, of heavy petroleum-oils, used not only for paving but for other purposes.

The residuum which remains after the illuminating-oils known in the market as "kerosene-oils" have been distilled off from petroleum is now generally used in combination with asphaltum, &c., in the manufacture of asphalt paving-cement. This residuum is a compound of different hydrocarbon oils, chiefly paraffine; and the object of thus using it is to obtain a softer and less brittle cement than would be produced by asphalt alone. Owing, however, to the fact that the residuum is wanting in very important qualities—viz., adhesiveness, tensile strength, and impermeability, resulting from lack of affinity for moisture—pavements made of asphaltic cement in which the residuum is employed are liable to crack in winter and to become unduly soft in summer, and also greatly affected by moisture or water. I have discovered that by subjecting this residuum, and indeed heavy petroleum-oil generally, to the treatment hereinafter described, I obtain a material which, in all physical characteristics, so far as I have been able to ascertain, resembles an asphaltic product; or, in other words, to all practical intents and purposes, I transform heavy petroleum-oil into an asphalt, imparting to it impermeability to moisture, adhesiveness, and tensile strength, and putting it in a condition in which it ceases to be liable to appreciable evaporation or oxidation under the natural influences to which it or the cement or composition of which it is a component part may be subjected during its period of use.

The principal feature of my invention consists in subjecting, while in a heated condition, heavy petroleum-oils, whether natural or artificial—by which term I intend the residuum of distillation of petroleum after the illuminating or kerosene oils have been distilled off, in contradistinction to a natural heavy petroleum, such as some oils obtained in Canada and other localities—to the action of an oxidizing agent, or an agent which will readily give up its oxygen to said products when brought into contact with it under such conditions. By this means I more or less completely oxidize the said product, preliminary to using it in a cement or bituminous composition. And a further feature of my invention consists in submitting said oil, after its treatment with the oxidizing agent, to a still higher heat, in order to evaporate or drive off volatile substances—some pre-existent in the oil and others formed by and during the oxidizing process—and also some oils not oxidized, in order to obtain a thoroughly homogeneous product, which product, after this treatment, has all the physical characteristics and properties of an asphalt, so far as I have been able to determine.

I will now proceed to describe more in detail the preferred mode of operation which I follow, and also the preferred oxidizing agent employed by me.

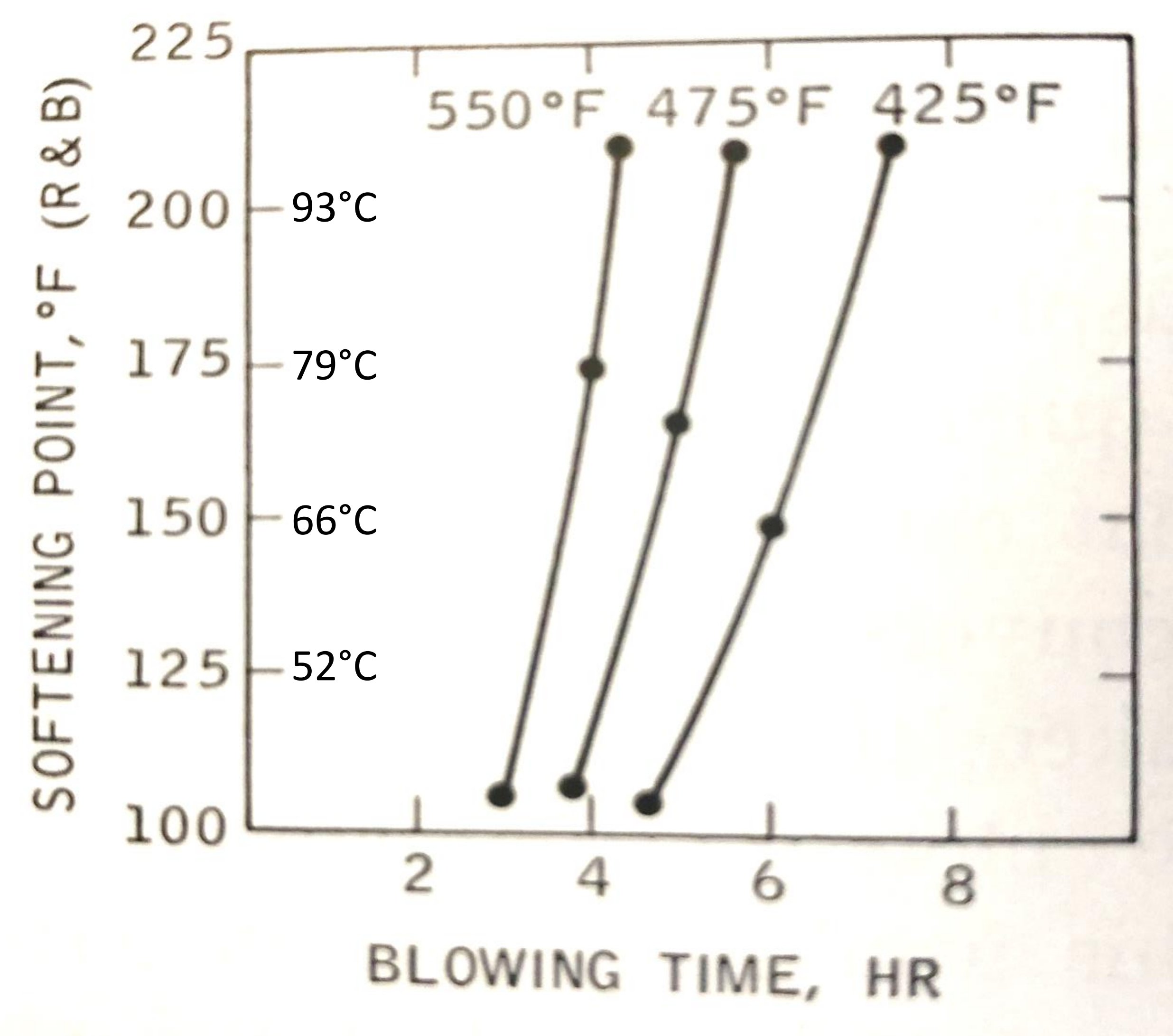
The heavy petroleum-oil is placed in a suitable tank or vessel, and is there heated to, say, about 250° Fahrenheit. While in this heated condition I gradually and thoroughly mix into the mass the oxidizing agent—for instance, permanganate of potash, or preferably permanganic acid, (Mn_2O_7,) or picric acid, ($C_{12}H_2(NO_4)_3OHO$.) Either one of these agents gives up its oxygen freely to the heated petroleum-oil, and thus oxidizes the latter more or less completely, according to the proportion of acid used. I find that for all practical purposes three hundred grams of the oxidizing agent to one ton of the heavy petroleum is a sufficient quantity; and practically the oxidizing process is completed in from a quarter

Ref. 1. Edward J. De Smedt, US Patent 237,662, February 8, 1881.

Temperature (& Time) Effects on Binder Stiffening were Long-ago Studied to Improve Air Blowing Processes

In the 19th century, temperature (& time) were understood to be key variables in the success of airblowing processes, the first of which was patented by E.J. De Smedt, U.S.Patent 237,662 (1881) as a means of improving durability of asphalt, was long-ago understood to depend on temperature and time.

It was understood that as process temperatures increase, the rate of binder stiffening (in the graph at right, measured as R&B softening point) increases. (Ref. 2)



Ref. 2. Hoibert, A.J., Editor, "Bituminous Materials: Asphalts, Tars, & Pitches," Vol. II, John Wiley & Sons, 1965, p. 98.

100 Years Ago Technologists Spoke of "Aging" as "Weathering"

By at least 1925, oxidation studies had revealed evidence that **air exposure** converted **resins to asphaltenes** and that different bitumen components adsorbed (reacted with oxygen differently) (Ref. Hoibert).

As early as the 1930's, oxygen uptake, light, solar radiant energy, and heat were among the well recognized causes of binder stiffening. (Ref. Hoibert)

By 1956, when W.P. van Oort published his seminal work on oxygen adsorption, "weathering" was called "aging."

Hoibert, A.J., Editor, "Bituminous Materials: Asphalts, Tars, & Pitches," Vol. II, John Wiley & Sons, 1965, p. 98.

Durability of Asphalt

Its Aging in the Dark

W. P. VAN OORT

N. V. De Bataafsche Petroleum Maatschappij, Koninklijke-Shell Laboratorium, Amsterdam, The Netherlands

ONE of the important factors determining the lifetime of constructions in which asphalt has been used is the influence exerted on the asphalt by the weather. The entire complex of changes in the properties of asphalt by atmospheric influences, to the detriment of the construction concerned, is called aging. The degree to which asphalt resists these influences is called its durability.

Literature (1, 3) on the aging phenomena of asphalt is extensive. However, most of the published studies describe only the phenomena observed. Frequently, correlations between aging phenomena and properties of the asphalt are sought by purely empirical methods. Many methods described aim at obtaining direct information by short-time tests on asphalt behavior after long exposure.

According to the literature, the action of oxygen is one of the principal factors responsible for the occurrence of aging phenomena. When asphalt is exposed to atmospheric oxygen, a slow autoxidation occurs, the chemical nature of which depends to a very large extent upon the temperature. At temperatures above 100° C. dehydrogenation takes place, as is evident from the water produced. Some carbon dioxide is also formed (5). At lower temperatures—e.g., 25° or 50° C.—the oxygen involved in the oxidation is quantitatively bound in the bitumen and no water or carbon dioxide is formed.

The rate of the oxidation may be followed by means of oxygen absorption measurements. The over-all rate of oxygen absorption was found to be not only determined by the chemical nature of the asphalt, but also by the physical transport of the oxygen from the surrounding atmosphere to the interior of the material. Therefore, it is also a physical problem, one of diffusion in particular.

A study of the time-absorption curve for oxygen is presented. Both experimental and theoretical investigations are included to acquire an understanding of phenomena involved by the transfer of oxygen and related factors determining the velocity of the entire process.

In order not to complicate this fundamental study, aging in the absence of light was investigated. Such an investigation is very important, as most of the asphalt is employed in road carpets and similar constructions, where the greater part of the asphalt is subjected to slow oxidation in the dark, owing to the porous structure of the mixture that usually exists. Some practical data on the change in mechanical properties as a result of aging are given to substantiate this theoretical investigation. A microviscometer developed by Labout and van Oort (2) was used to collect these data.

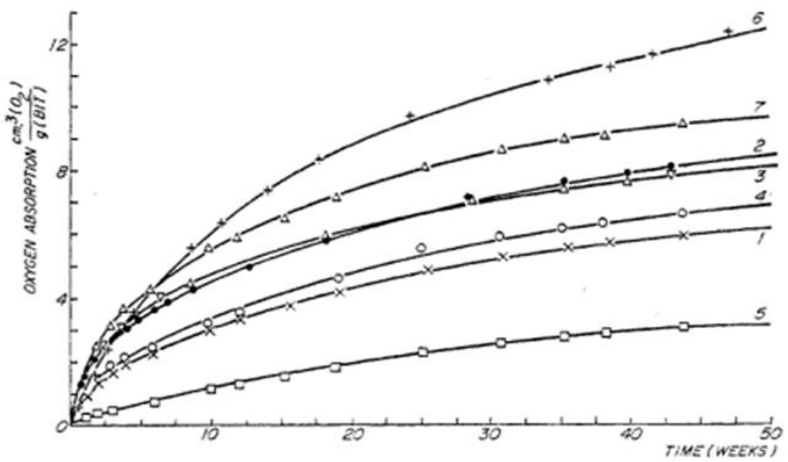


Figure 1. Absorption of oxygen by different asphalts in the dark

In 7-micron layers at 22° C. and 1-atm. pressure

	Pen 25° C.	Softening point R and B ° C.

RESULTS OF MEASUREMENTS

Oxygen Absorption. The conditions under which the absorption of oxygen was measured were chosen so as to accord as closely as possible with conditions of actual service. Measurements were made

1970 European Road Tests in France (& Germany)

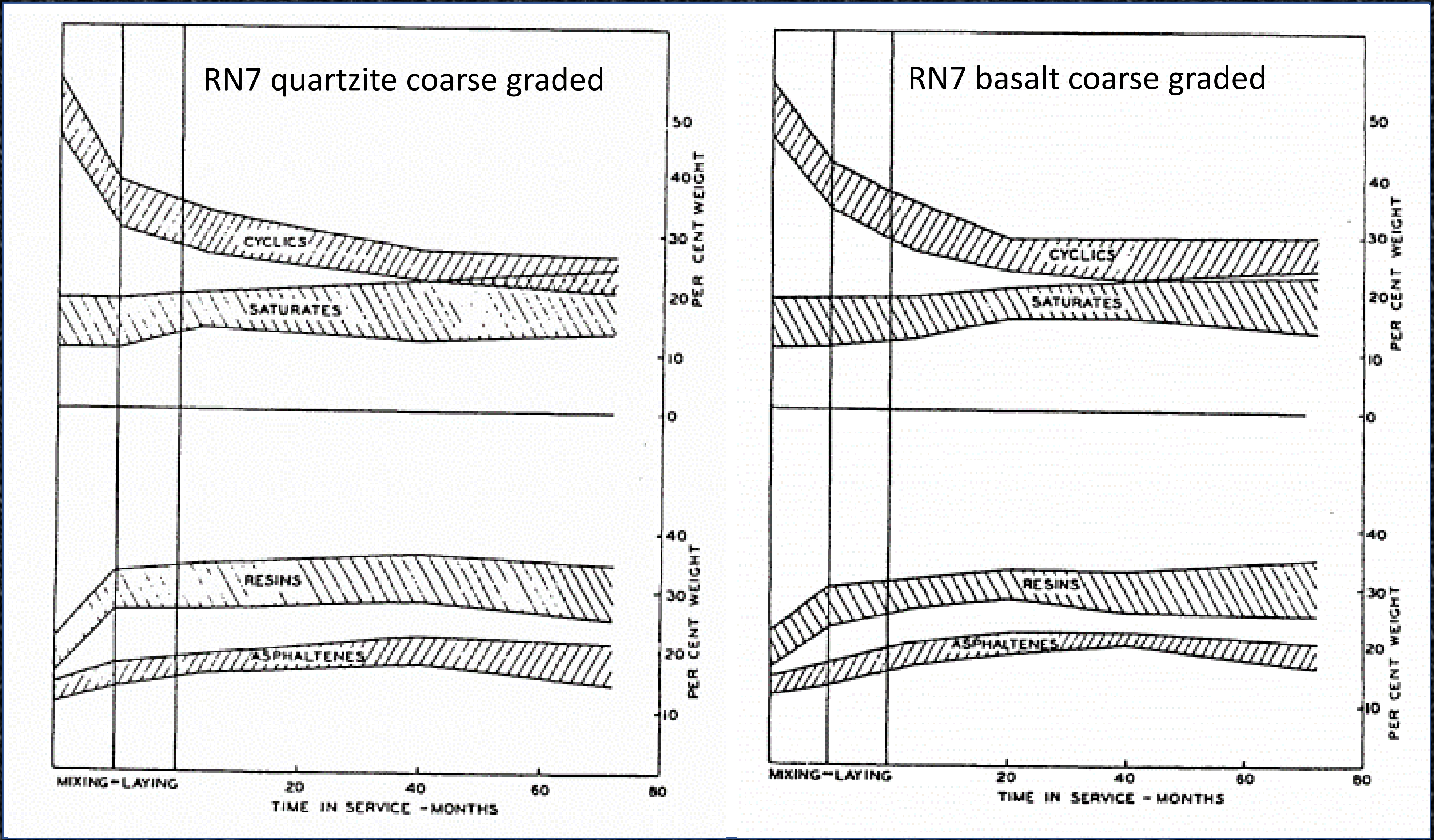
9 different, 70/100 pen bitumen (R&B = 47-50.5°C)

1.5-inch overlays

110 sections

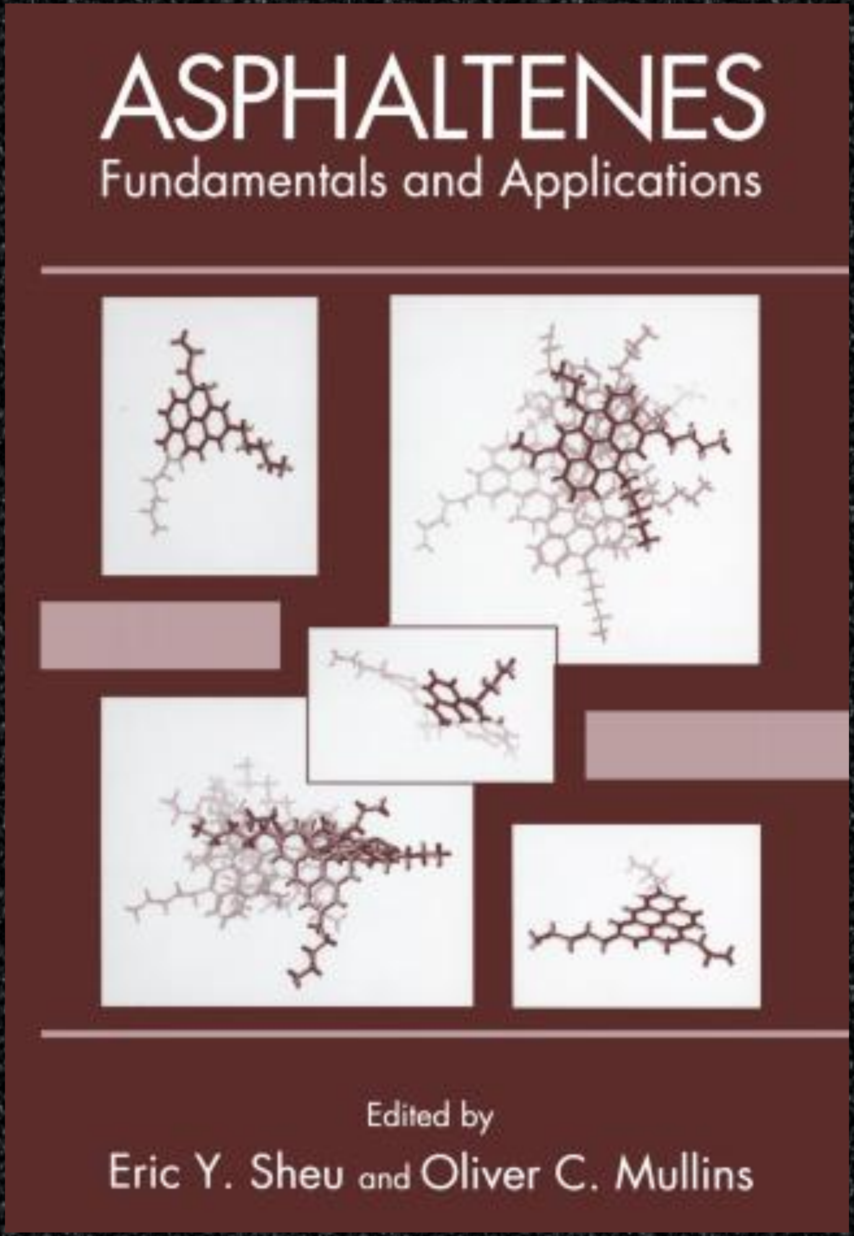
VA 3-6%

"At less than 3 percent air voids, changes in asphalt properties were relatively insignificant."



Finn, F.N., et.al., "Asphalt Properties and Relationship to Pavement Performance," SHRP Task 1.4, May 4, 1990, pages 3-44 – 3-48.

By the 1990'S Oxidation Chemistry Was Being Fully Elucidated



Chapter V

1995

THE EFFECTS OF ASPHALTENES ON THE CHEMICAL AND PHYSICAL CHARACTERISTICS OF ASPHALT

M. S. Lin, K. M. Lunsford, C. J. Glover, R. R. Davison, and J. A. Bullin

Texas A&M University

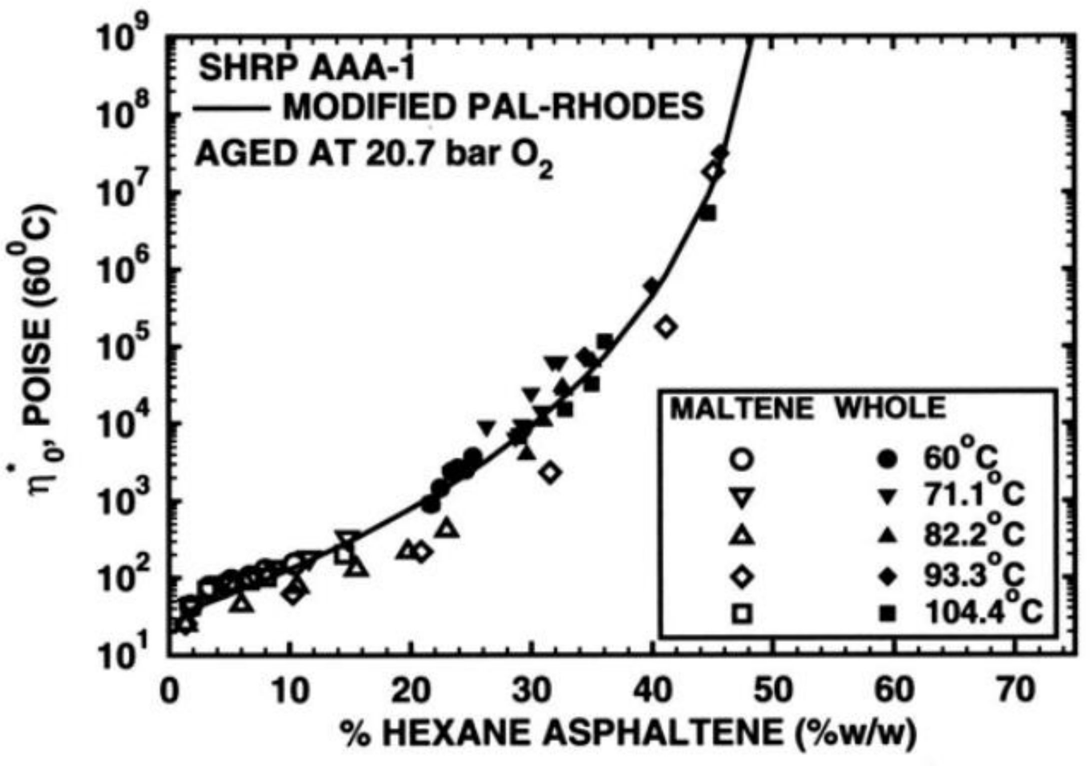


Figure 14. η^*_0 versus %AS for SHRP AAA-1 whole asphalt and maltene.

By the 1990'S Oxidation Chemistry Was Being Fully Elucidated

Numerous studies have clearly shown that for a given binder, the higher the aging (in this case oxidation) temperature, the quicker the binder stiffens. Stiffening in this case as measured by the log(viscosity).

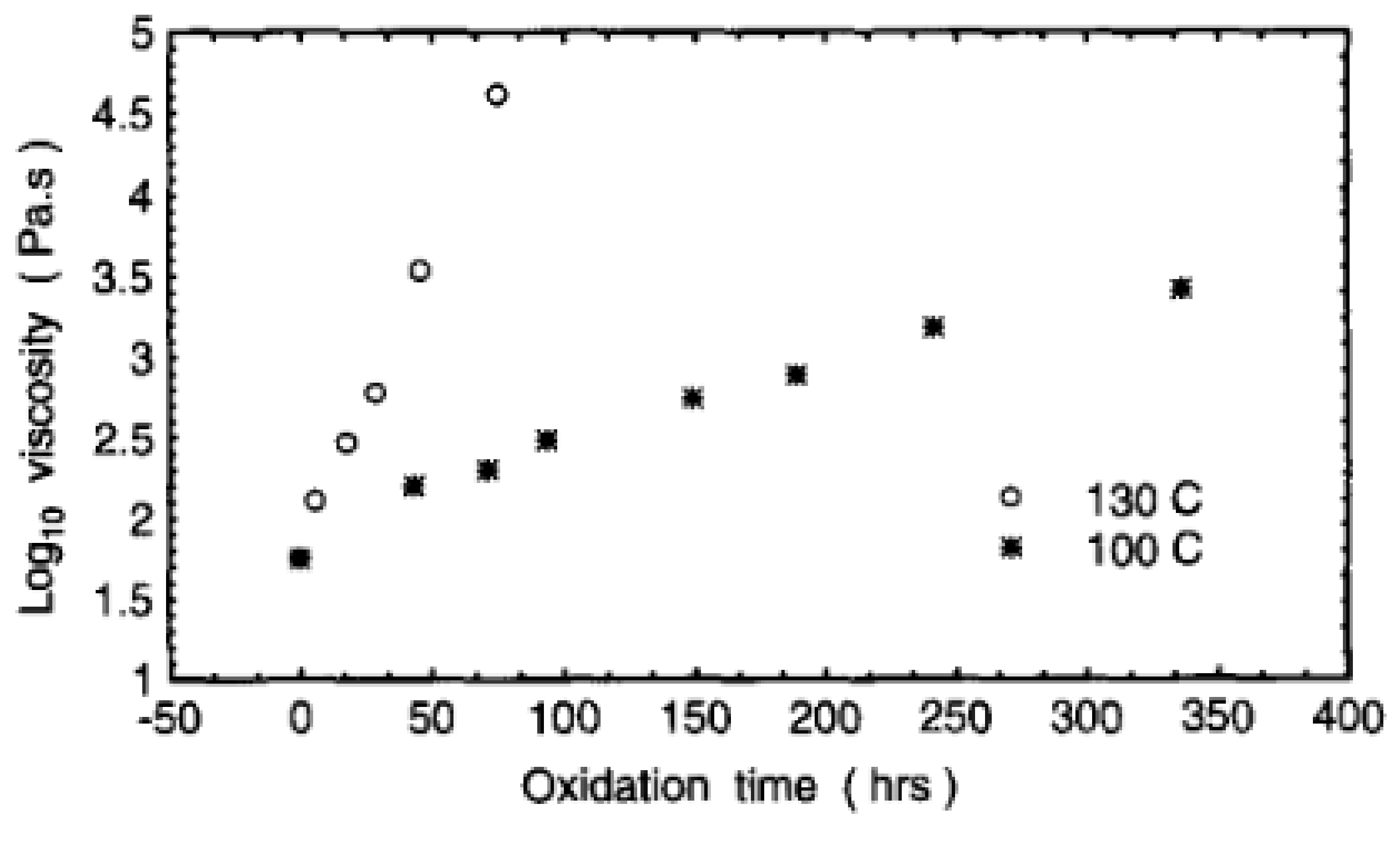


Figure 1 Effect of oxidation time on asphalt viscosity at 60°C

Herrington, P.R., Ball, G.F.A., "Temperature Dependence of Asphalt Oxidation Mechanism," **Fuel**, Vol. 95, No. 9, pp 1121-1131, 1996.

By 2006 Oxidation Reaction Laws Were Being Developed

OXIDATIVE AGING MODEL

HOW IT RELATES TO THE PREDICTION OF PAVEMENT PERFORMANCE

By

J. Claine Petersen

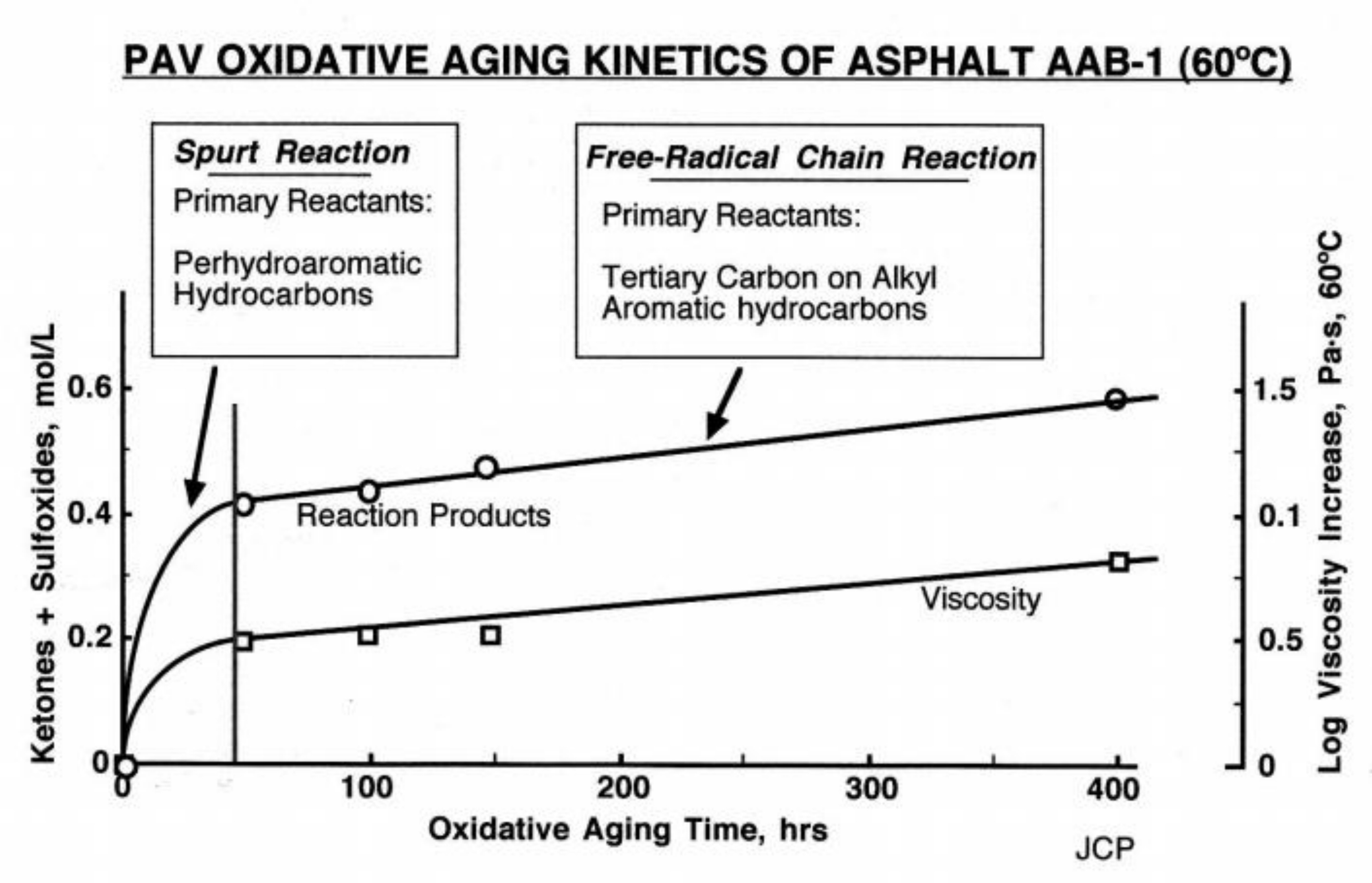
Consulting Services

Asphalt Chemistry and Related Technology

WRI/FHWA Symposium: Models Used to Predict Pavement Performance
Laramie, Wyoming, June 21-23, 2006

Oxidation Studies Showed a Fast (Jump or Spurt) Reaction Occurs

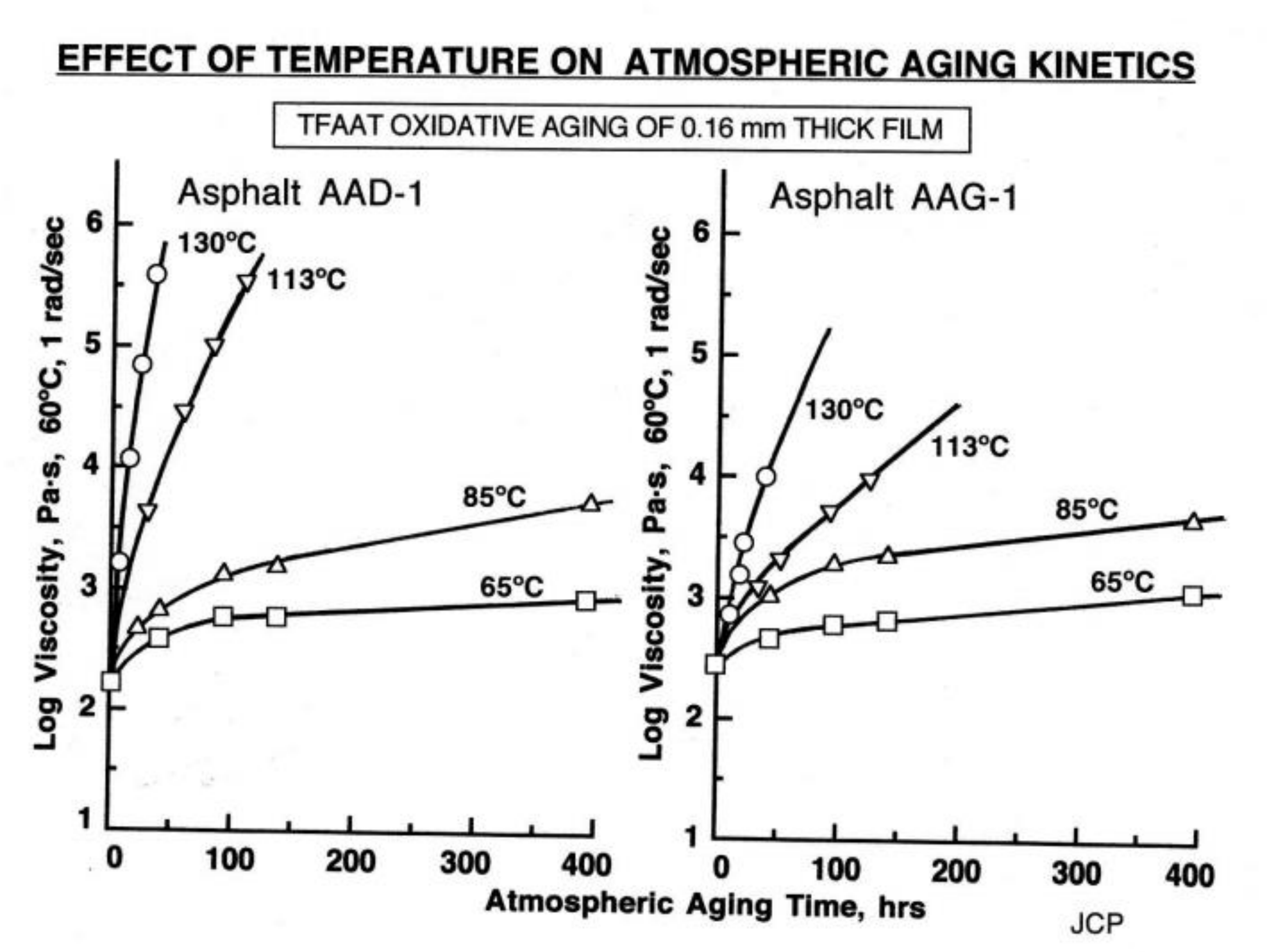
Results of intensive R&D through the 1990's & 2000's, began to reveal more clearly the chemo-mechanical connection between binder aging and compositional changes.



Petersen, J.C., "Oxidative Aging Model: How It Relates to the Prediction of Pavement Performance," WRI/FHWA Symposium, Laramie, WY, June 2006.

The Higher the Oxidation Temperature, Again the Faster the Stiffening

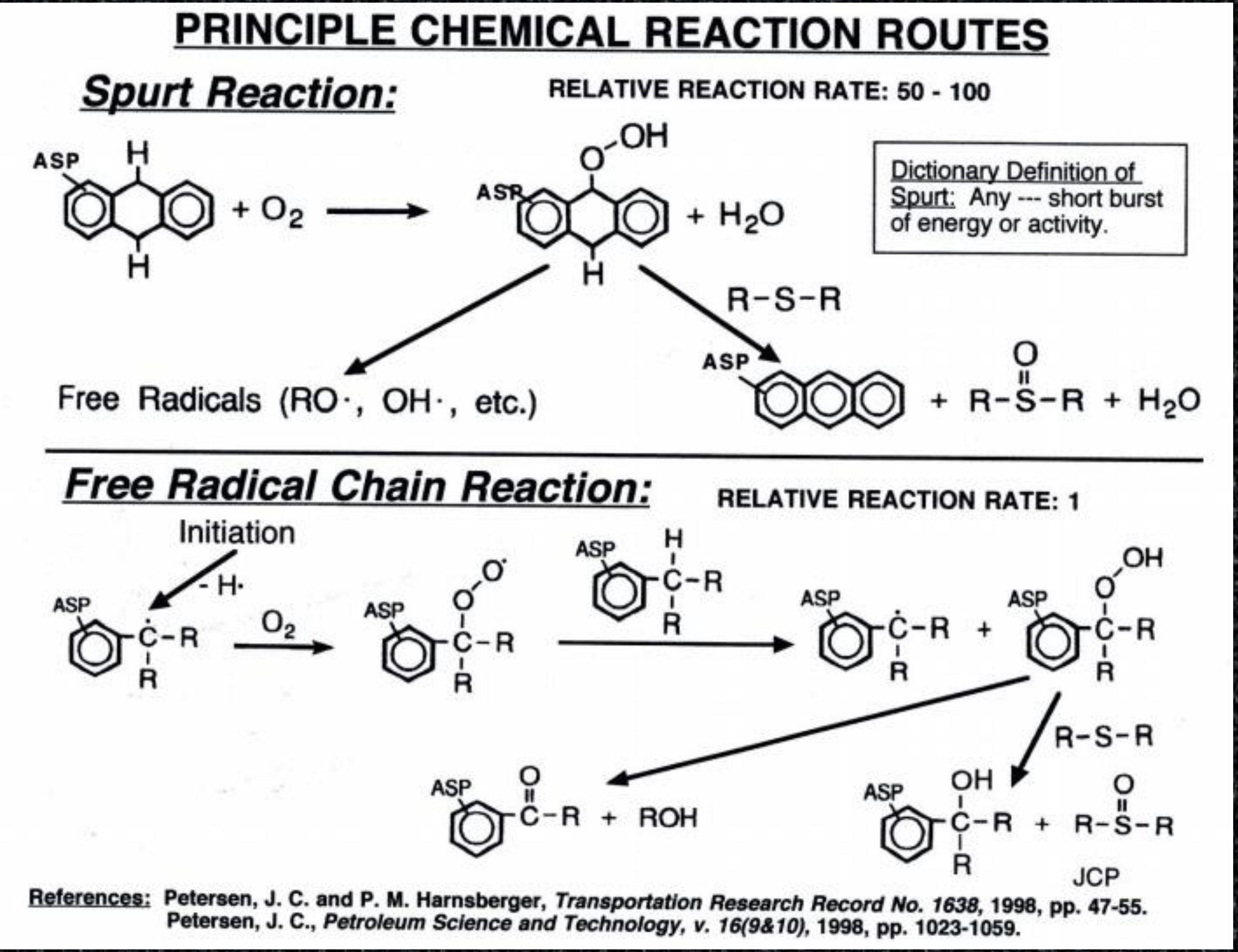
Work pointed to the key role that temperature plays in the rate of alteration of binder composition, alterations which manifest themselves in physical and rheological properties. The graph at right shows the rate of change in log Viscosity depends greatly on the temperature during oxidation.



Petersen, J.C., "Oxidative Aging Model: How It Relates to the Prediction of Pavement Performance," WRI/FHWA Symposium, Laramie, WY, June 2006.

The Chemical Changes due to Aging Were Being Revealed

In addition to a clearer understanding of the kinetics of aging reactions, greater insight was gained into the chemical changes (asphaltene growth particularly) but in all the asphalt components (SARA).



Petersen, J.C., "Oxidative Aging Model: How It Relates to the Prediction of Pavement Performance," WRI/FHWA Symposium, Laramie, WY, June 2006.

Many Researchers Contributed to Our Understanding of Asphalt

Technical Report Documentation Page

1. Report No. FHWA/TX-07/0-4688-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle POLYMER MODIFIED ASPHALT DURABILITY IN PAVEMENTS		5. Report Date November 2006 Published: July 2007 6. Performing Organization Code
7. Author(s) Won Jun Woo, Edward Ofori-Abebresse, Arif Chowdhury, Jacob Hilbrich, Zachary Kraus, Amy Epps Martin, and Charles J. Glover		8. Performing Organization Report No. Report 0-4688-1
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135		10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project 0-4688
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P. O. Box 5080 Austin, Texas 78763-5080		13. Type of Report and Period Covered Technical Report: September 2004-August 2006 14. Sponsoring Agency Code

15. Supplementary Notes
Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.
Project Title: Development of a Long-Term Durability Specification for Modified Asphalt
URL: http://tti.tamu.edu/documents/0-4688-1.pdf

16. Abstract

This project was designed to develop 1) a better quantitative understanding of the relation between laboratory accelerated binder aging and field aging, 2) a test procedure to measure properties of an aged binder that relate to failure on the road, and 3) a proposed specification for estimating the relative durability of binders in the presence of oxidative aging. Tests were conducted on original base and polymer modified binders, laboratory compacted mixtures, and pavement-aged binders. The project necessarily evolved to a more comprehensive approach to improving pavement service life.

Methods for significantly improving pavement durability should be implemented: 1) construct pavements with the lowest possible accessible (interconnected) air voids, consistent with other best construction and mix design practices; 2) use mix designs that have an inherently low decrease in fatigue life with binder oxidation, coupled with an appropriately high initial fatigue life; 3) use binders with a minimum stiffness at the PAV* 16 hour condition (consistent with the appropriate performance grade); 4) use the pavement aging model for pavement design; 5) use binders that have inherently slow hardening rates kinetics; and 6) use modifiers that provide the most reduction in the hardening rate. Items 1 and 2 have a dramatic impact on pavement service life but require additional research for the most effective implementation: 1) determine the parameters that govern the decline of mixture fatigue life with binder hardening; 2) determine methods to reliably, and with minimal risk to other construction parameters, achieve very low accessible air voids in pavements.

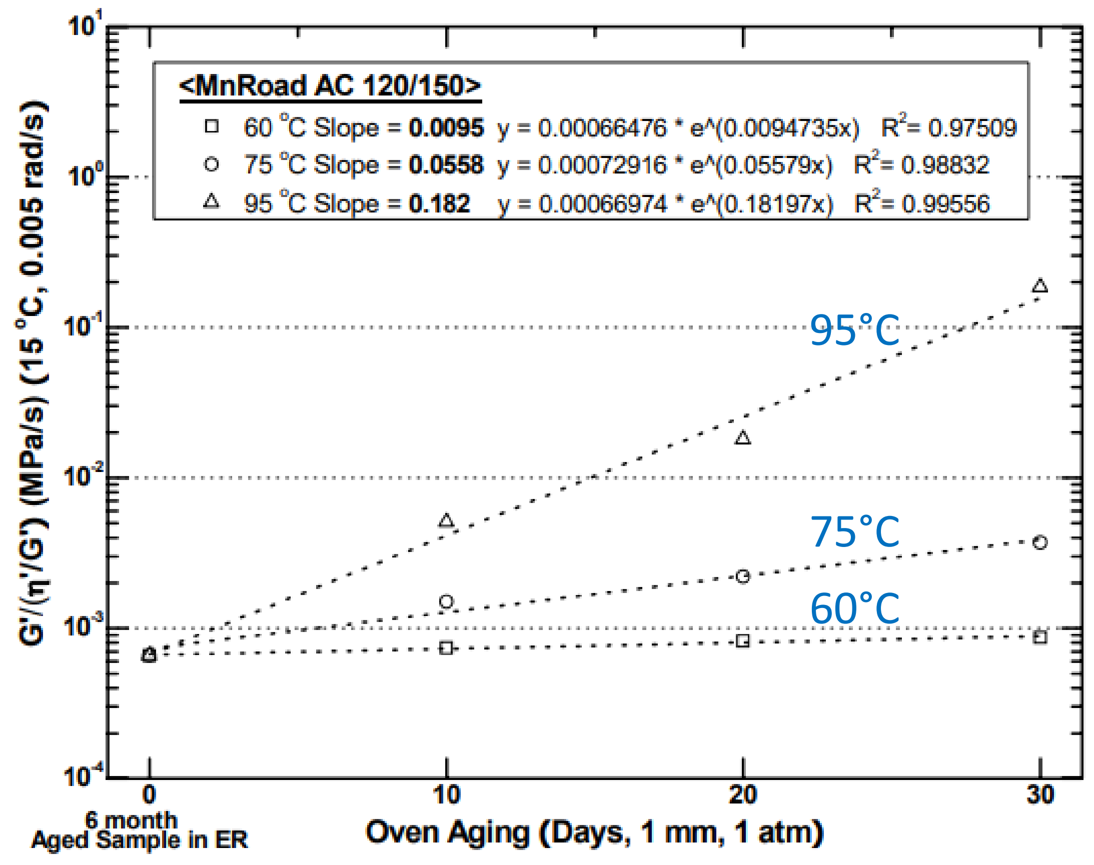


Figure 5-25. Effect of Temperature on MnRoad AC 120-150 Hardening Rate.

https://static.tti.tamu.edu/tti.tamu.edu/documents/0-4688-1.pdf,

A General Law of Asphalt Aging Reactions Eventually Developed

Technical White Paper

Asphalt Film Aging Model

Fundamental Properties of Asphalts and Modified Asphalts III Product: FP 05

March 2015

Prepared for
Federal Highway Administration
Contract No. DTFH61-07-D-00005

By
Ronald R. Glaser, Jenny Loveridge, Fred Turner, and
Jean-Pascal Planche
Western Research Institute
3474 North 3rd Street
Laramie, WY 82072
www.westernresearch.org

Western Research INSTITUTE

Work eventually led to a number of models that described binder aging in terms of conventional chemical reaction kinetics.

The basic rate equations can be written as:

$$\frac{dP_1}{dt} = k_1^{'}\left[C_{fast}\right]\left[O_2\right]^{0.5}$$
$$= k_1^{'}\left[O_2\right]^{0.5}\left[C_{fast,0} - P_1\right]$$

$$\frac{dP_2}{dt} = k_2^{'}\left[C_{slow}^{*}\right]\left[O_2\right]^{0.5} = k_2\left[P_1\right]\left[O_2\right]^{0.5}$$

where:

P_1 and P_2 = the product concentrations of the fast and slow reactions, respectively.
$k_1^{'}$ and $k_2^{'}$ = the isothermal rate constants (Arrhenius temperature dependency) for the fast and slow reactions, respectively.
C_{slow}^{*} = the free radical concentration, determined by the fast reaction and proportional to P_1.

BINDER AGING AS A FUNCTION OF TEMPERATURE

TECHBRIEF

The Asphalt Binder Oxidative Aging Chemo-Mechanical Model

FHWA Publication No.: FHWA-HRT-15-052

FHWA Contact: Jack Youtcheff, HRDI-10, (202) 493-3090, jack.youtcheff@dot.gov

Rationale for Asphalt Binder Oxidation Studies

The concept of designing perpetual pavements has obvious economic advantages when lifecycle costs are evaluated. The realization of extended pavement life resulting in reduced cost requires developing technologies to monitor and/or mitigate the effects of asphalt binder oxidation, which stiffens and embrittles the binder.

A fundamental understanding of the phenomena causing asphalt oxidation may suggest ways to control or stop it, either through material design or pavement design. A fundamental understanding of oxidation is also beneficial for designing cost-effective monitoring protocols for pavement to rationally assess when and what maintenance measures should be applied. An understanding of the oxidation processes is also essential to producing robust pavement performance models for use in pavement design.

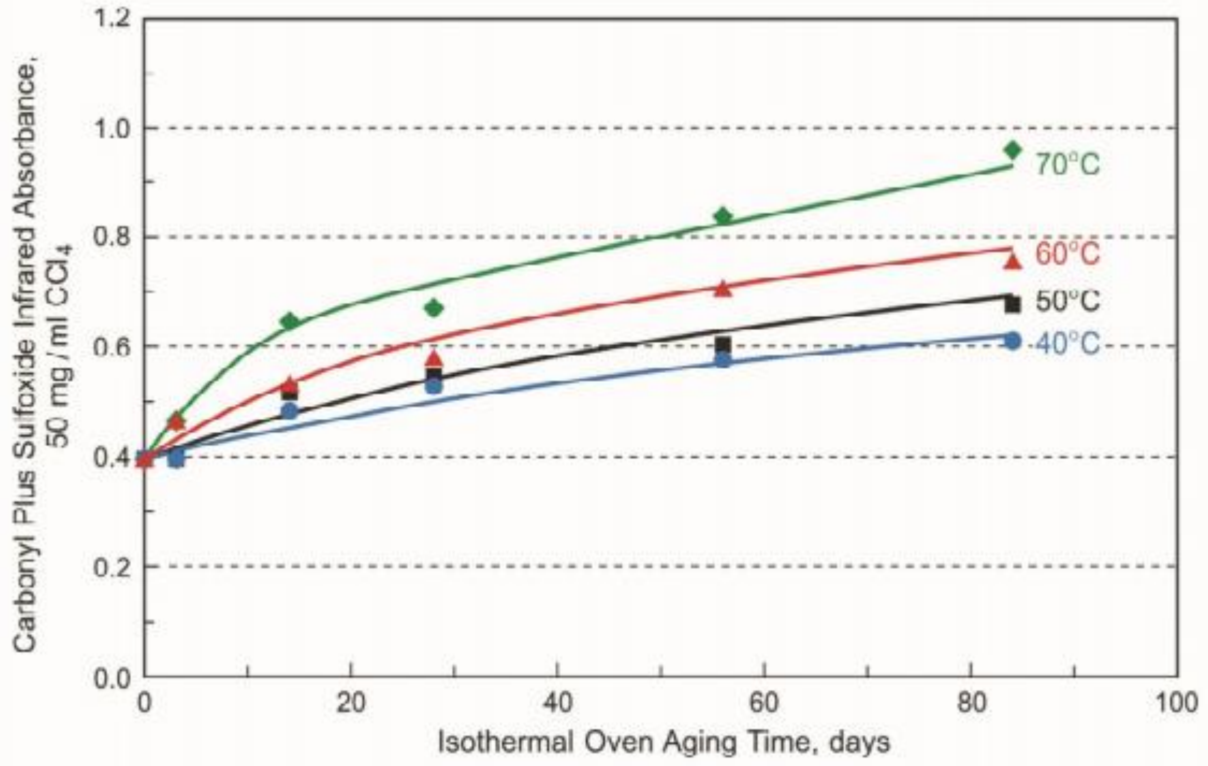
The rheological properties of asphalt binder change with oxidation, and these changes must be predicted over the service life of the pavement. The oxidized binder is stiffer, and stresses relax more slowly at comparable temperatures. The oxidized binder and the pavement it holds together accumulate stresses due to temperature drops much more quickly and at higher temperatures than the freshly placed binder. This shifts the effective performance grade to warmer values. Not only does the pavement accumulate stresses more readily in a given climate with oxidized binders compared with recently placed pavements, but the extent of oxidation is also more severe at the surface than deeper in the asphalt concrete, causing higher stress concentrations at the surface than

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

www.fhwa.dot.gov/research

Figure 1. Graph. Oxidation model fits to isothermal oxidation infrared absorption data for the ALF unmodified binder.



Source: WRI.

Youcheff, J. "The Asphalt Binder Oxidative Aging Chemo-Mechanical Model," FHWA Publication No. FHWA-HRT-15-052, 2018.

BINDER AGING AS A FUNCTION OF TEMPERATURE

TECHBRIEF

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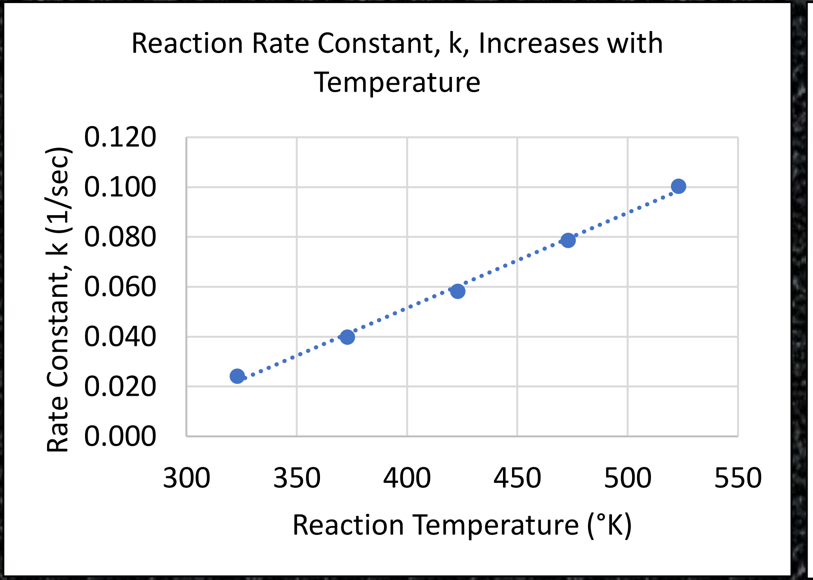
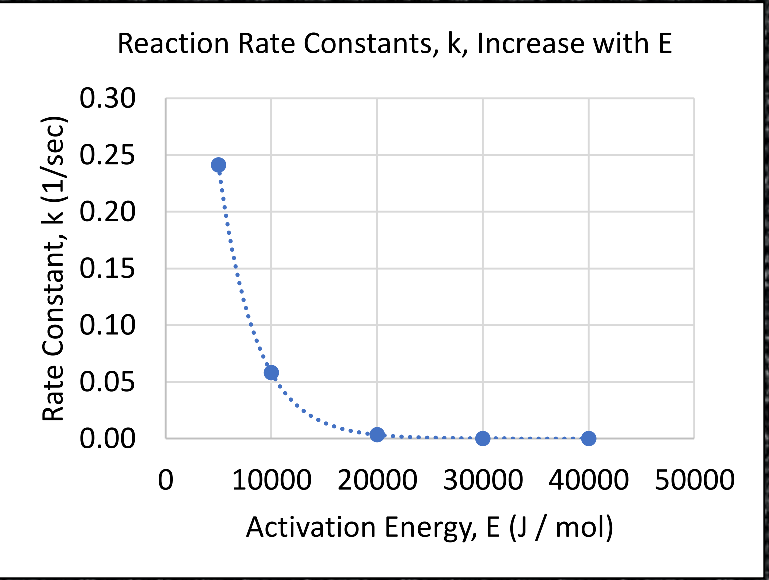
Rate of a reaction = $\frac{-dC}{dt} = k[C]$

Figure 8. Equation. The fast reaction temperature dependence.

$$k_1' = A_1 e^{\frac{-E_{a,1}}{RT}}$$

Rate constant, k
Frequency factor, A_1
Activation energy, $E_{a,3}$
Gas constant, R
Temperature, T





Youcheff, J. “The Asphalt Binder Oxidative Aging Chemo-Mechanical Model,” FHWA Publication No. FHWA-HRT-15-052, 2018.

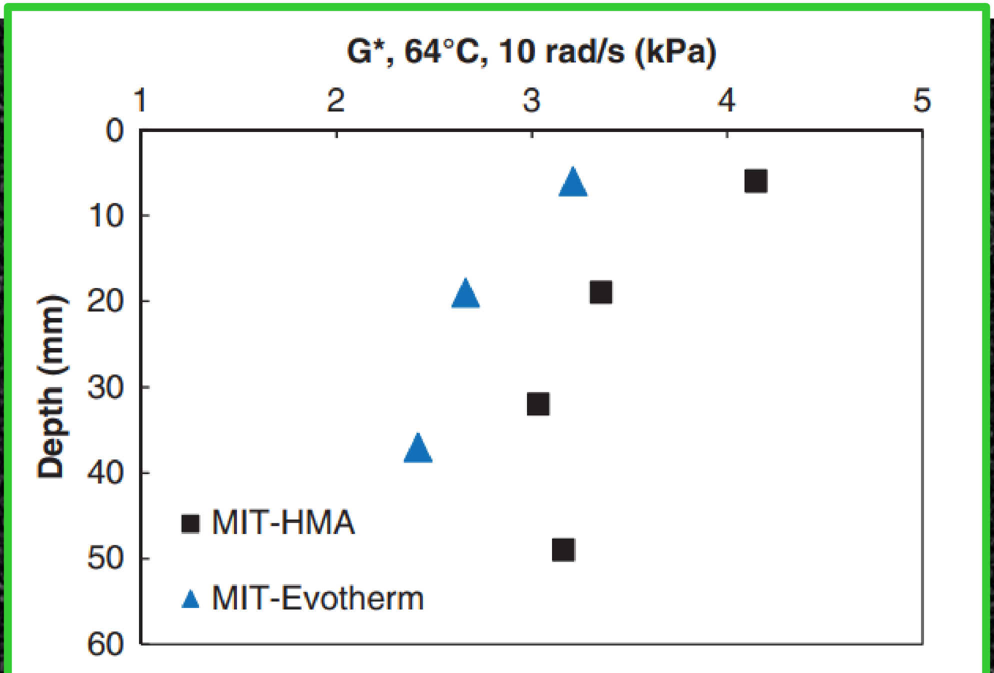
BINDER AGING AS A FUNCTION OF TEMPERATURE

More recent studies have taken a look at the effect of short-term aging temperature on rheological properties such as the crossover temperature ($\tan \delta = 1$).

Here the positive impact of lower heating temperatures (123°C versus 163°C) on two binders (B502 & B504) is apparent as well as it is in properties such as the Glover-Rowe damage parameter.

BINDER AGING AS A FUNCTION OF TEMPERATURE

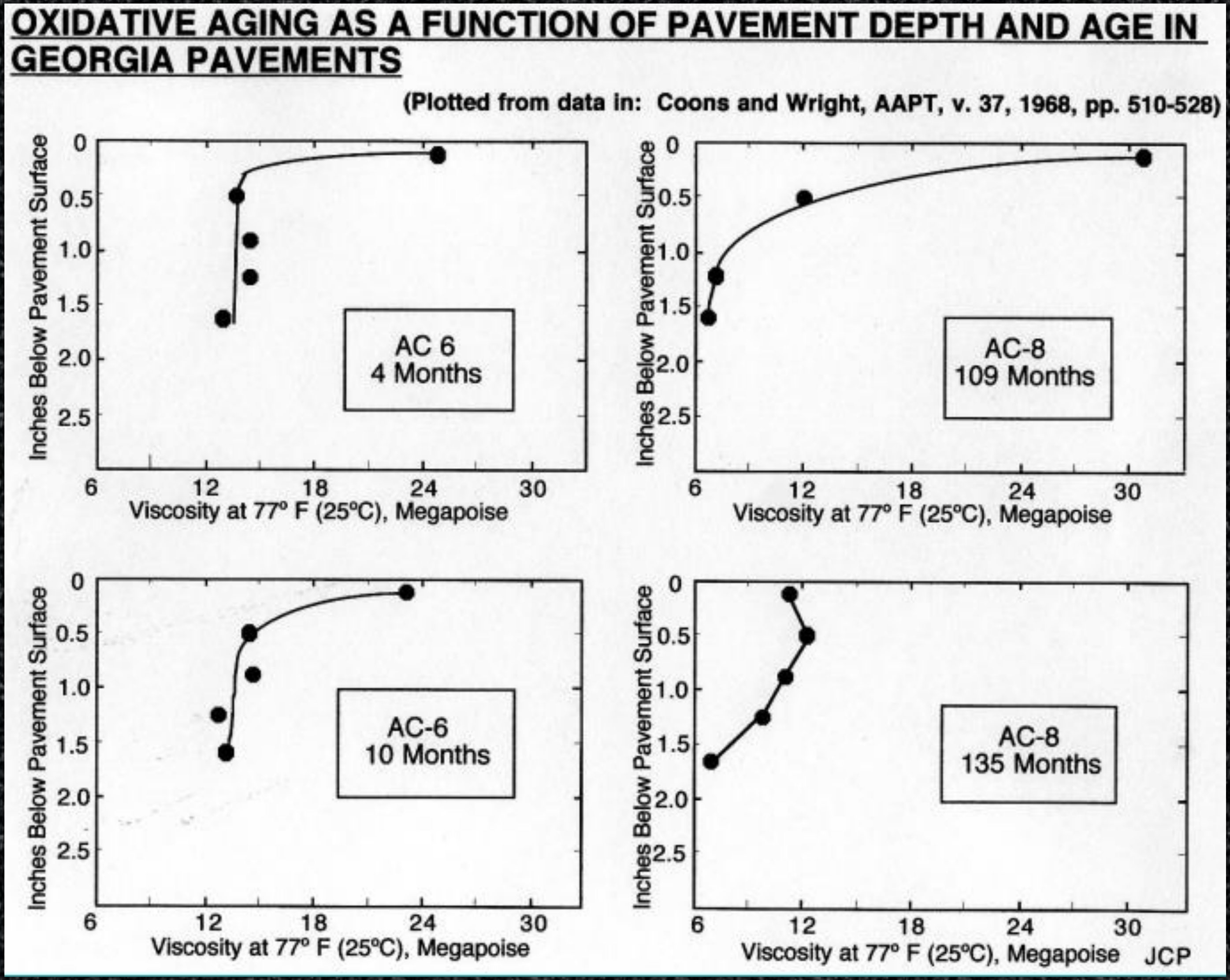
Site ID	Location	Binder / Modification	Date Built	Date Core Extracted
MB	Manitoba, Canada	Control HMA, Foam WMA, Evotherm WMA	2010	2014



(a)

National Academies of Sciences, Engineering, and Medicine 2017. Long-Term Aging of Asphalt Mixtures for Performance Testing and Prediction. Washington, DC: The National Academies Press. https://doi.org/10.17226/24959. Pages 56 and 57.

BINDER AGING AS A FUNCTION OF TEMPERATURE



Petersen, J.C., "Oxidative Aging Model: How It Relates to the Prediction of Pavement Performance," WRI/FHWA Symposium, Laramie, WY, June 2006.

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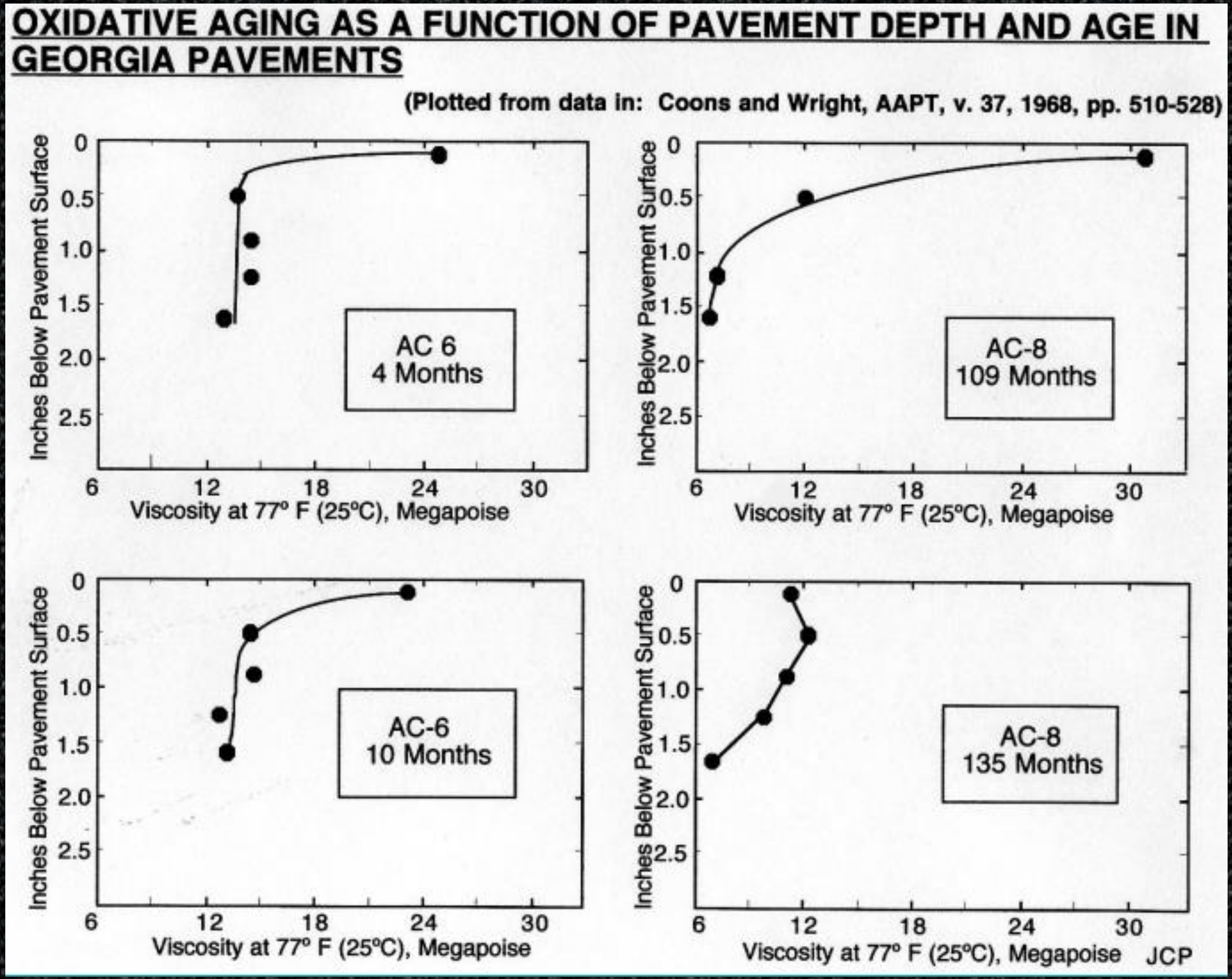

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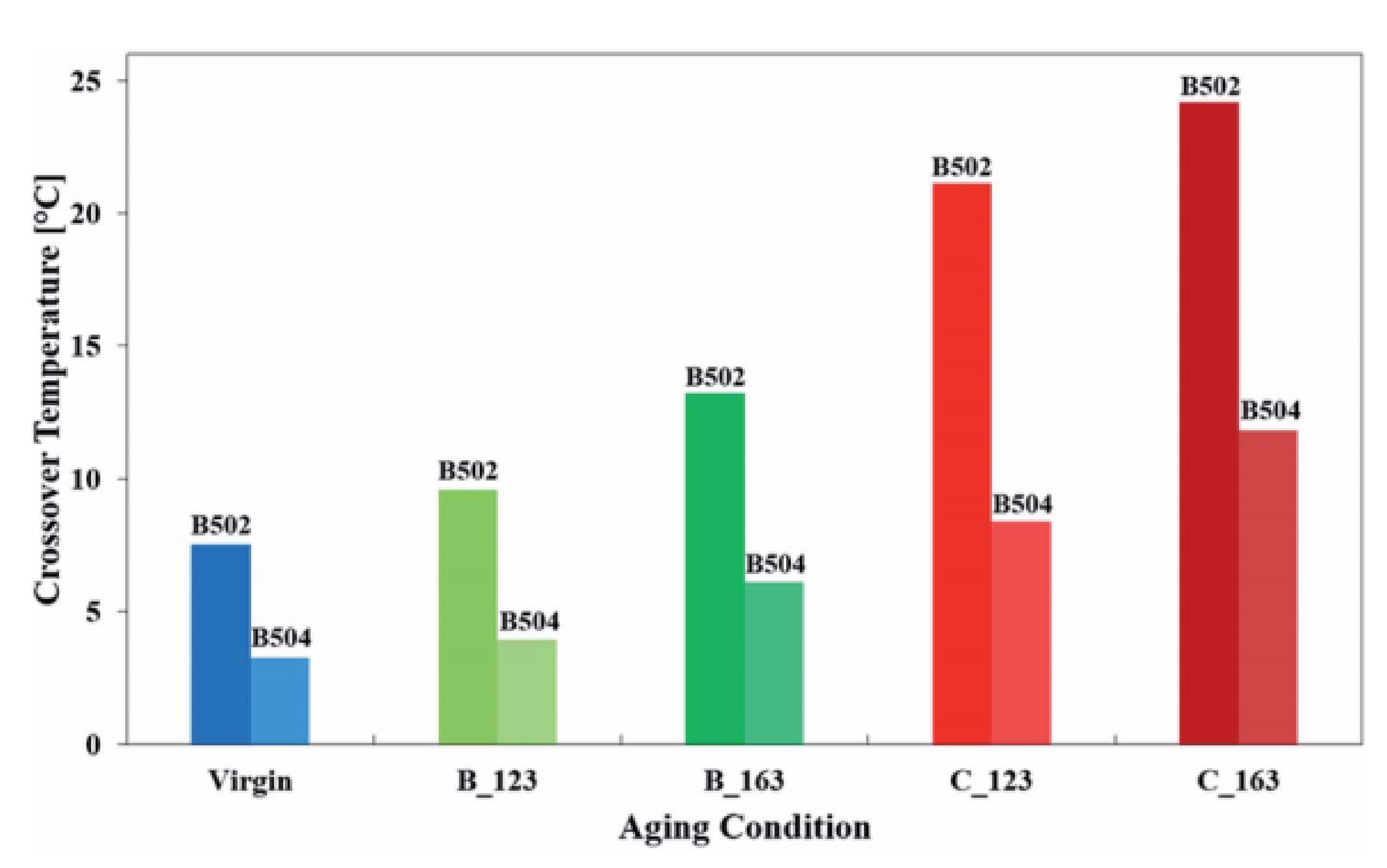


Poulikakos L. D., Cannone Falchetto A.,Wang D.,Porot L., Hofko B, “Impact of asphalt aging temperature on chemomechanics,” Royal Society of Chemistry Advances, : RSC Adv., 2019, 9, 11602.

Lower Aging Temperatures Alter the Asphalt Composition

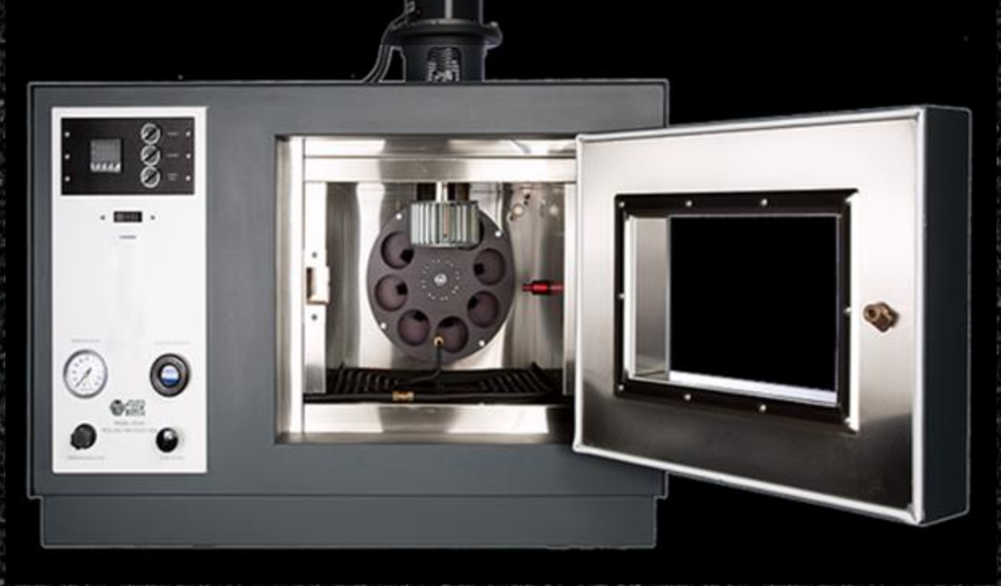
Code	Bitumen Grade	Aging and Sample Preparation Method	SARA Fractional Groups, %				Gaestel Index I_c
			Saturates	Aromatics	Resins	Asphaltenes	
1-RT	70/100	RTFOT	5.28	43.66	36.30	14.76	0.251
1-P1	70/100	PAV I (22 h)	5.21	27.86	51.95	14.97	0.253
1-P2	70/100	PAV II (44 h)	4.94	23.87	53.54	17.66	0.292
4-RT	PMB 45/80-55	RTFOT	5.18	34.32	41.76	18.73	0.314
4-P1	PMB 45/80-55	PAV I (22 h)	5.12	30.94	48.54	15.40	0.258
4-P2	PMB 45/80-55	PAV II (44 h)	5.03	24.82	55.55	14.60	0.244
7-RC	Unknown	Recovered	7.68	30.56	41.70	20.05	0.384
8-RC	Unknown	Recovered	6.01	31.52	44.72	17.75	0.312
9-RC	Unknown	Recovered	6.50	31.67	43.14	18.68	0.337
10-RC	Unknown	Recovered	6.79	33.23	42.09	17.88	0.328
11-RC	Unknown	Recovered	6.70	29.55	44.58	19.18	0.349

Kleiziene, R., et. al. “Effect of Aging on Chemical Composition and Rheological Properties of Neat and Modified Bitumen,” Materials 2019, 12, 4066, page 8.

What Are Our Key Aging Test Approaches Today

Short-term Aging

Rolling Thin Film Oven

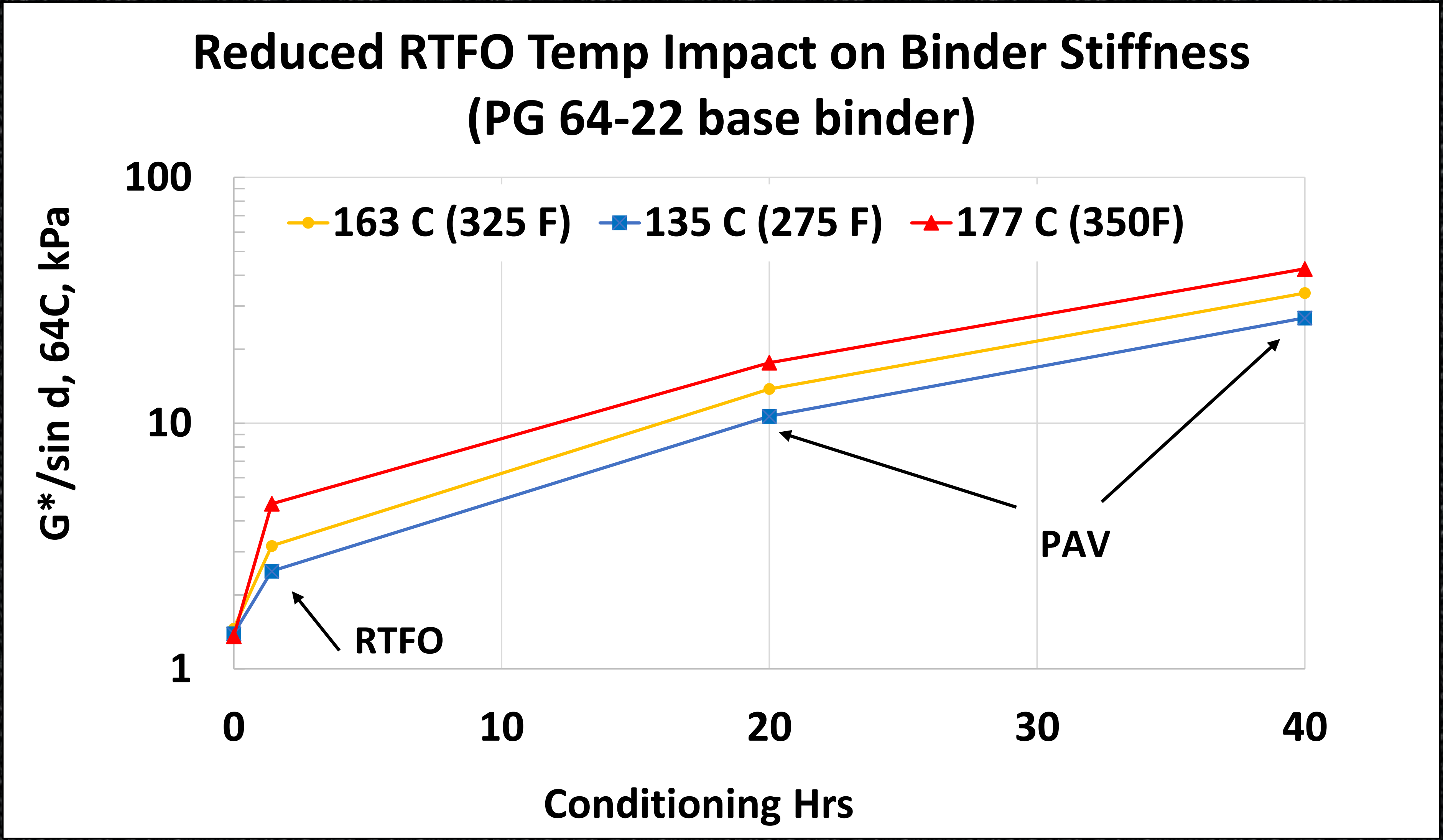


In-service Aging

Pressure Aging Vessel

Plllllersen, J.C., “Oxidative Aging Model: How It Relates to the Prediction of Pavement Performance,” WRI/FHWA Symposium, Laramie, WY, June 2006.

What Happens When We Lower RTFO Temperatures



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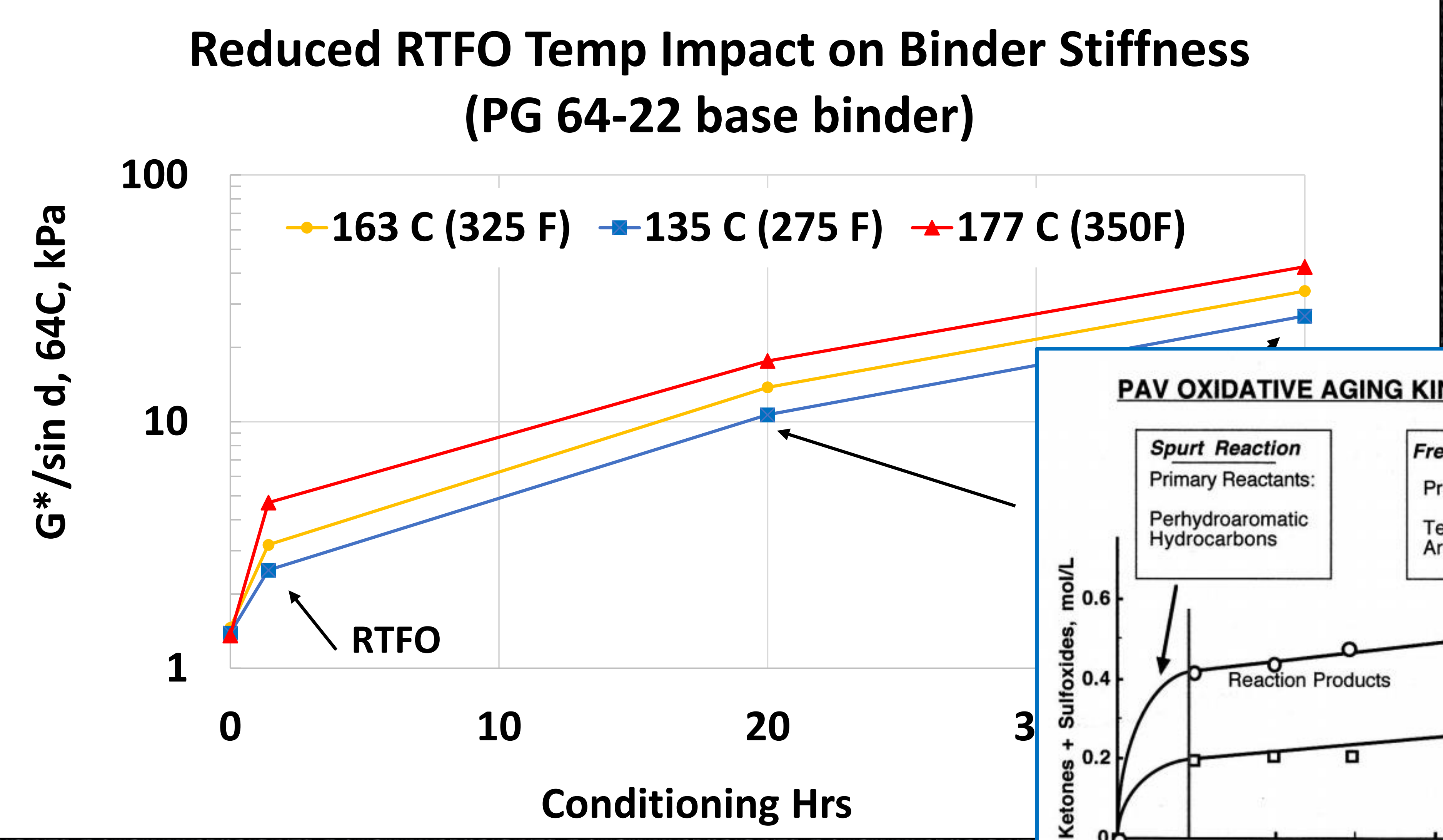
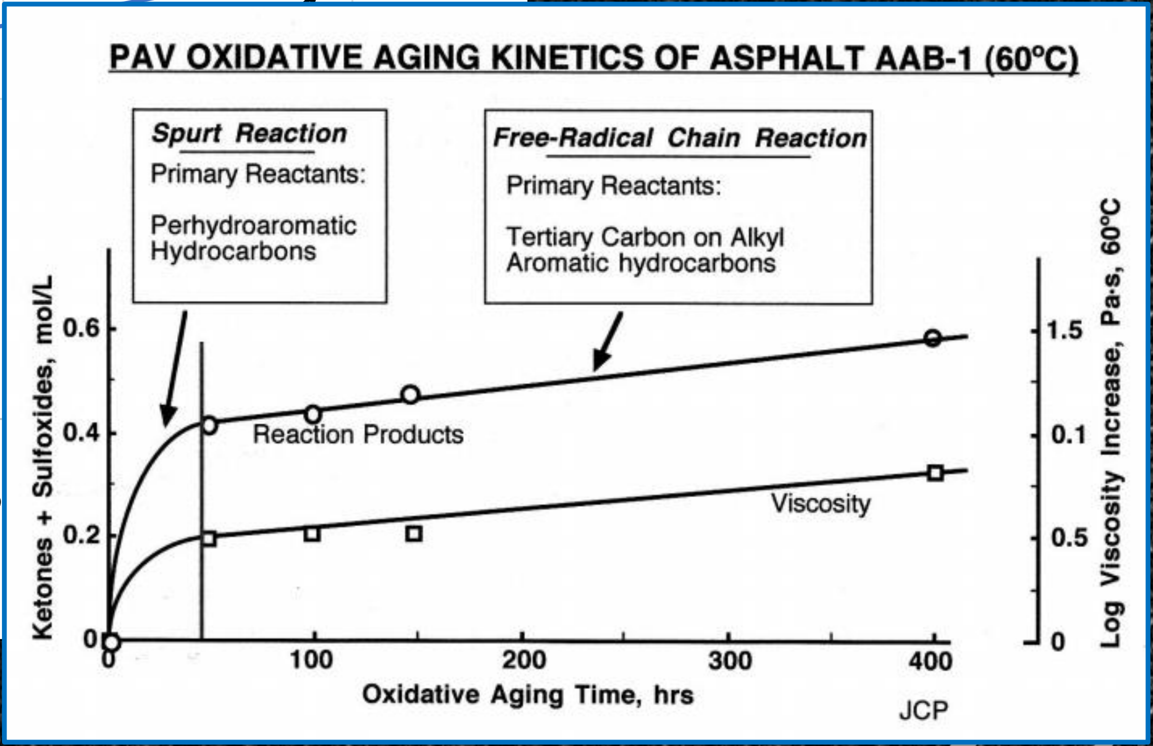
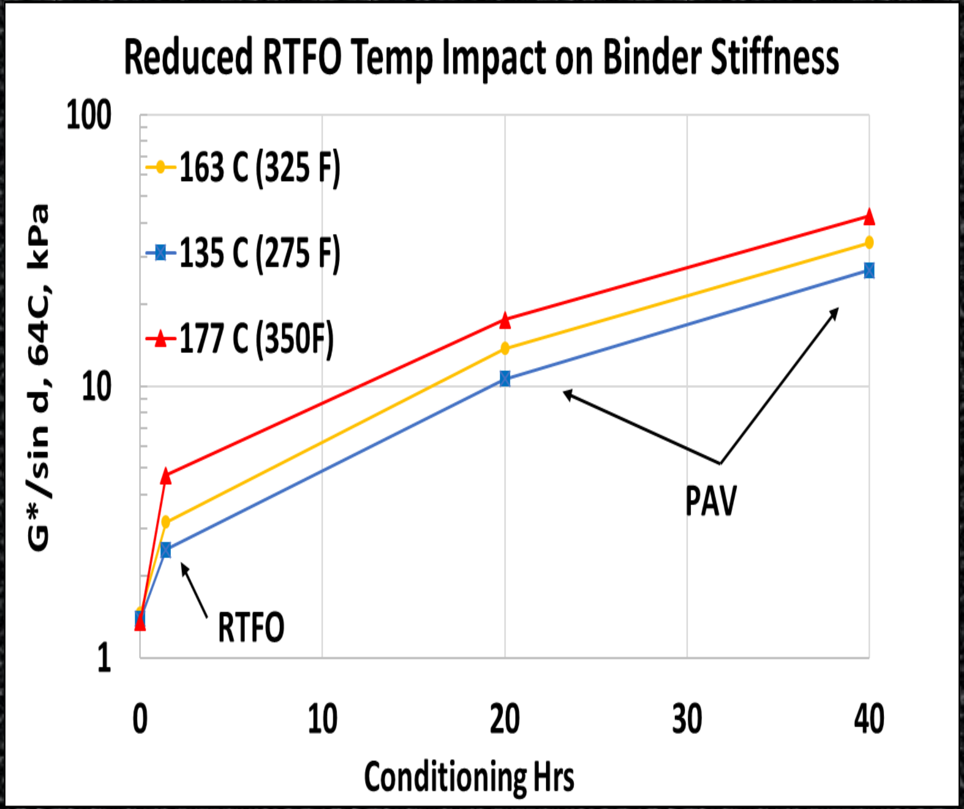
Lower RTFO Temperatures Reduce the Rapid "Jump" Aging (Petersen)





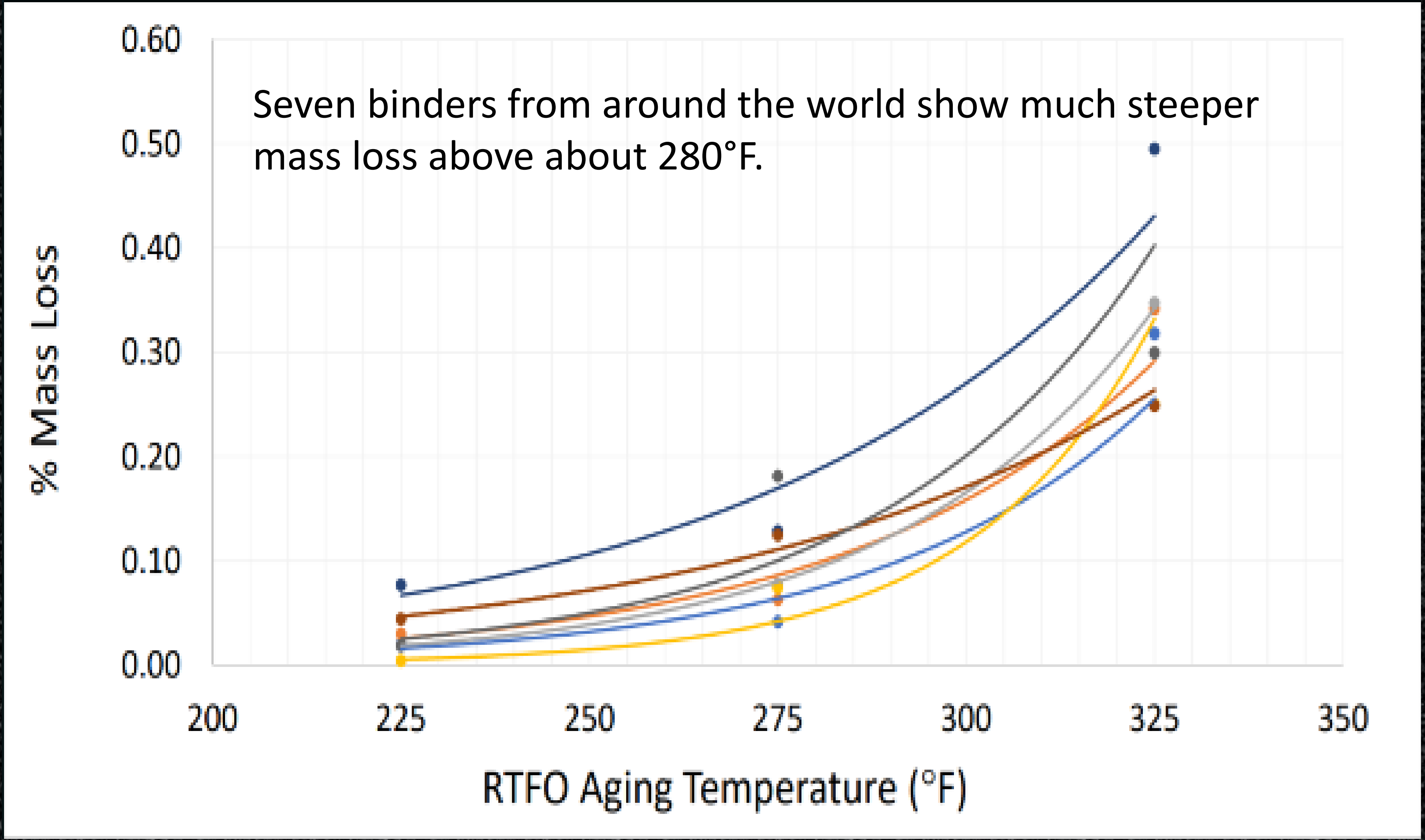
The Effect of Lower RTFO Temperatures Is Significant

	RTFO +25 F 177 C (350 F)	Std RTFO 163 C (325 F)	RTFO -50 F 135 C (275 F)
PG 64-22	High Temp Aging Rate G*/sin d, kPa / Hr		
RTFO Conditioning	2.32	1.24	0.77
PAV Conditioning	1.02	0.77	0.61
Rate Change Relative to STD, %	87		-38



87% = (2.32-1.24)*100/1.24
-38% = (0.77-1.24)*100/1.24

Lower RTFO Temp Reduces Binder Loss



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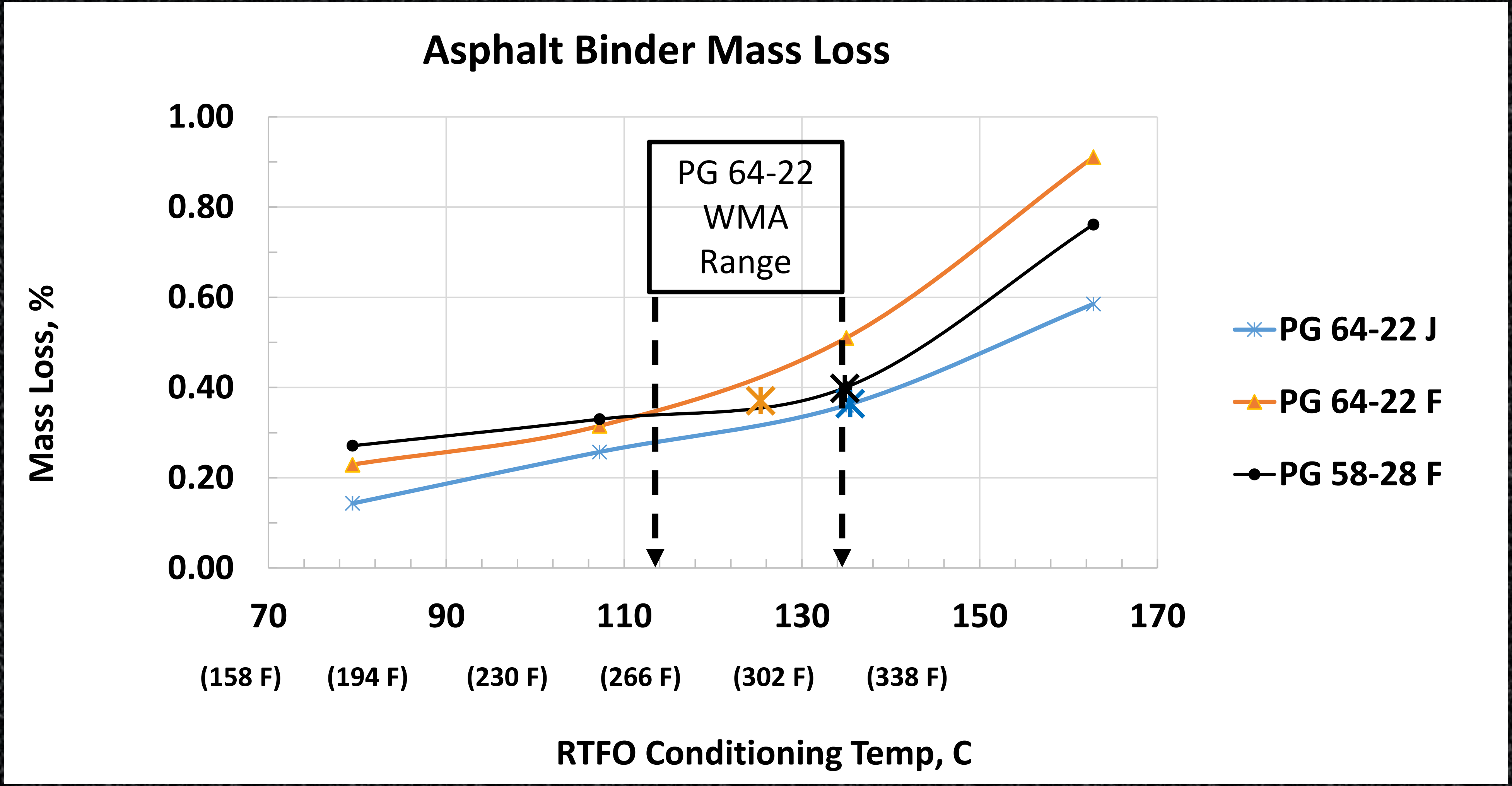
Lower RTFO Temp Reduces Binder Loss



Above WMA typical temperatures, mass loss tends to increase.

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- How do lower short-term temperatures (WMA) impact binder low and mid temperature performance?

- Does the typical PG grading (20 Hours PAV) show value of lower short-term temperatures?

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Binder Performance at Varying RTFO Temperature and Varying Percent ABR

Binder Blends	RTFO Temperature
PG 64-22	163°C (325°F) (Std Temp)
PG 64-22	177°C (350°F) (Std Temp + 14°C (25°F))
PG 64-22, 10% SynRAP ABR, 0.5% WMA	135°C (275°F) (Std Temp – 28°C (50°F))
PG 64-22, 25% SynRAP ABR, 0.5% WMA	135°C (275°F) (Std Temp – 28°C (50°F))

All other testing conditions were fixed:

PAV, 100C : 20, 40, and 60 Hrs

PG Low critical temperature (PG -YY)

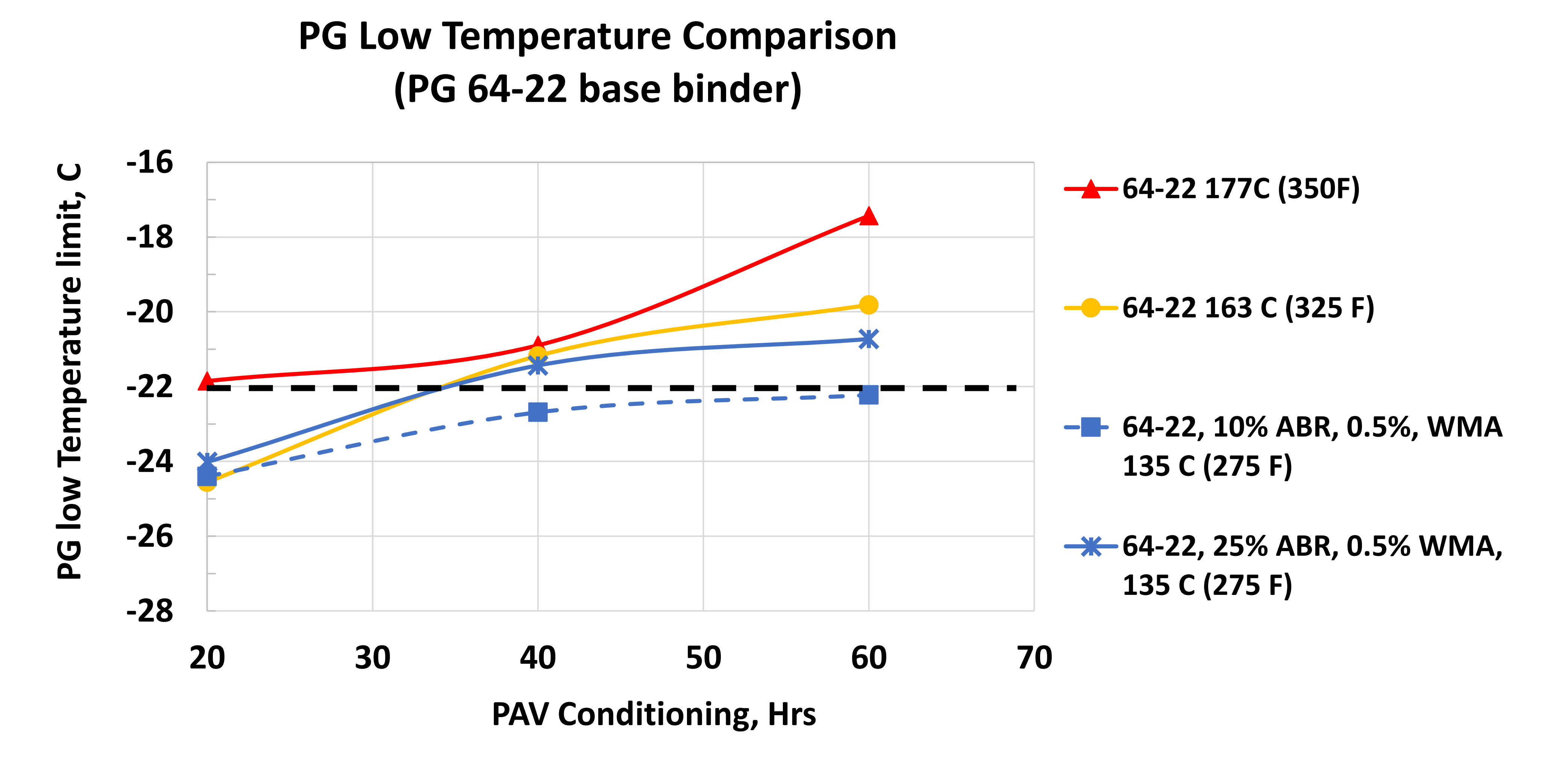
$\Delta T_{critical}$ and Glover-Rowe Parameter

Binder Performance Criteria

Criteria	Ductility 15C & 1 cm/min. (cm)	Glover DSR Function[1] 44.7°C 10 rad/sec (MPa/sec)	DTc Anderson et al recommended value (°C)	G-R Parameter Calculated from Glover et al.'s values 15°C 0.005 rad/sec (kPa)
Cracking Warning	5	3.0E-3	-2.5	180
Cracking Limit	3	9.0E-4	-5.0	600[2]

Ref. Rowe, Geoff. *The development of the ΔTc and Glover-Rowe parameters for the control of non-load associated cracking.* CAPSA, 2019

Lower RTFO Temp Improves Long-Term PG Performance, PG -YY



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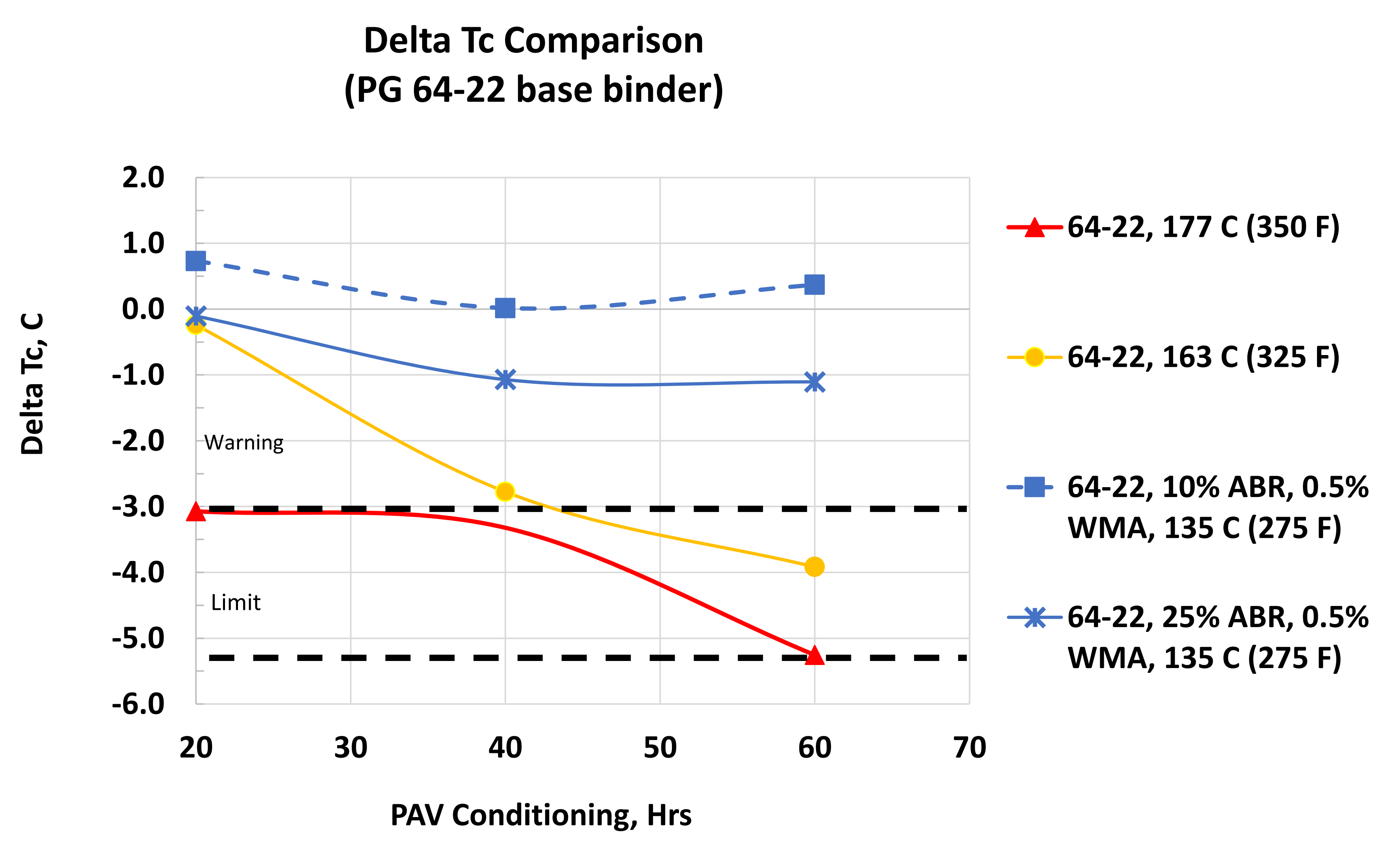
Lower RTFO Temperature Improves Long-Term ΔTc



$$\Delta Tc = T_{cont}\,S - T_{cont}\,m$$

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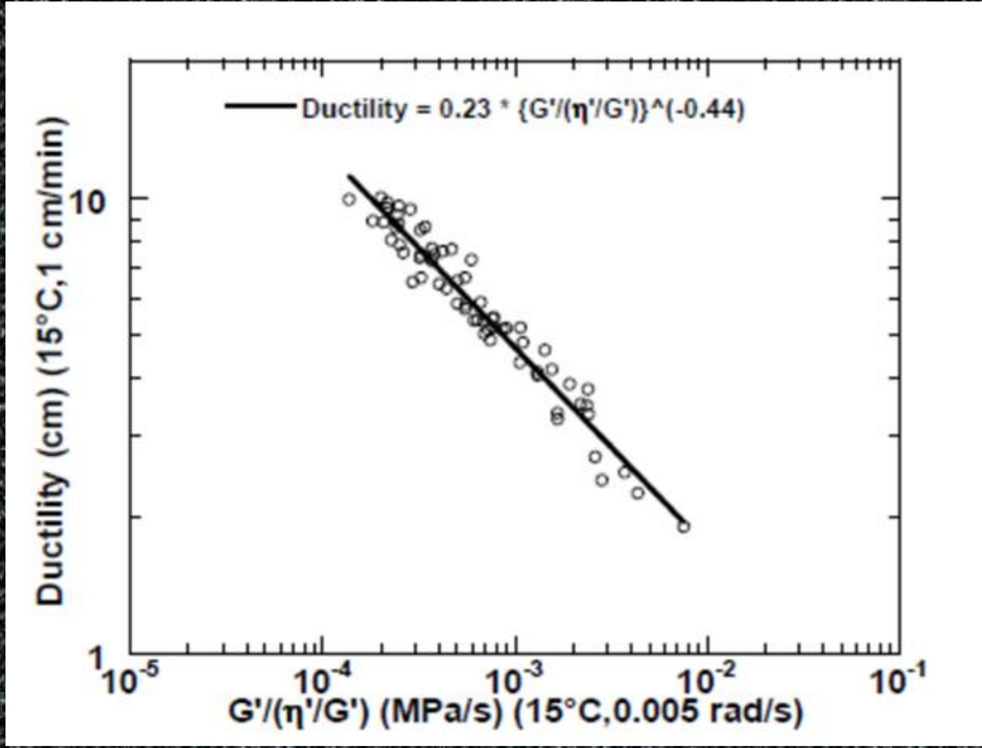
Glover-Rowe Parameter (background)

Kandahl, 1977

Ductility at 15.5C & 5 cm/min (cm)	Pavement Condition Observed
>10	Satisfactory
8 to 10	Loss of Fines (matrix)
5 to 8	Raveling
3 to 5	Cracking, needs resurfacing
<3	Very poor, extensive cracking

Glover, et al. FHWA- 2005

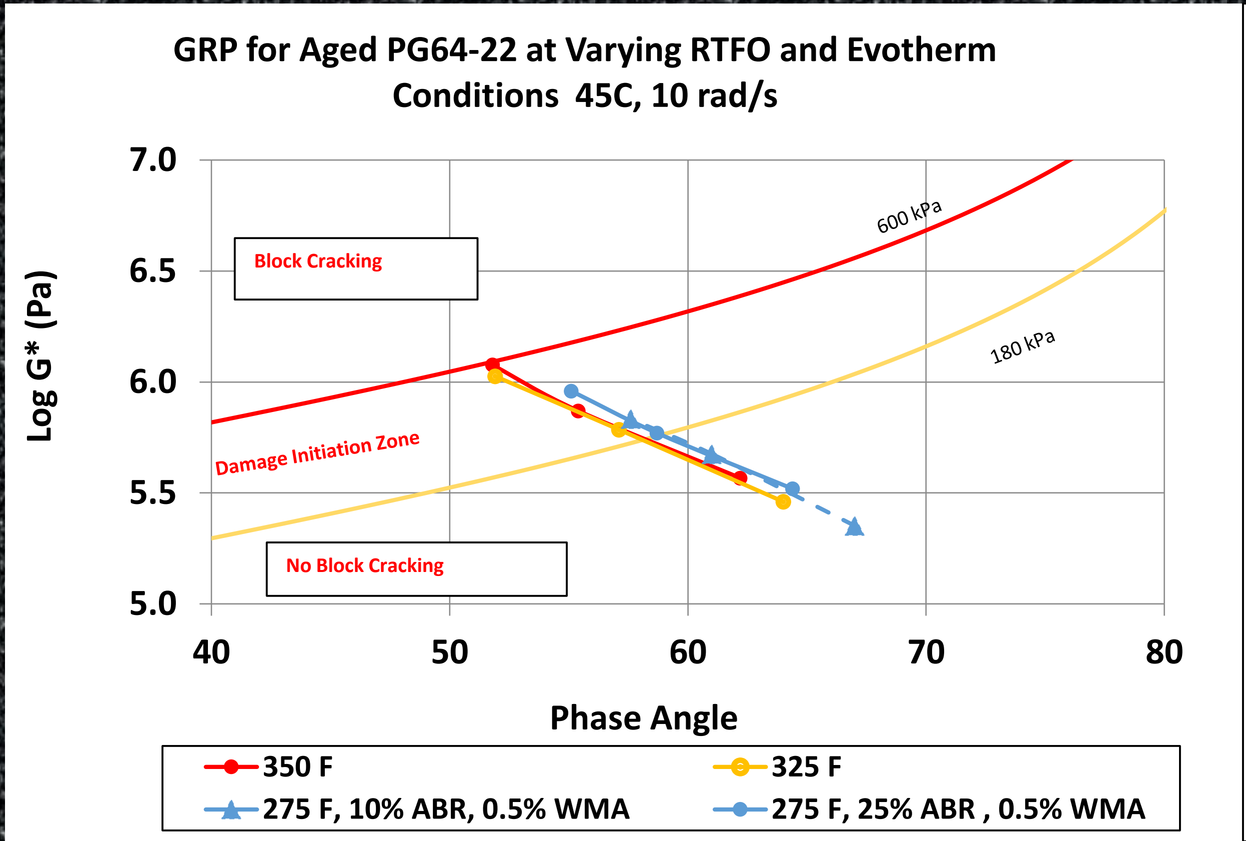


Rowe, AAPT 2011

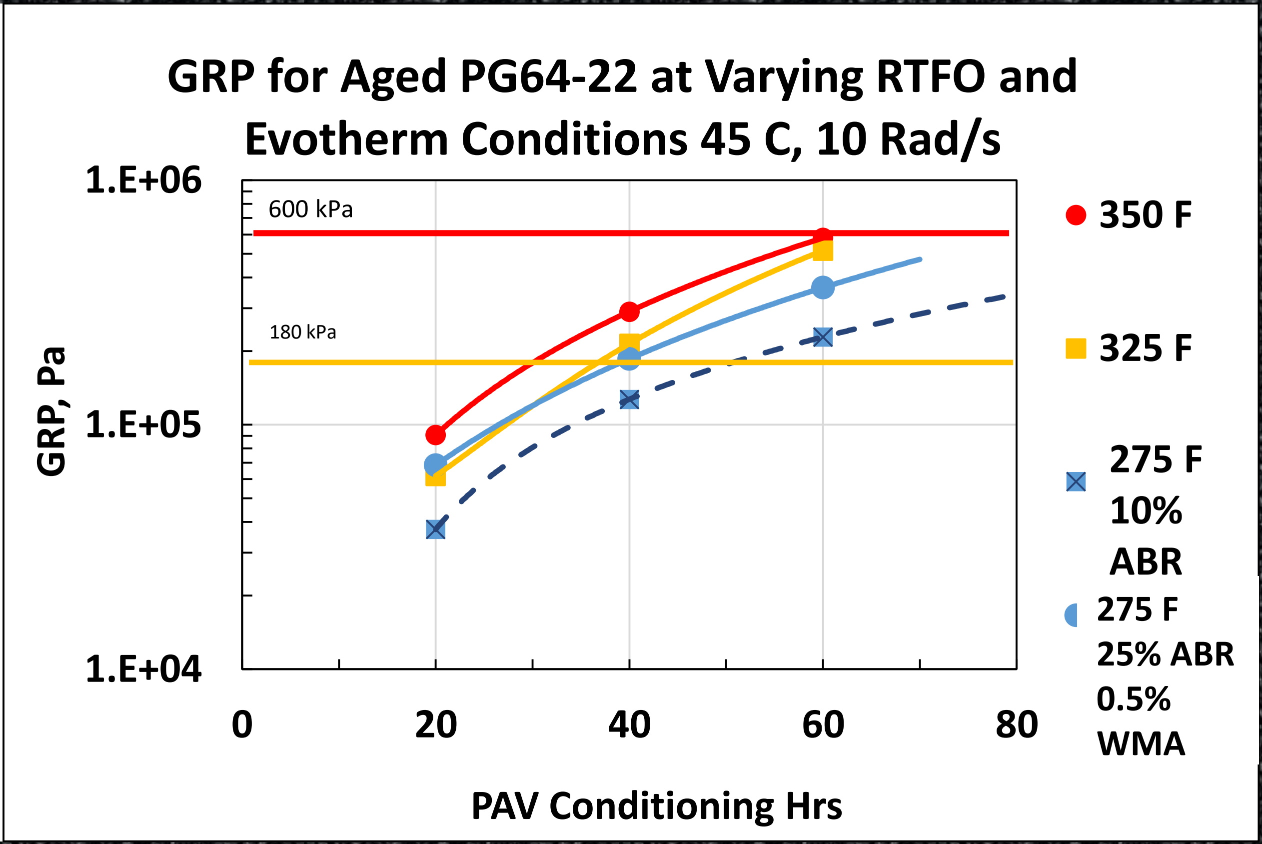
- $\frac{G'}{\frac{\eta'}{G'}} = \frac{G^*(\cos(\delta))^2}{\sin(\delta)}$ ← Glover-Rowe Parameter (GRP)
- $\frac{G^*(\cos(\delta))^2}{\sin(\delta)}$ at 15C & 0.005 rad/sec ≤ 180 kPa

Glover-Rowe Parameter (GRP) Examples

Black Space Diagram



GRP Values



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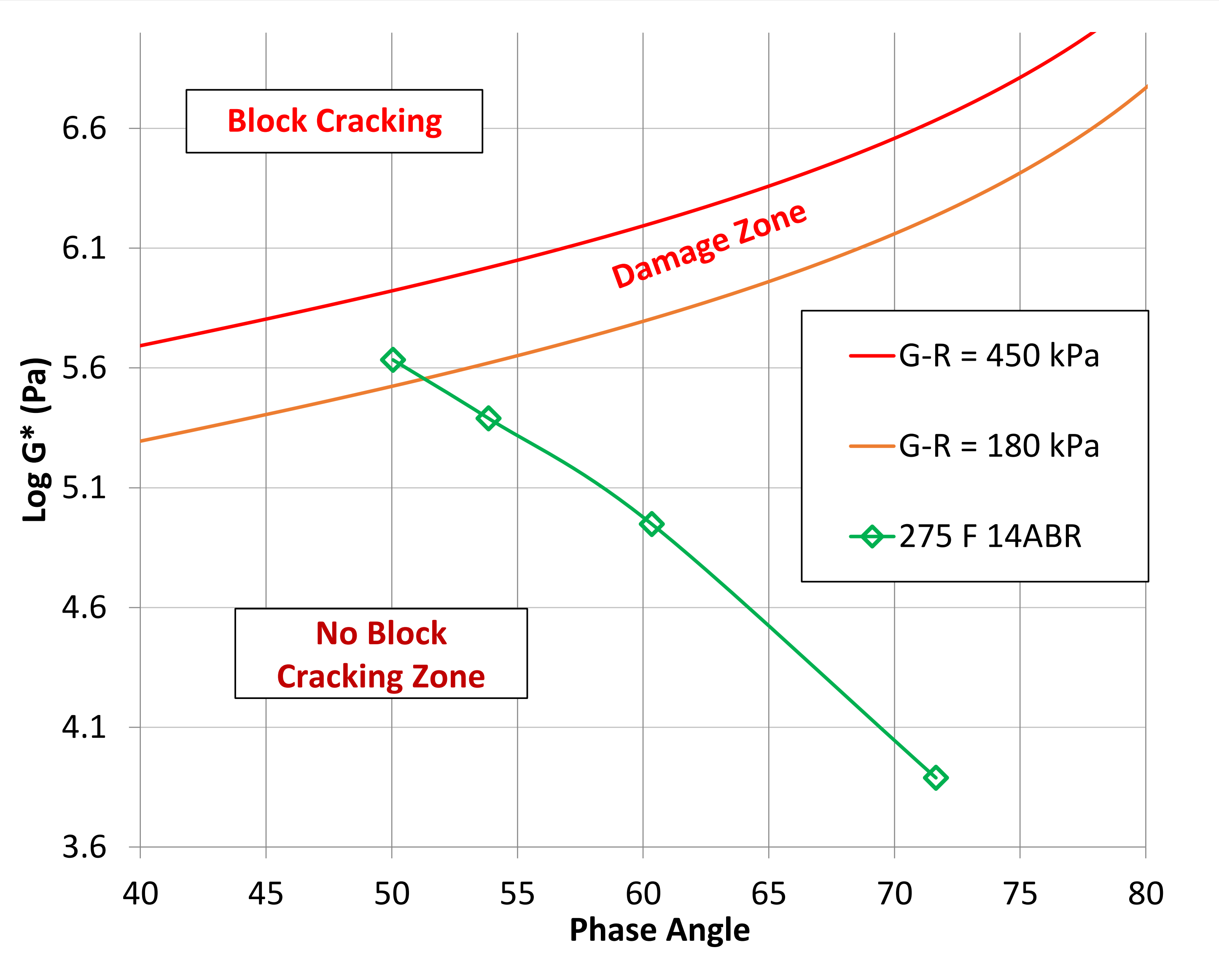
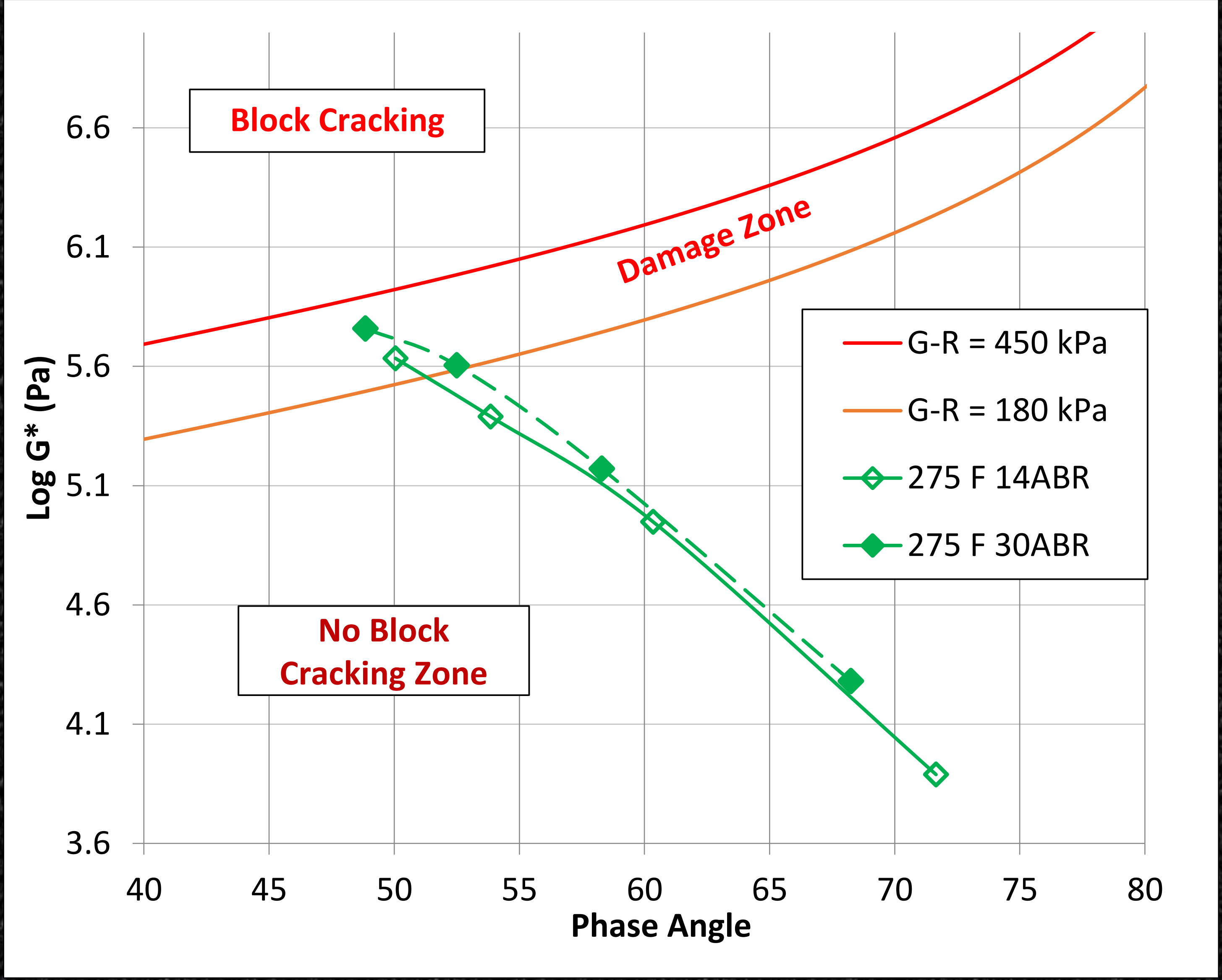
BINDER AGING AS A FUNCTION OF TEMPERATURE

Condition	PAV h	G-RP	δ
275 RTFO, 14 ABR	0	3.88934	71.7
	20	4.94801	60.4
	40	5.3897	53.9
	60	5.63377	50.1



BINDER AGING AS A FUNCTION OF TEMPERATURE

Condition	PAV h	G-RP	δ
275 RTFO, 14 ABR	0	3.88934	71.7
	20	4.94801	60.4
	40	5.3897	53.9
	60	5.63377	50.1
275 RTFO, 30 ABR	**0**	**4.28082**	**68.3**
	20	**5.17084**	**58.3**
	40	**5.60446**	**52.5**
	60	**5.75896**	**48.9**



BINDER AGING AS A FUNCTION OF TEMPERATURE

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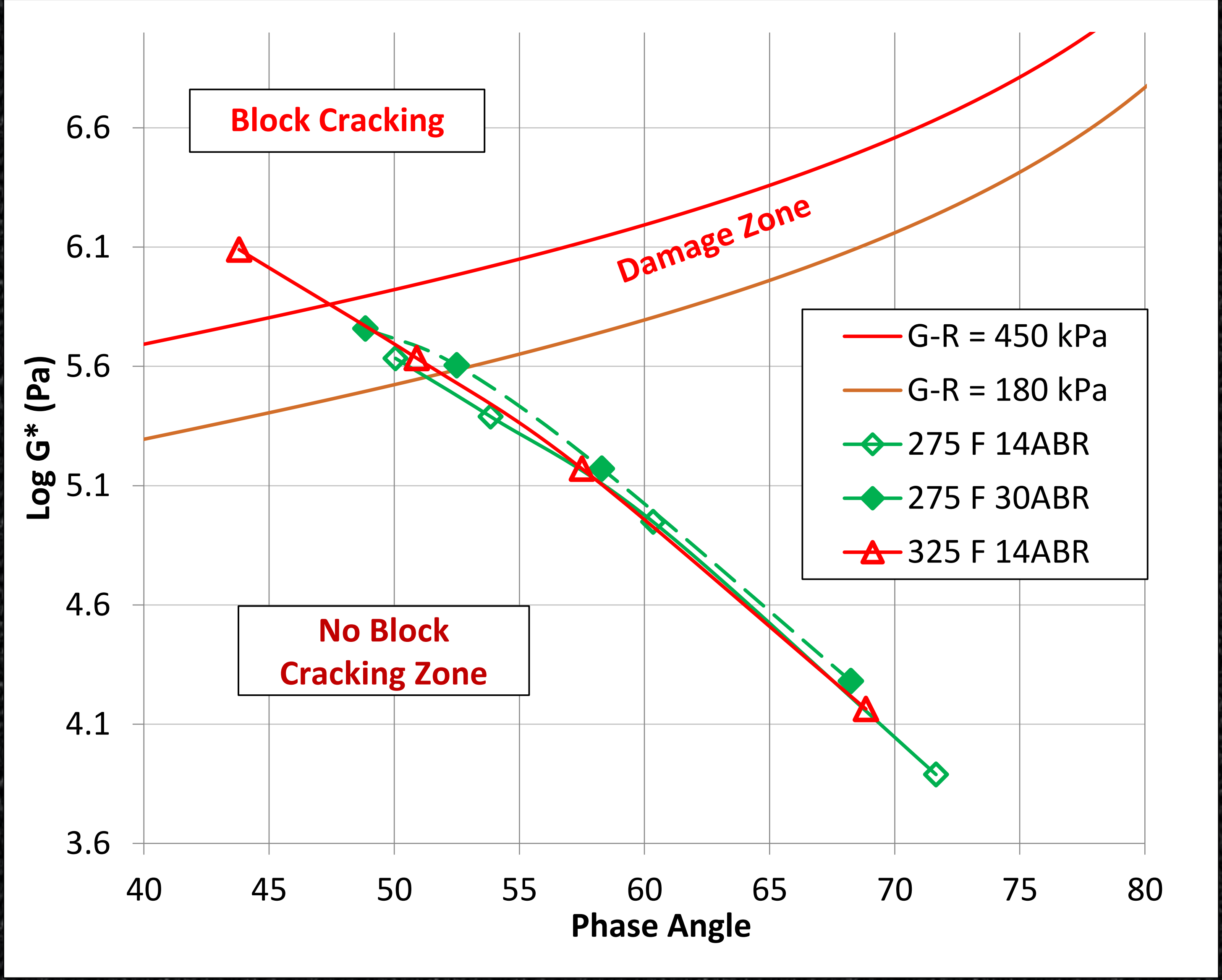
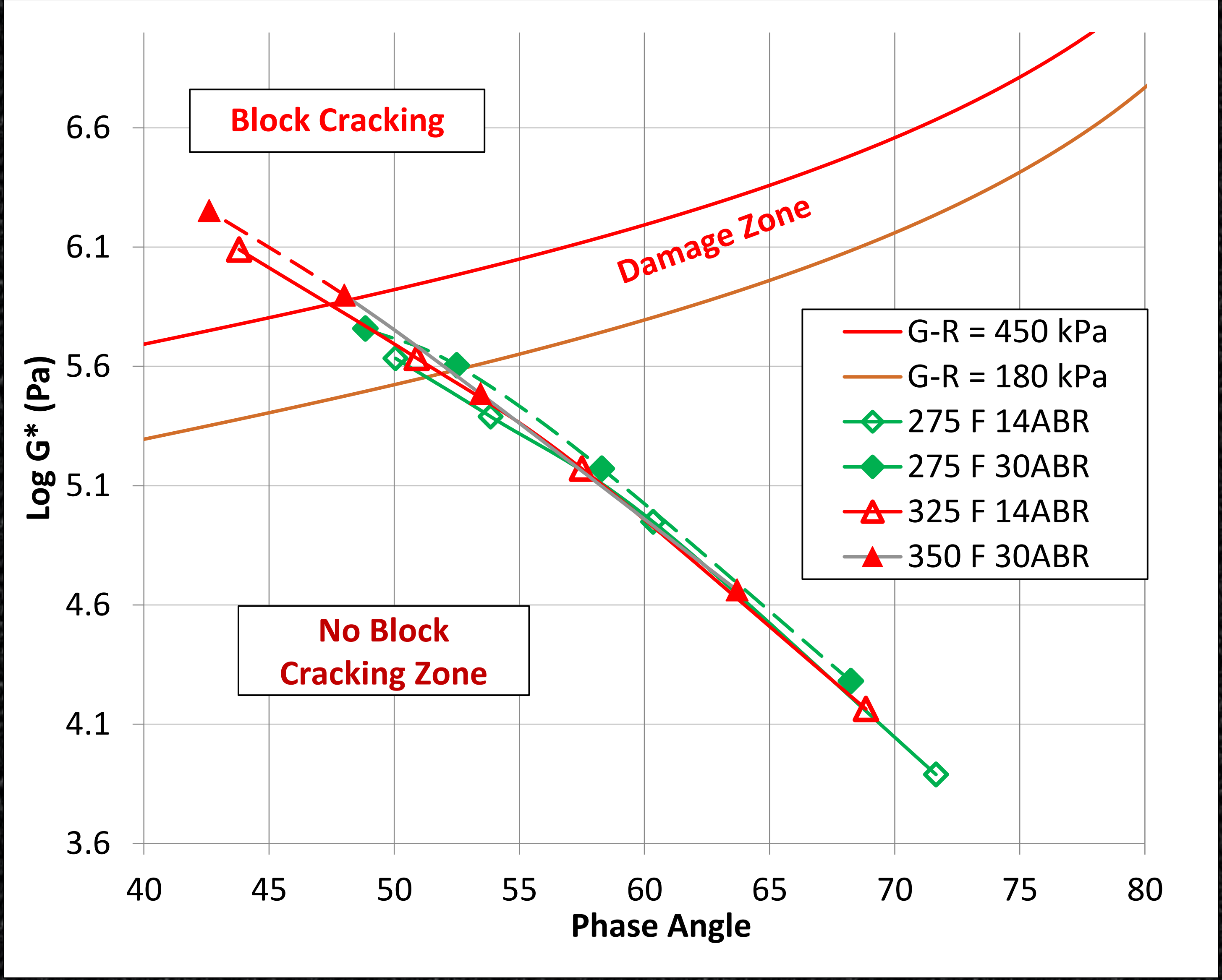
275 RTFO, 30 ABR	**0**	**4.28082**	**68.3**
	20	**5.17084**	**58.3**
	40	**5.60446**	**52.5**
	60	**5.75896**	**48.9**
325F RTFO, 14 ABR	0	4.16373	68.9
	20	5.17109	57.5
	40	5.63455	50.9
	60	6.08978	43.8

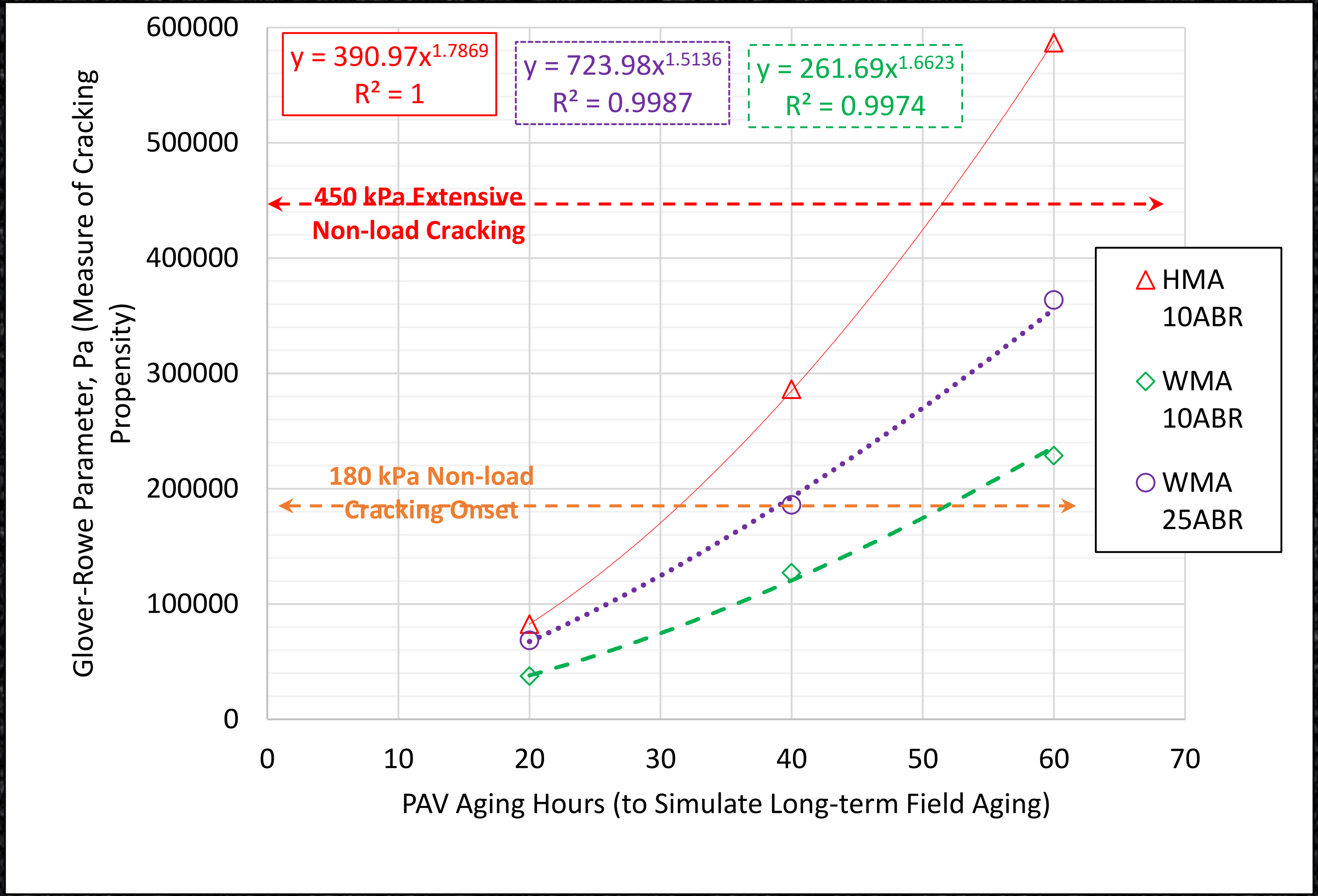


BINDER AGING AS A FUNCTION OF TEMPERATURE

Condition	PAV h	G-RP	δ
275 RTFO, 14 ABR	0	3.88934	71.7
	20	4.94801	60.4
	40	5.3897	53.9
	60	5.63377	50.1
275 RTFO, 30 ABR	**0**	**4.28082**	**68.3**
	20	**5.17084**	**58.3**
	40	**5.60446**	**52.5**
	60	**5.75896**	**48.9**
325F RTFO, 14 ABR	0	4.16373	68.9
	20	5.17109	57.5
	40	5.63455	50.9
	60	6.08978	43.8
350 RTFO, 30 ABR	**0**	**4.66262**	**63.7**
	20	**5.48548**	**53.5**
	40	**5.89931**	**48.0**
	60	**6.25298**	**42.6**

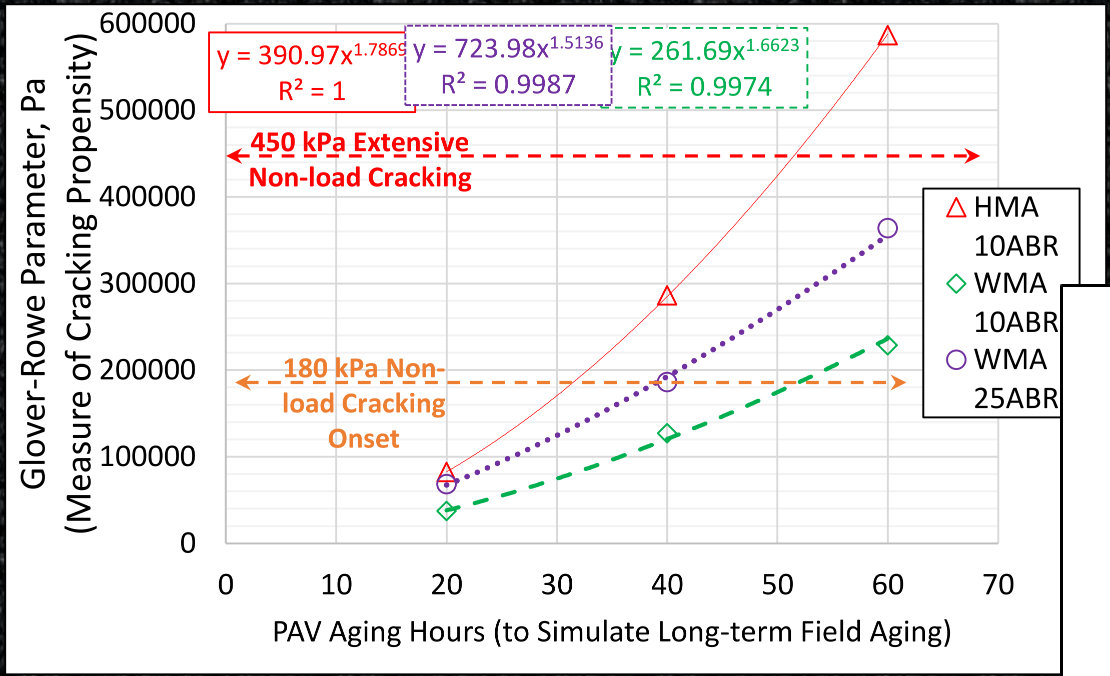


Another Way to Look at the Glover-Rowe Parameter (450 kPa limit)

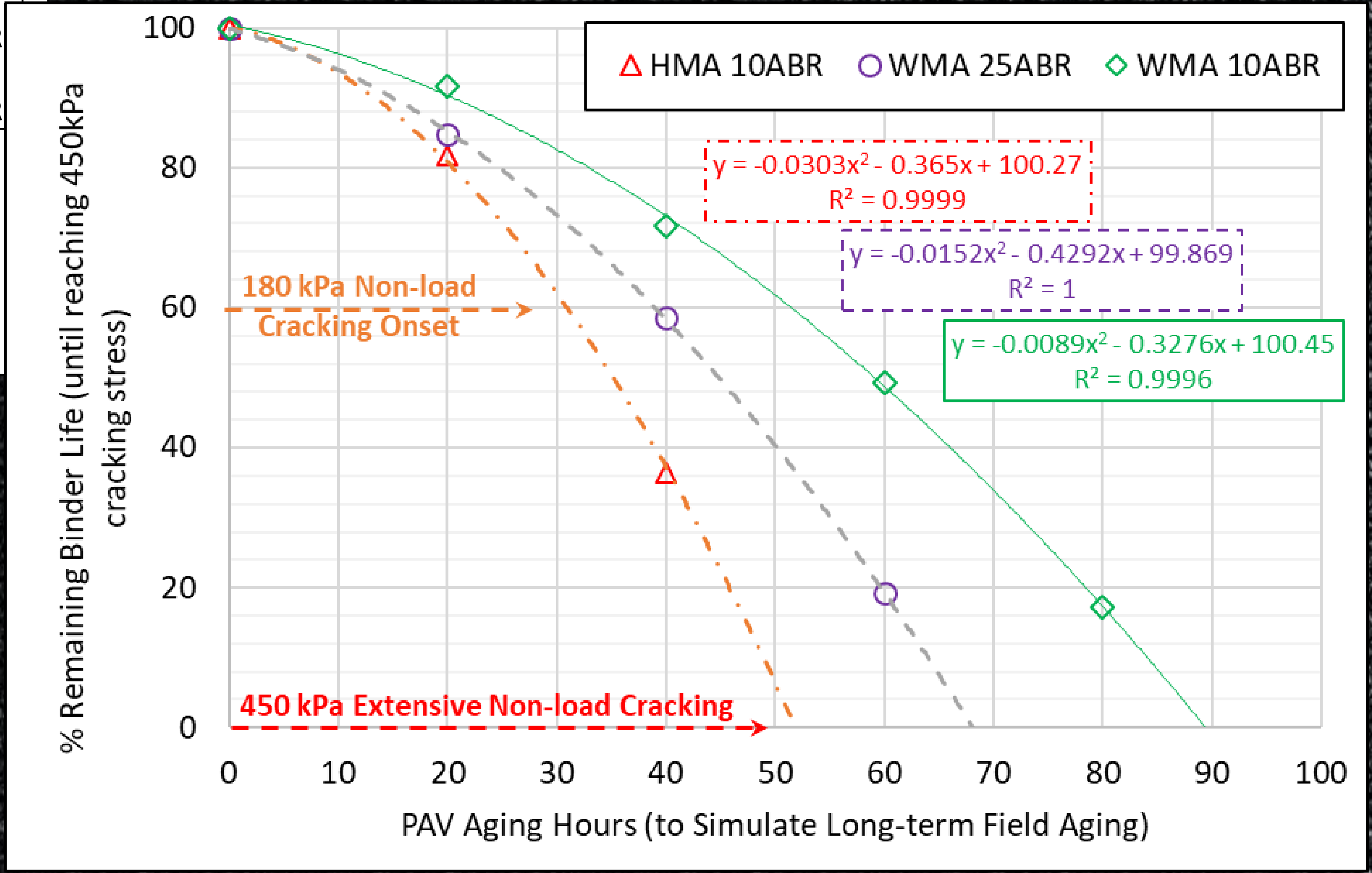


Glover-Rowe Parameters (GRP) measure the cracking resistance of an asphalt binder. Above 180kPa, a binder can be expected to begin showing cracks. Above 450kPa, the binder will exhibit extensive block cracking.

Another Way to Look at the Glover-Rowe Parameter (450 kPa limit)



Glover-Rowe Parameters (GRP) can be converted into values representing the percent of binder life remaining (PBLR) before extensive age-related block cracking occurs.

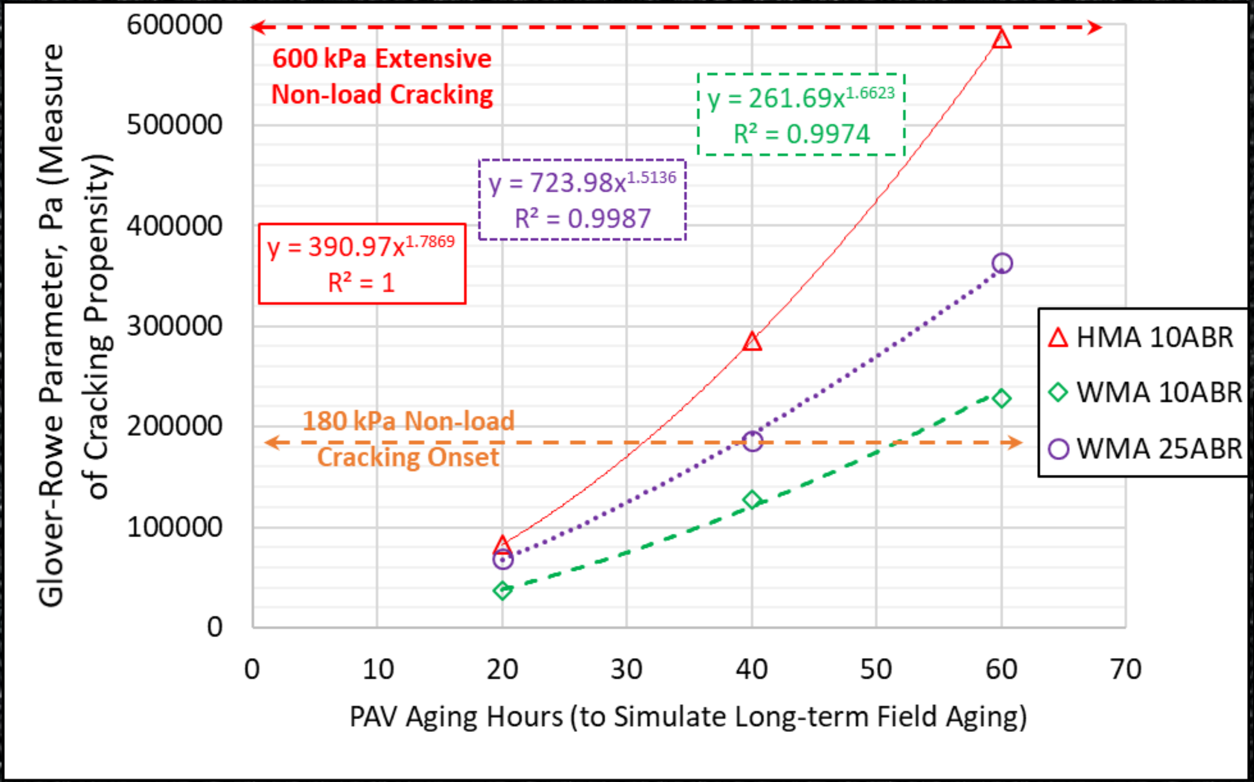


At 0h PAV all binders have 100% remaing life.

At each PAV cycle, we calculate PBLR as

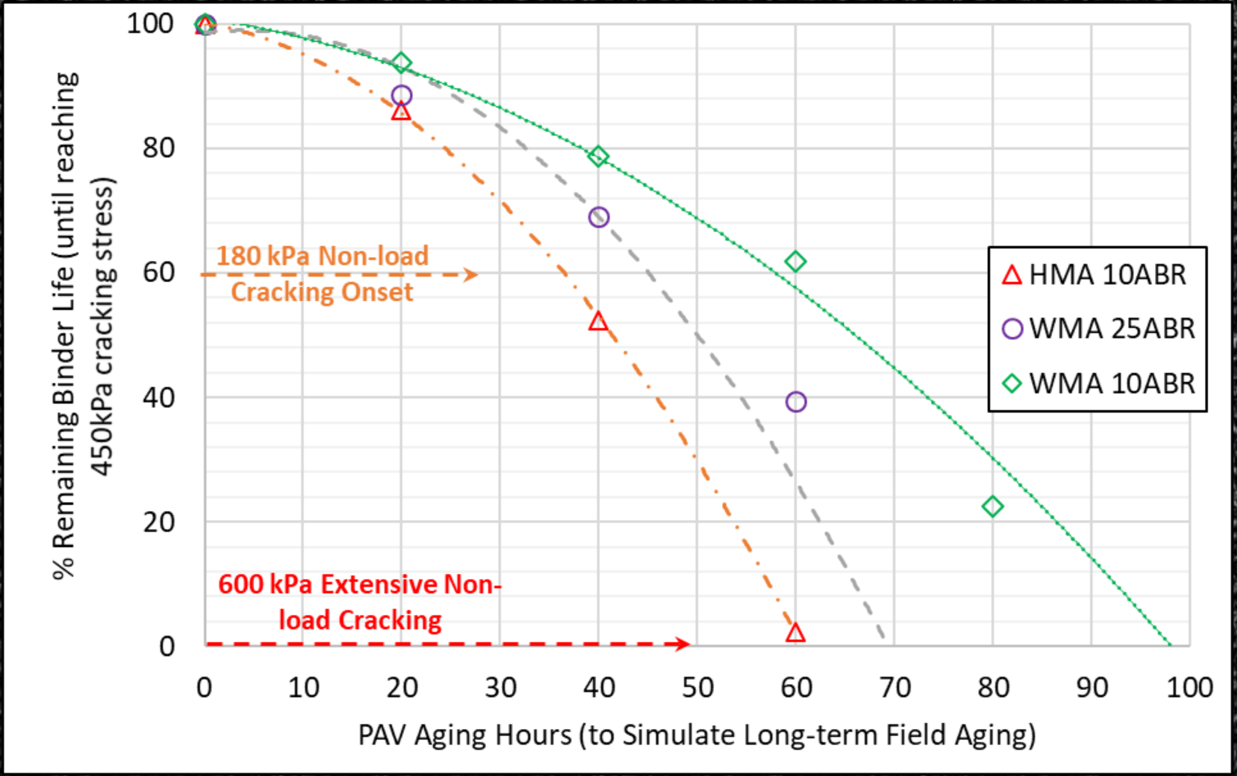
$$\frac{(450{,}000 - \text{GRP at PAV cycle}) * 100}{450{,}000}$$

Using the Limiting Glover-Rowe Value of (600 kPa limit)



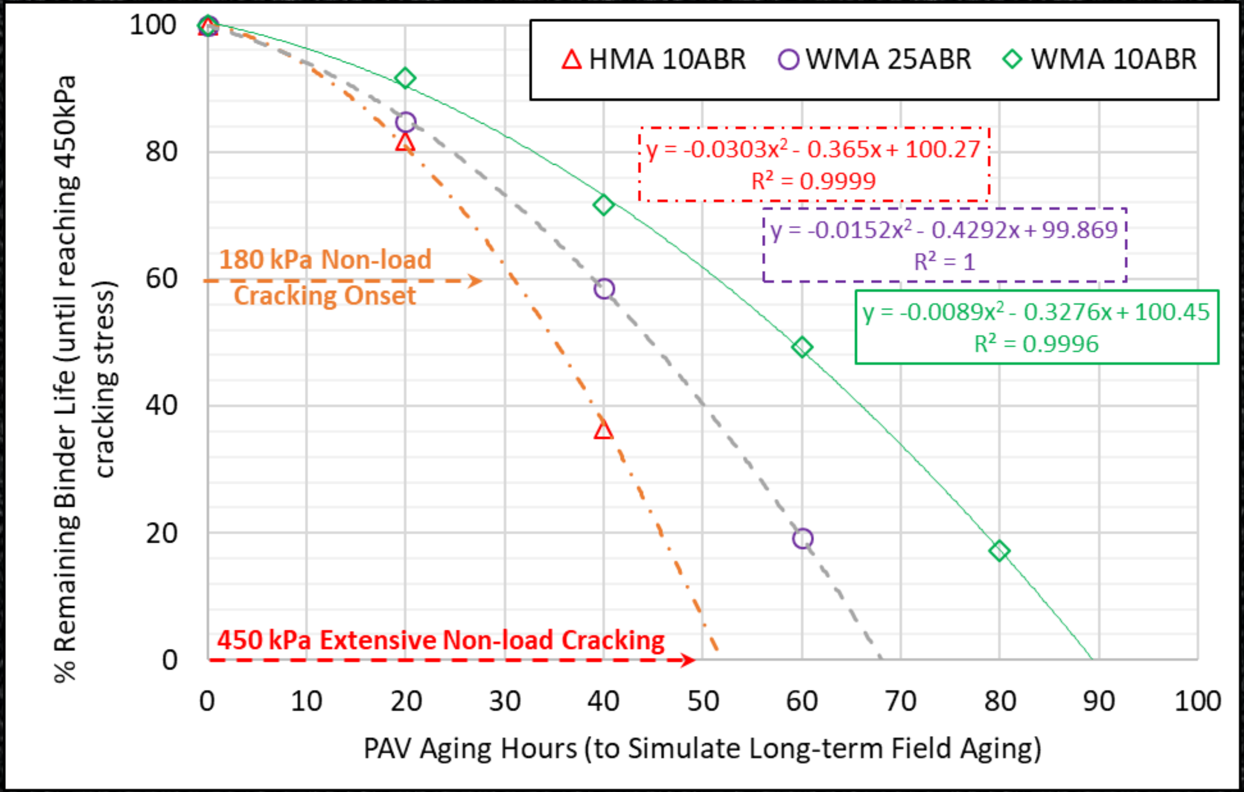
Using the Rowe-recommended 600 kPa limit, one can see that Percent Remaining Binder Life (y-axis) as a function of PAV aging hours (x-axis) for each sample is substantially extended as compared to the graph on the preceding page with a 450 kPa limit).

The above graph is the same as that on the previous slide, except that the Glover-Rowe Parameter at which extensive non-load cracking occurs is 600 kPa, not 450 kPa. G. Rowe (1) recommends the 600 kPa limit, not 450 kPa.



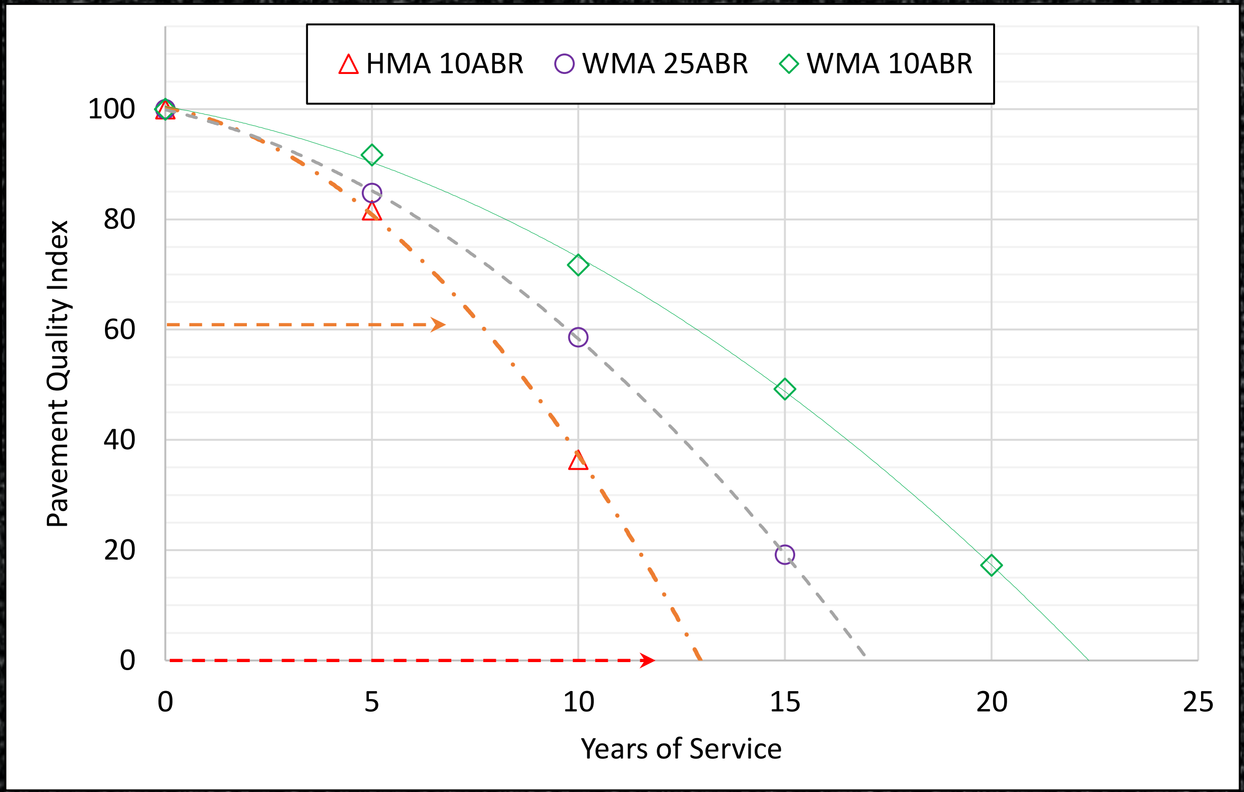
(1)www.asphaltpavement.org/PDFs/Engineering_ETGs/Binder_201604/13%20Rowe%20-%20DTc%20-%20Historical%20development.pdf

Converting PAV Aging Hours to Years of Service

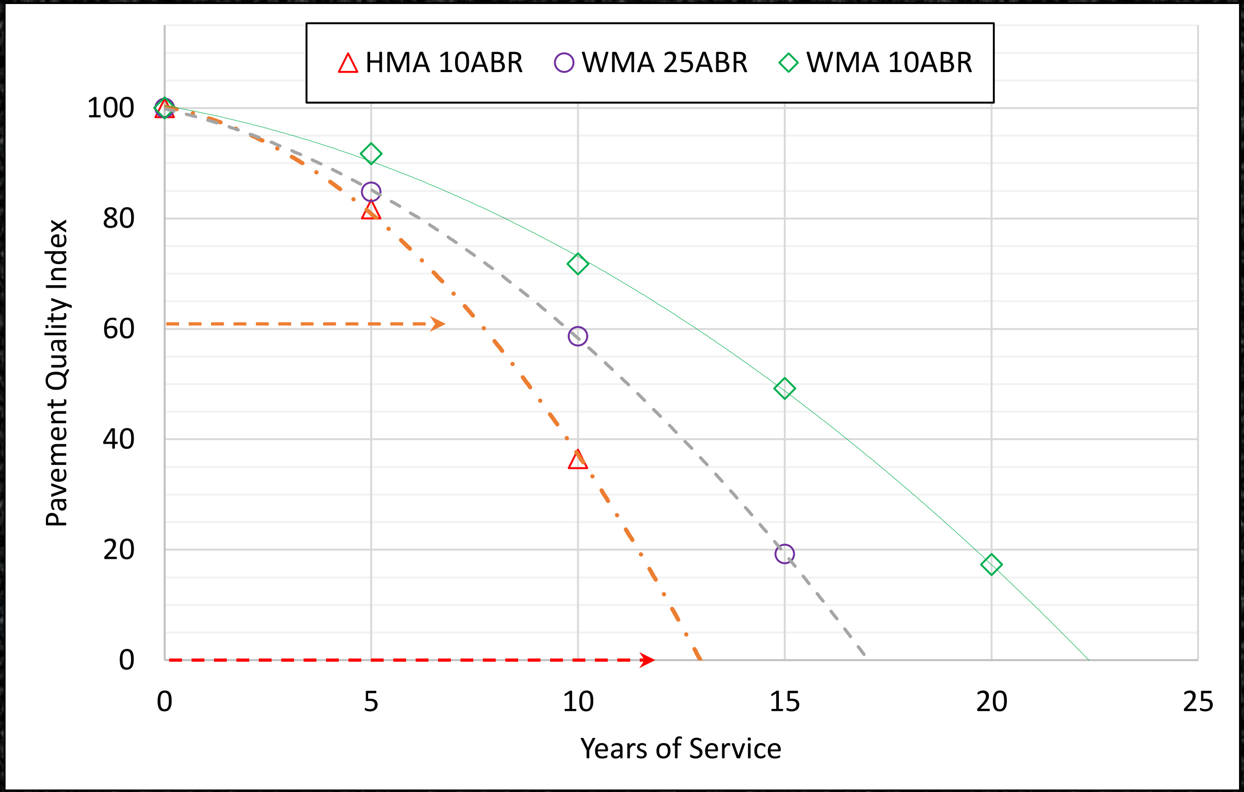


Each 20-h PAV cycle is equal to 5-10 years of field life. Using the value of 5 years, the PRBL aging curves can be projected over a span of years (in this case, 25 years).

The PRBL values from the curves using the 450 kPa limit can be fit with second-order polynomial curves.

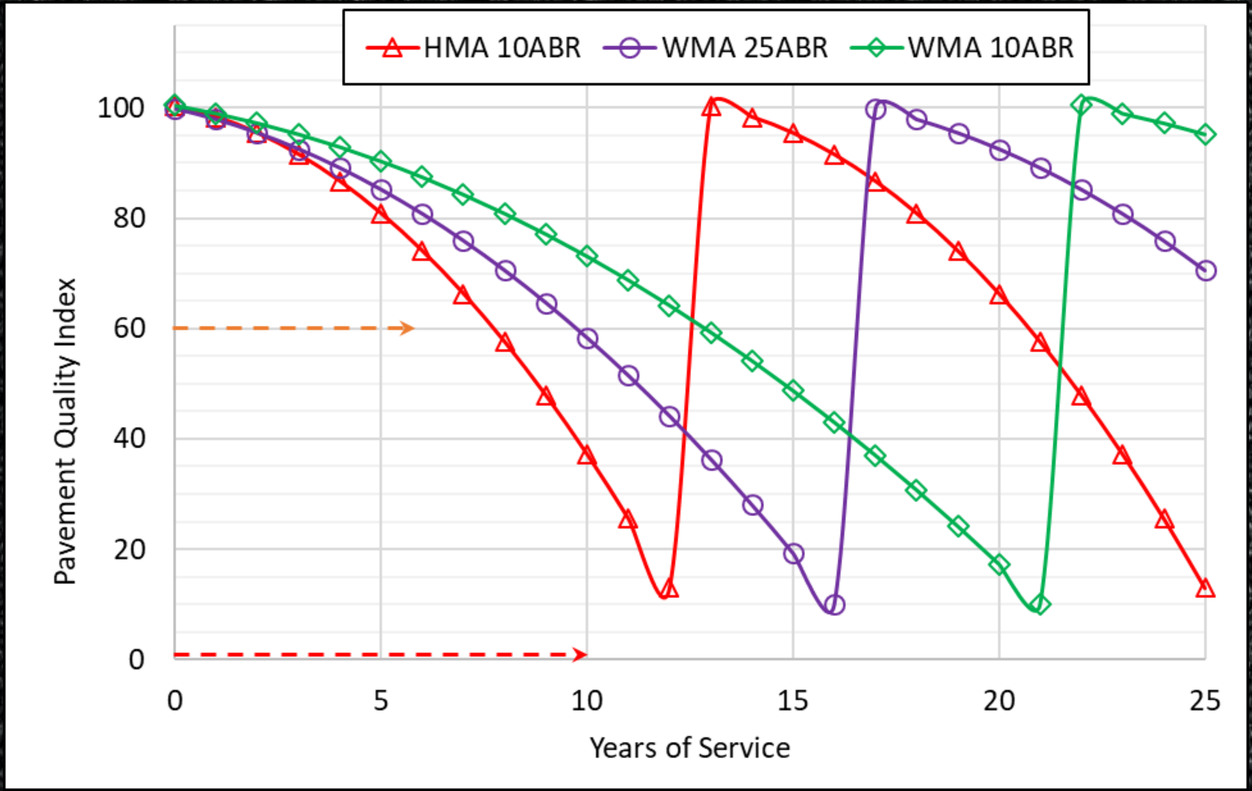


Considering Maintenance Scenarios Over a Design Life

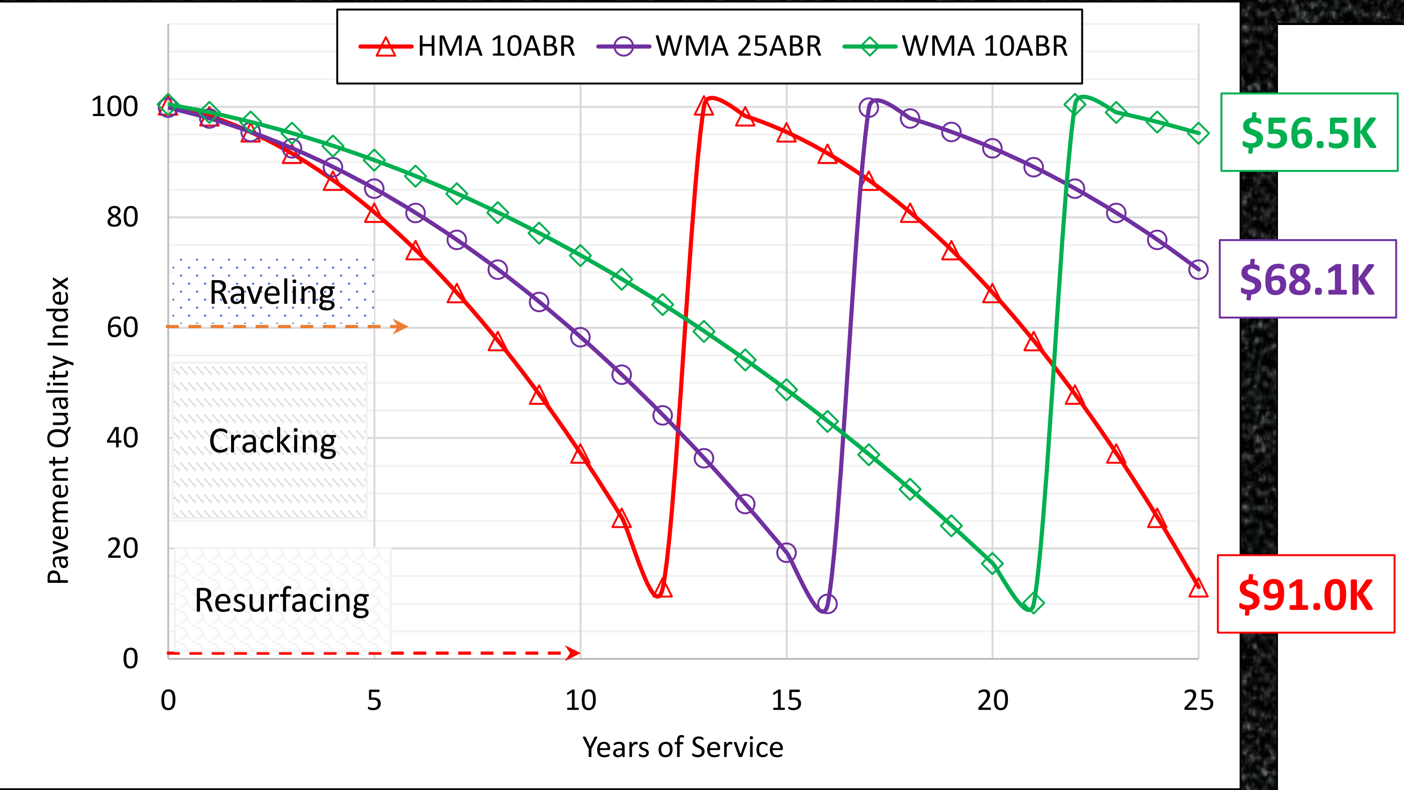


We assume that the same paving mixtures are reapplied during resurfacing and that the pavement is restored to a Pavement Quality Index of 100%. At that point, the aging cycle begins again according to the GRP's.

When each pavement reaches about 10-13% remaining binder life, the aged pavement is resurfaced. That is, the aged pavement is milled off and a new paving mixture is applied.



The Comparative Cost of the Maintenance Program Can Be Estimated



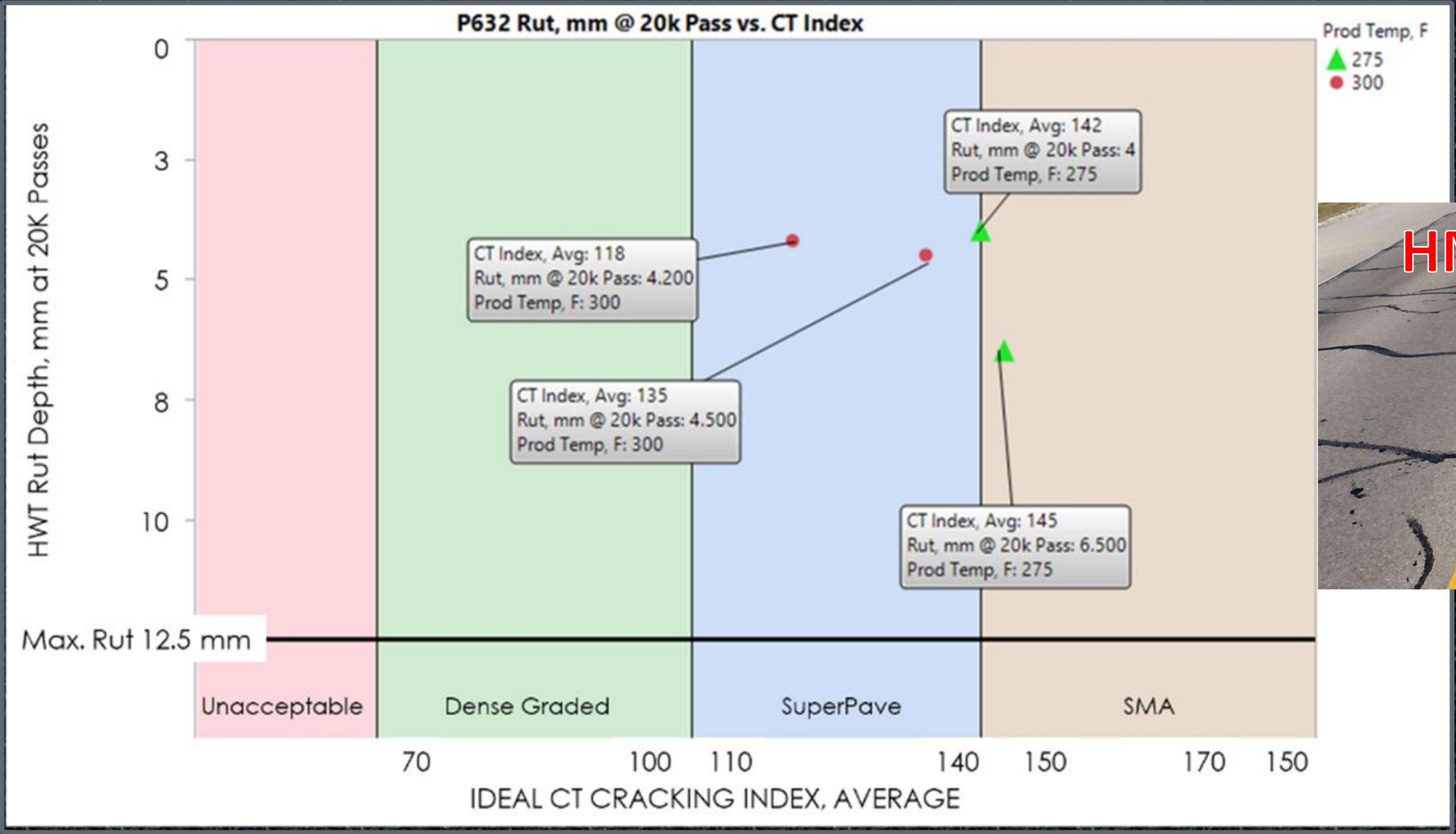
Years	PQI	Year	Mill & Fill	PQI	Year	Mill & Fill	PQI	Year	Mill & Fill
0	100		100	100		100	100		100
1	98		98	98		98	99		99
2	95		95	95		95	97		97
3	92		92	93		93	95		95
4	87		87	89		89	93		93
5	81		81	85		85	90		90
6	74		74	81		81	87		87
7	66		66	76		76	84		84
8	58		58	71		71	81		81
9	48		48	65		65	77		77
10	37		37	58		58	73		73
11	26		26	51		51	69		69
12	13		13	44		44	64		64
13	-0.6	0	100	36		36	59		59
14		1	98	28		28	54		54
15		2	95	19		19	49		49
16		3	92	10		10	43		43
17		4	87	0	0	100	37		37
18		5	81		1	98	31		31
19		6	74		2	95	24		24
20		7	66		3	93	17		17
21		8	58		4	89	10		10
22		9	48		5	85	3	0	100
23		10	37		6	81		1	99
24		11	26		7	76		2	97
25		12	13		8	71		3	95
Sq.Yd Cost, $	6.72		6.72	6.45			6.85		6.45
Cost per Lane-Mile, $	47309		47309	45408		48224	48224		45408
Residual Life, $			3639			25530			37152
Total Cost/Lane-Mile	**$**		**90,978.46**	**$**		**68,101.65**	**$**		**56,480.00**

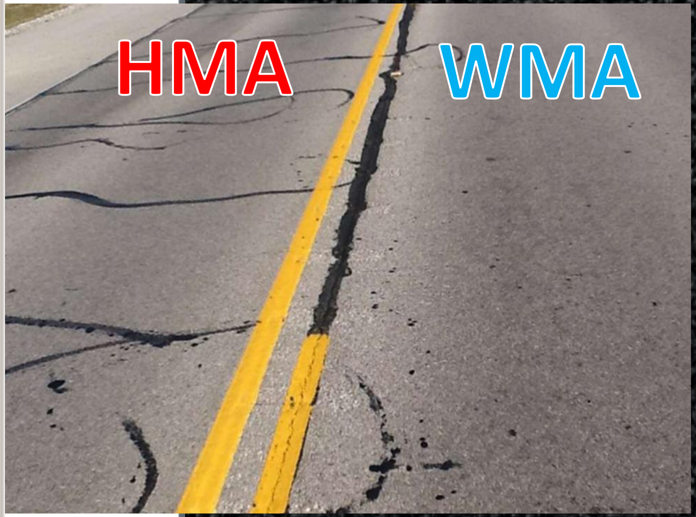
If we arbitrarily stop the analysis at 25 years of service, we can calculate the cost of each pavement over that 25-year period.

Over the 25-year period, the per lane-mile cost of each pavement:

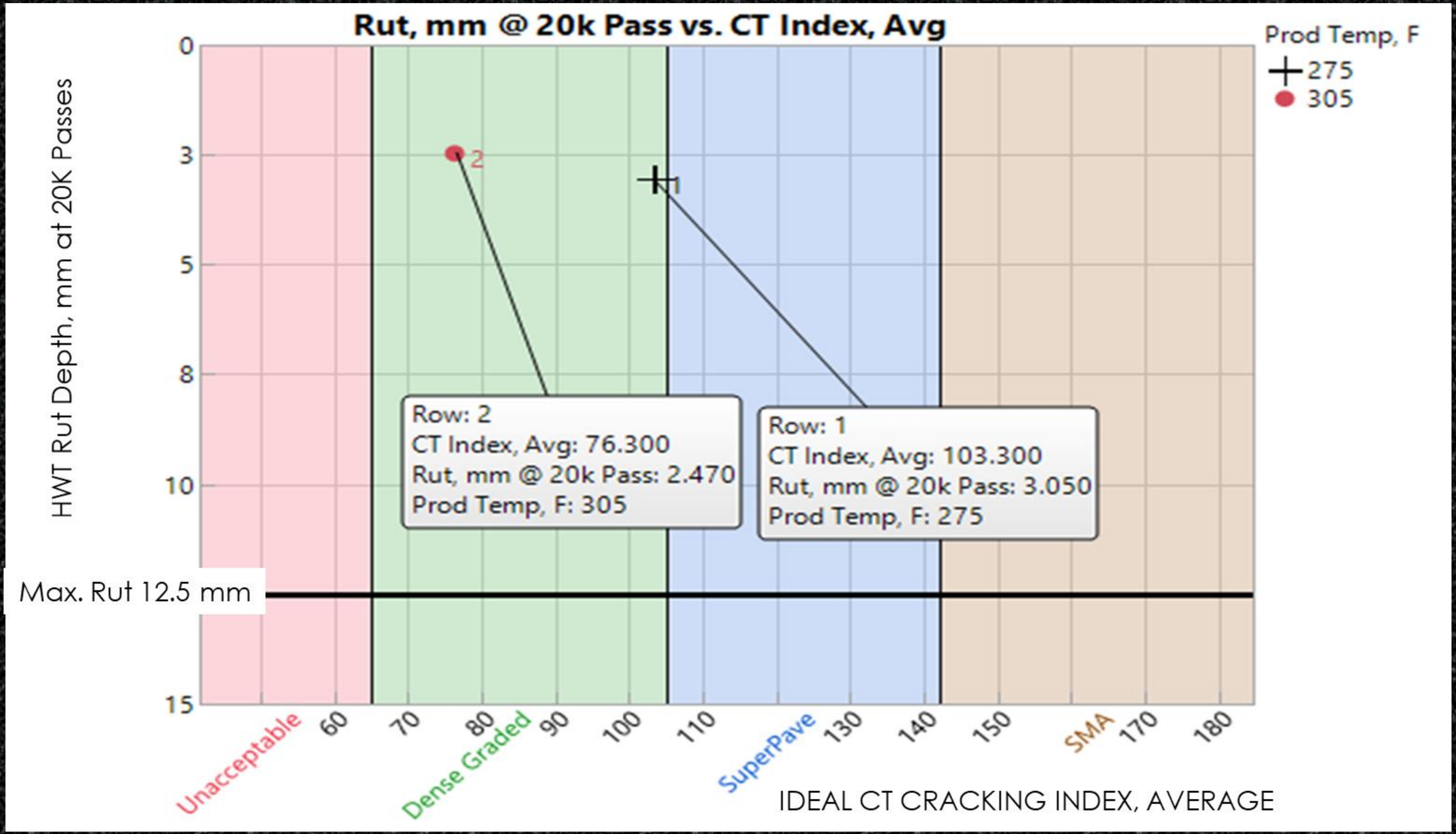
- **HMA with 10% RAP made at 325°F: $90,978.46**
- **WMA with 25% RAP made at 275°F $68,101.65 (↓25%)**
- **WMA with 10%RAP made at 275°F $56,480.00 (↓38%)**

Reduced Mix Temperatures Yield Performance Benefits

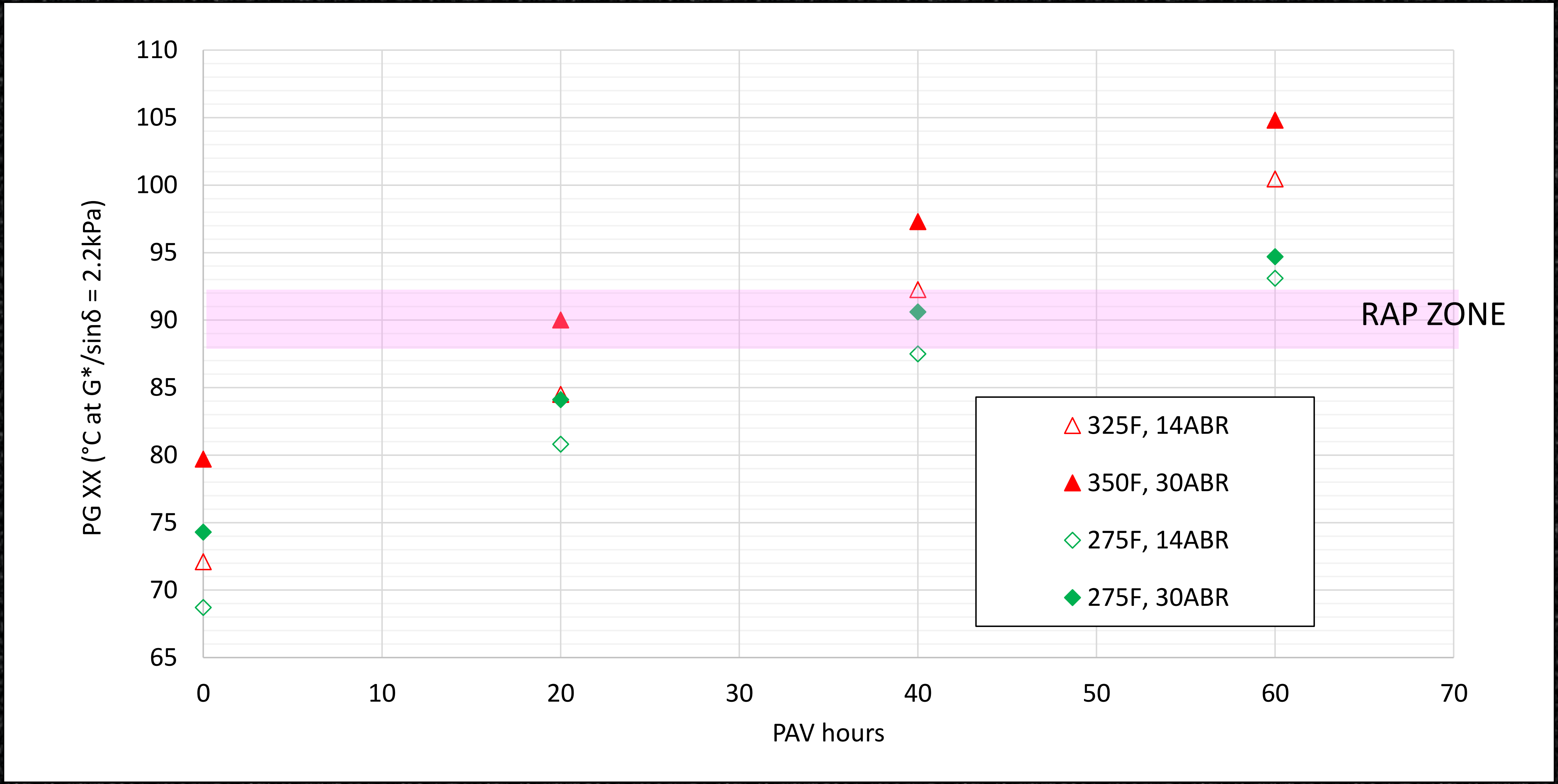




Reduced Mix Temperatures Yield Performance Benefits

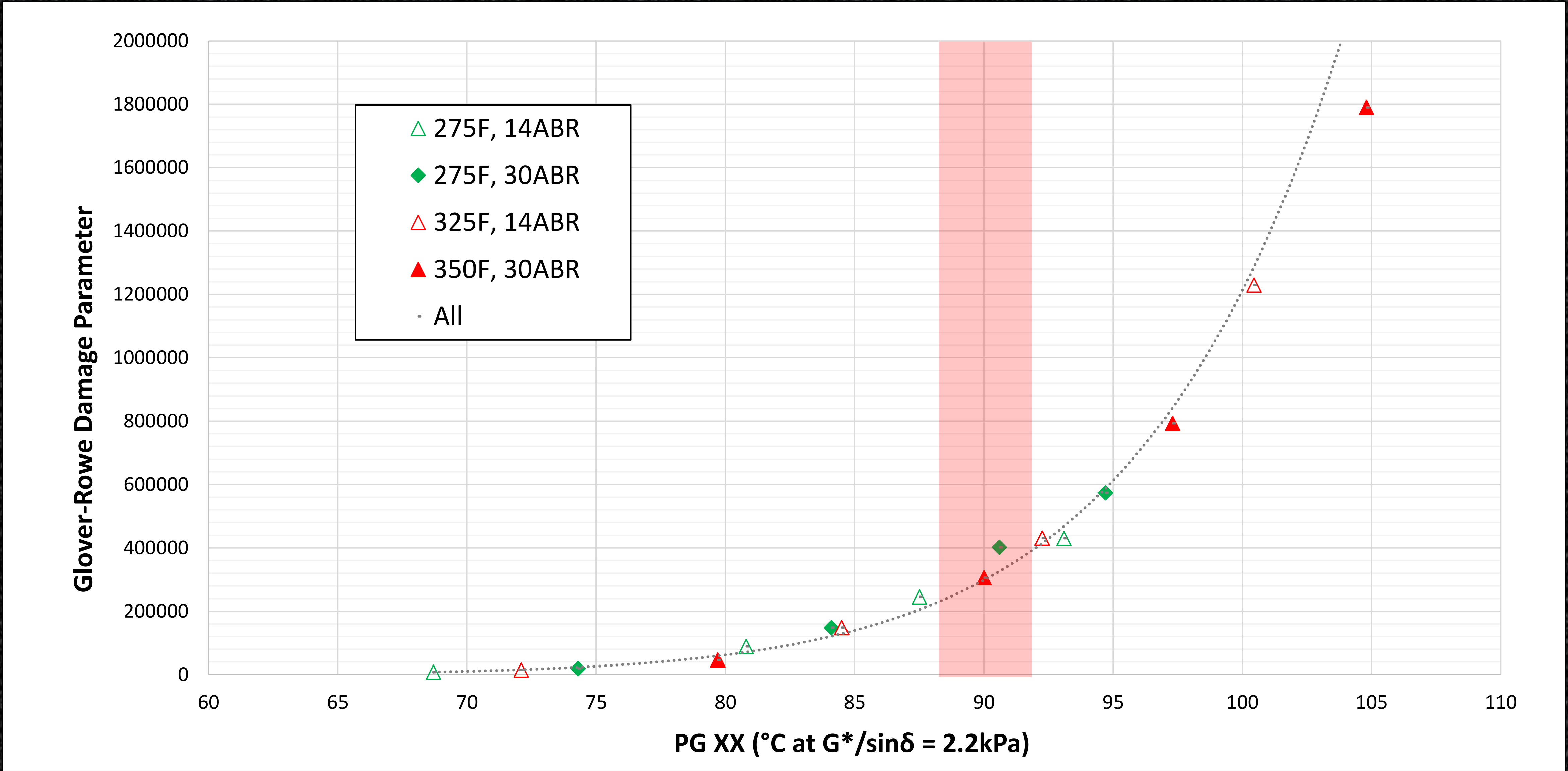


Aging Can Be Monitored Through Other Stiffness Parameters

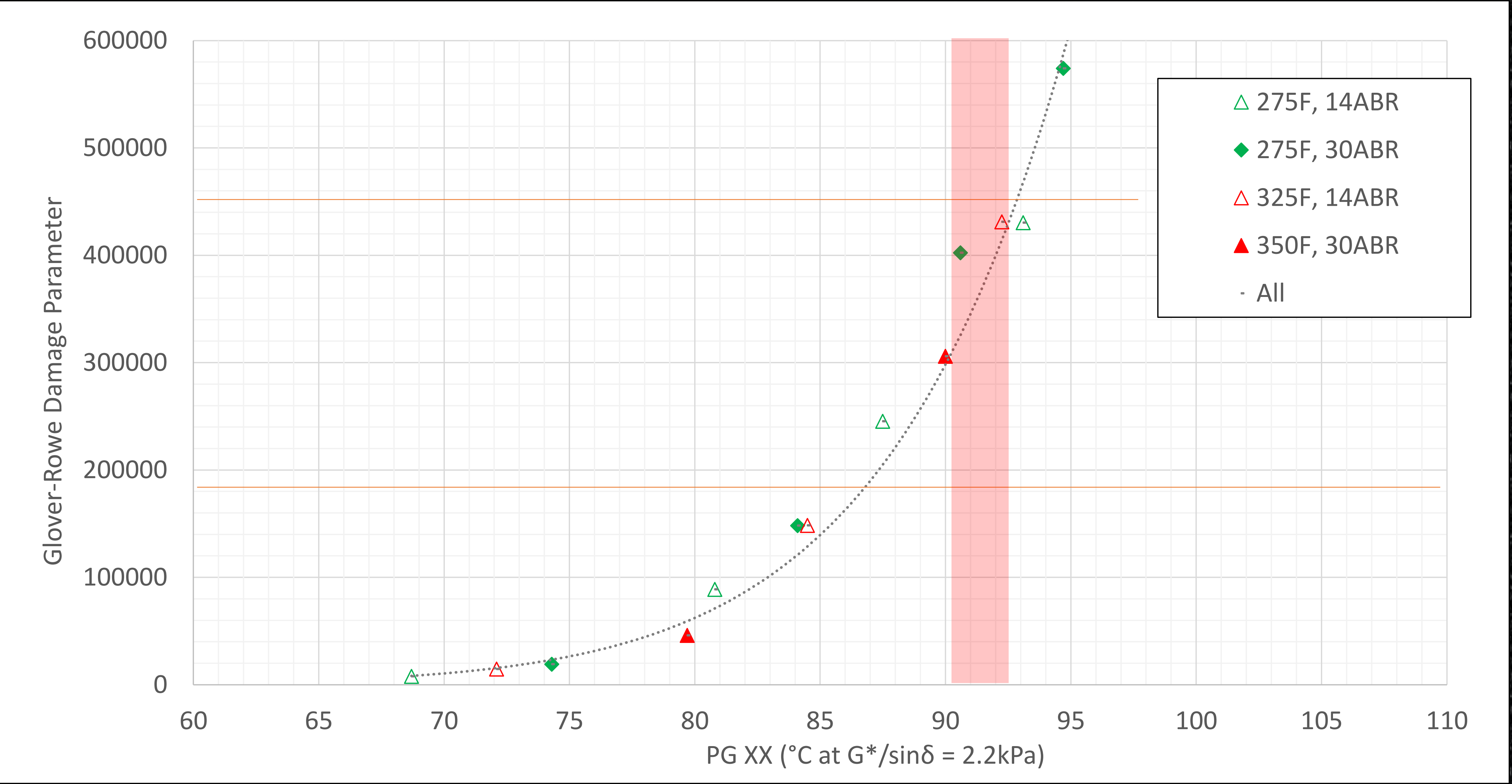


PG XX, °C = 41.581 + 0.2083*ABR + 0.0944*RTFO, °F + 0.4038*PAV h

Glover-Rowe Parameter and PG XX Values Trend with PAV Aging



BINDER AGING AS A FUNCTION OF TEMPERATURE



Can Lower Temperatures Bring Additional Benefits

LESS BINDER OXIDATION

HIGHER RECYCLE-ABLES CONTENT

LONGER HAUL DISTANCES

COLD WEATHER PAVING

FIBER-FREE SMA

MIX TYPES: OGFC, PMB, GTR, …

LESS THERMAL SEGREGATION = MORE UNIFORM MAT DENSITY

BETTER COMPACTION

DENSITY = BONUS PAY

LIME REPLACEMENT

REDUCED AGGREGATE ABSORPTION

WMA: Steady Growth in the U.S.A since 2002

2002
- NAPA led study tour to Europe

2004
- WMA demonstration at World of Asphalt
- First field trials in FL and NC

2005
- WMA TWG formed
- 1st WMA on NCAT Test Track
- Field trials in FL, IN, MD, NH, **OH**, TX & Canada

2007
- FHWA/AASHTO European Scan Tour
- NCHRP 9-43 on WMA Mix Design initiated

2008
- WMA trials in 32 states
- 1st International WMA Conference

2009
- NCAT Full-Depth WMA Test Sections
- NCHRP 9-47 on Eng. Props, emissions, field performance completed

2010
- WMA trials in 45 states / 10 Canadian Providences
- Over 20 WMA technologies in the US

2011
- NCHRP 9-43 completed
- 2nd International WMA Conference

2013
- NCHRP 9-49 on WMA Moisture Susceptibility completed

2014
- NCHRP 9-47A on WMA Properties and Performance completed

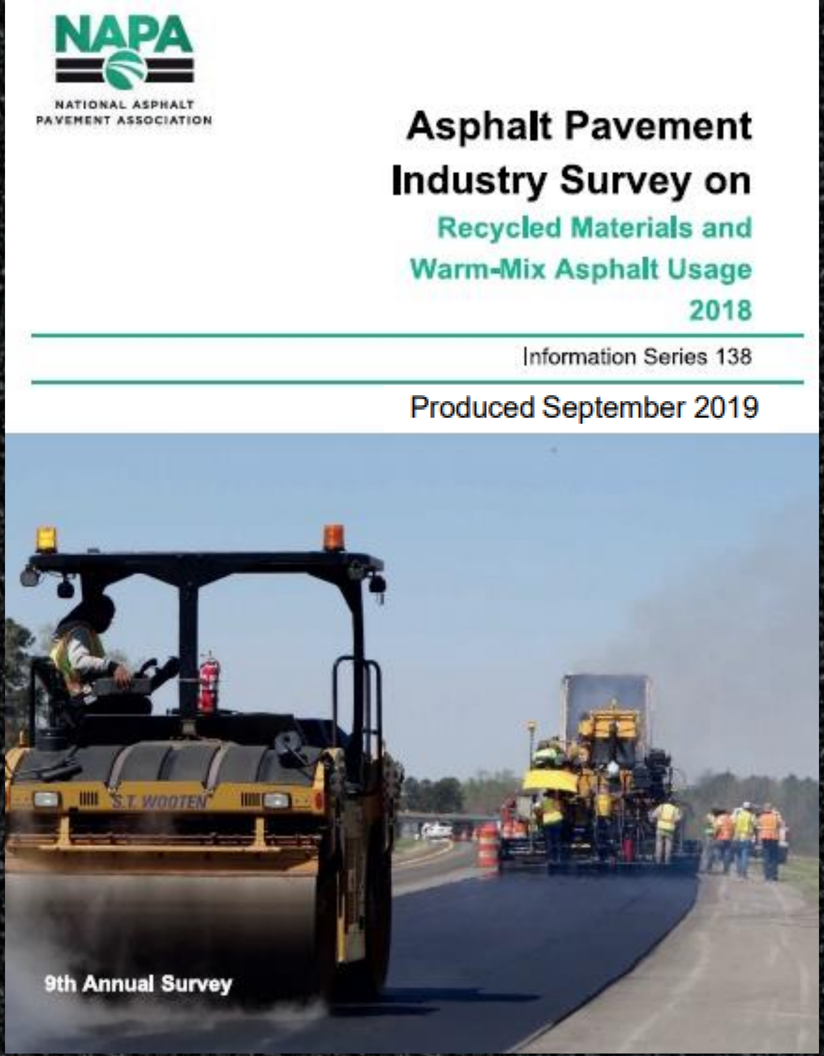
2015
- NCHRP 9-53 on Foamed Asphalt completed

2016
- NCHRP 9-49A on Long-Term Field Performance completed

2018
- NCHRP 9-55 on RAS + WMA completed

2020
- NCHRP 9-61 on binder aging to accurately reflect mix aging to be completed

WMA in the U.S.A. Today



The estimated total asphalt mixture tons for 2018 was 389 million tons. About 40% was WMA.

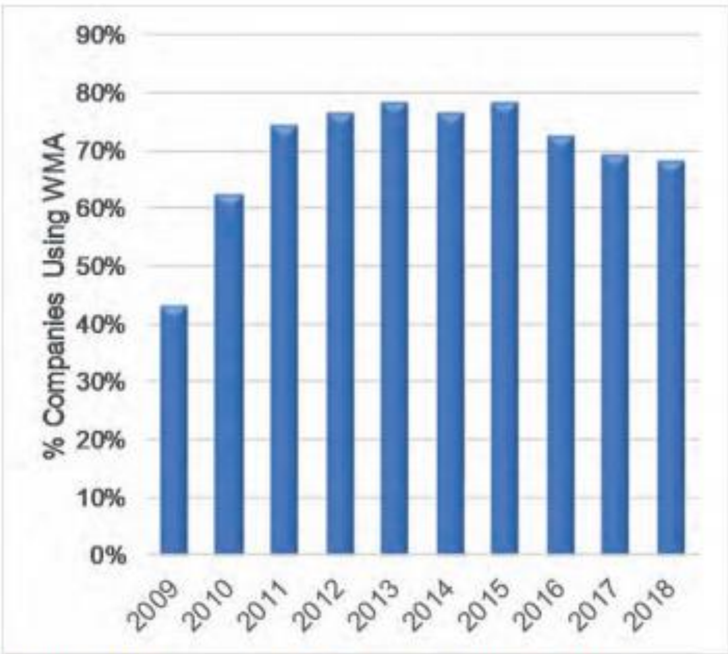


Figure 15: Percent of Companies Using WMA Technologies

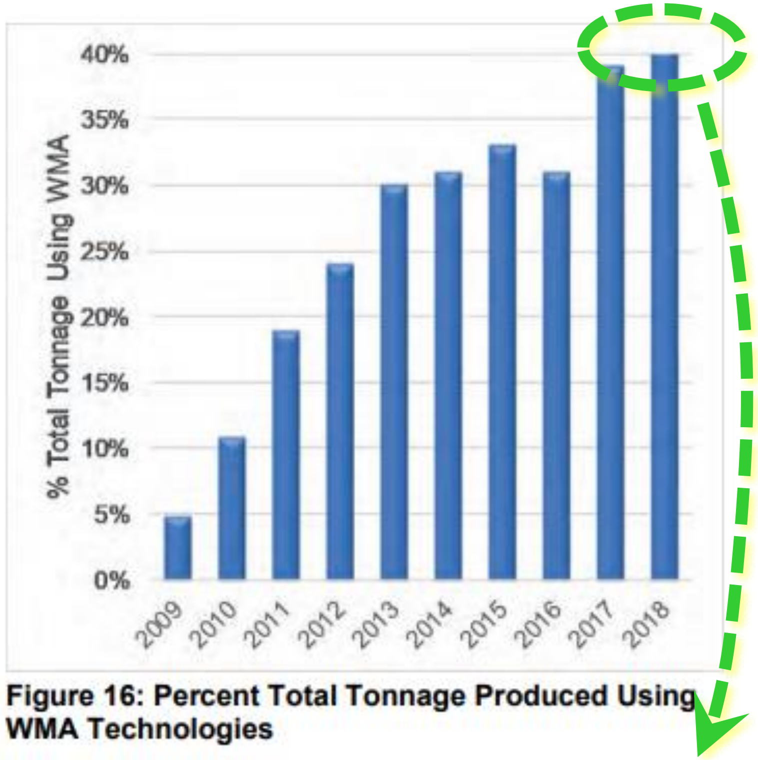


Figure 16: Percent Total Tonnage Produced Using WMA Technologies

~156 million tons of WMA in 2018

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www.asphaltpavement.org/PDFs/IS138/IS138-2018_RAP-RAS-WMA_Survey_Final.pdf

WMA in the U.S.A. Today

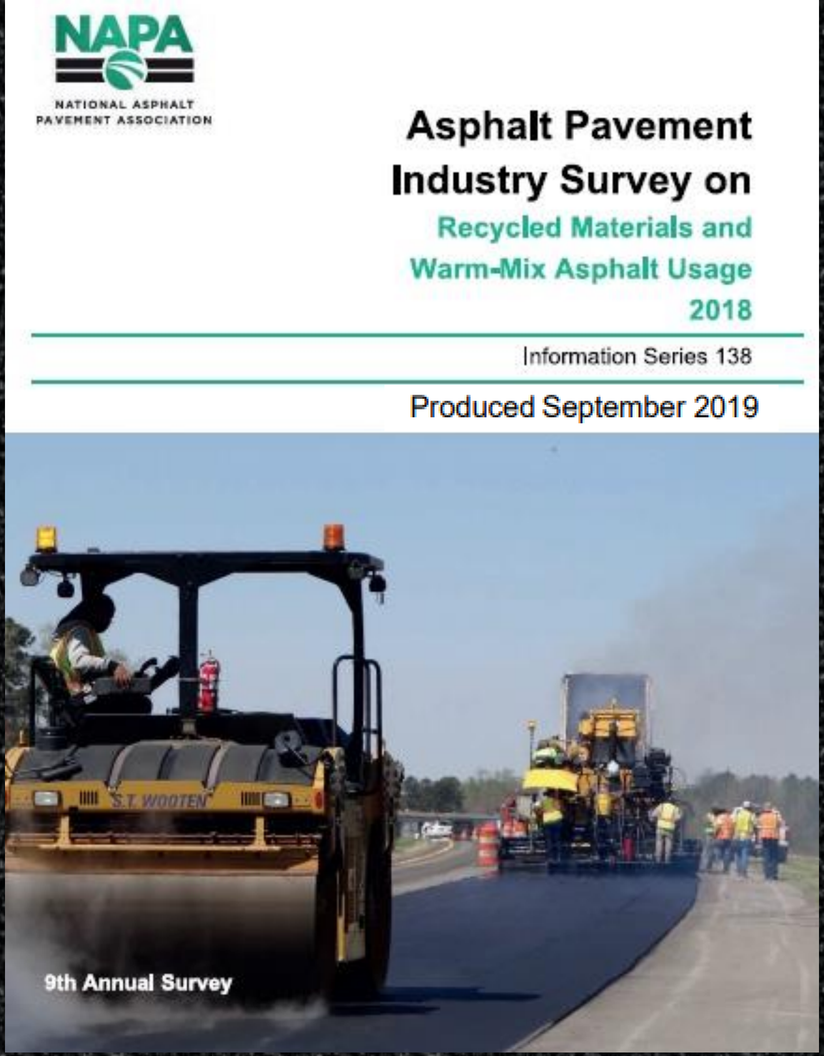

Table 15: Percent Production of WMA Technologies, 2009–2018

WMA Technology	% Production				
	2014	2015	2016	2017	2018
Production Plant Foaming %	84.5%	72.0%	76.9%	64.7%	63.2%
Additive Foaming %	0.0%	2.1%	0.0%	0.0%	0.7%
Chemical Additive %	15.0%	25.2%	21.1%	32.2%	34.3%
Organic Additive %	0.5%	0.7%	1.9%	3.1%	1.8%

Majority of WMA tonnage is produced with foaming technologies (63.2%) or with chemical additive (34.3%).

www.asphaltpavement.org/PDFs/IS138/IS138-2018_RAP-RAS-WMA_Survey_Final.pdf

WMA in the U.S.A. Today

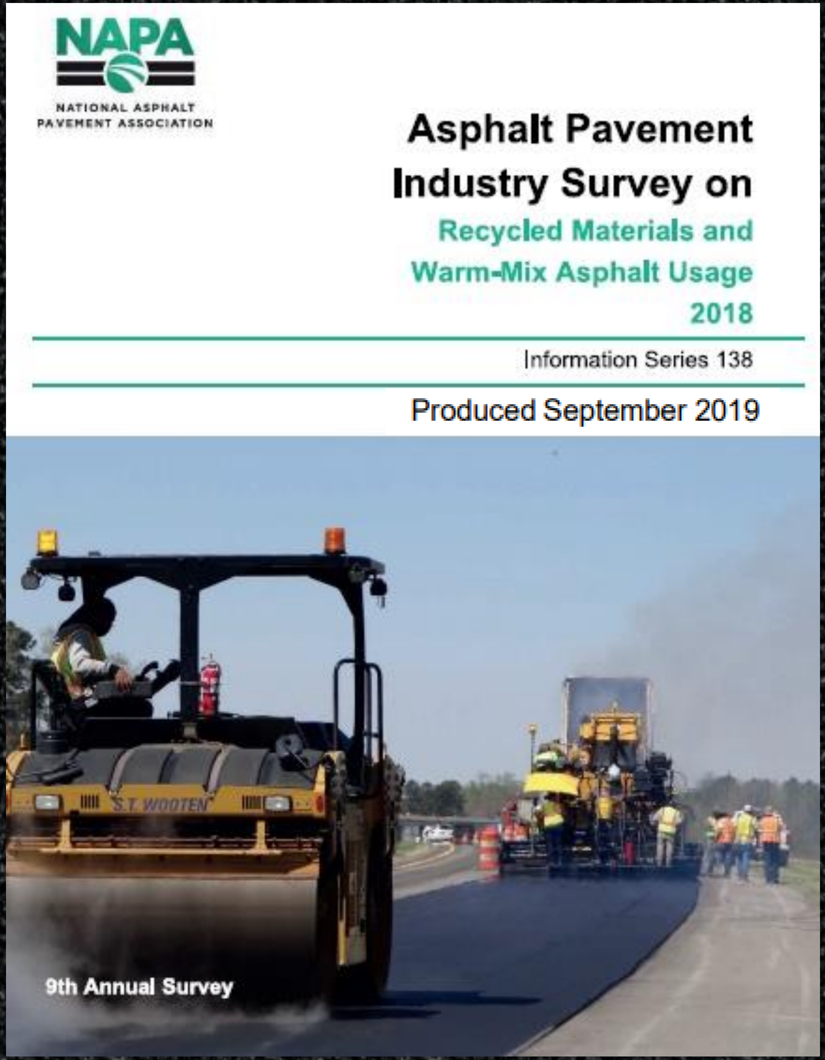

Table 15: Percent Production of WMA Technologies, 2009–2018

WMA Technology	% Production				
	2014	2015	2016	2017	2018
Production Plant Foaming %	84.5%	72.0%	76.9%	64.7%	63.2%
Additive Foaming %	0.0%	2.1%	0.0%	0.0%	0.7%
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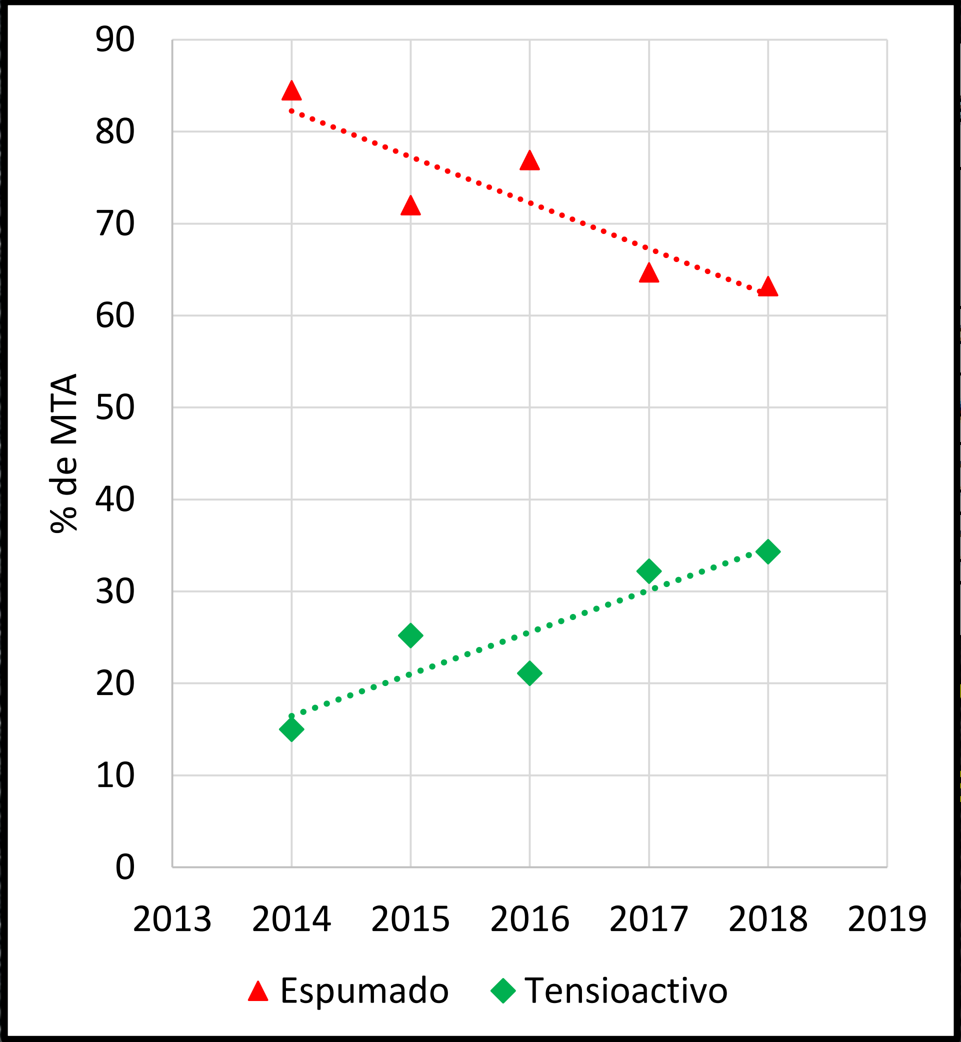

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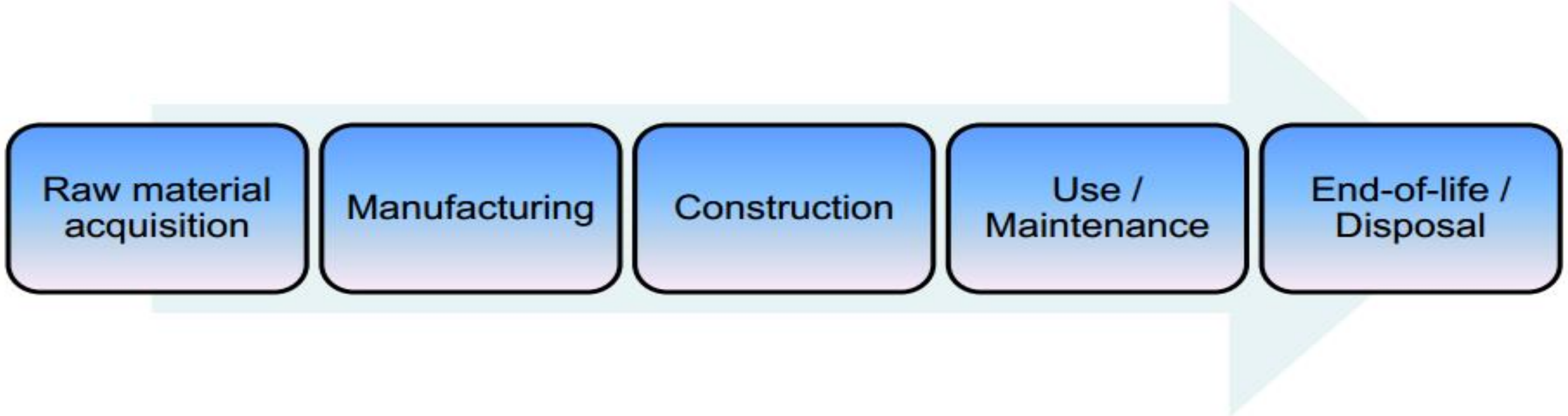
WMA: What Influence Our Evolution through the 2020's and 2030's

RUTGERS

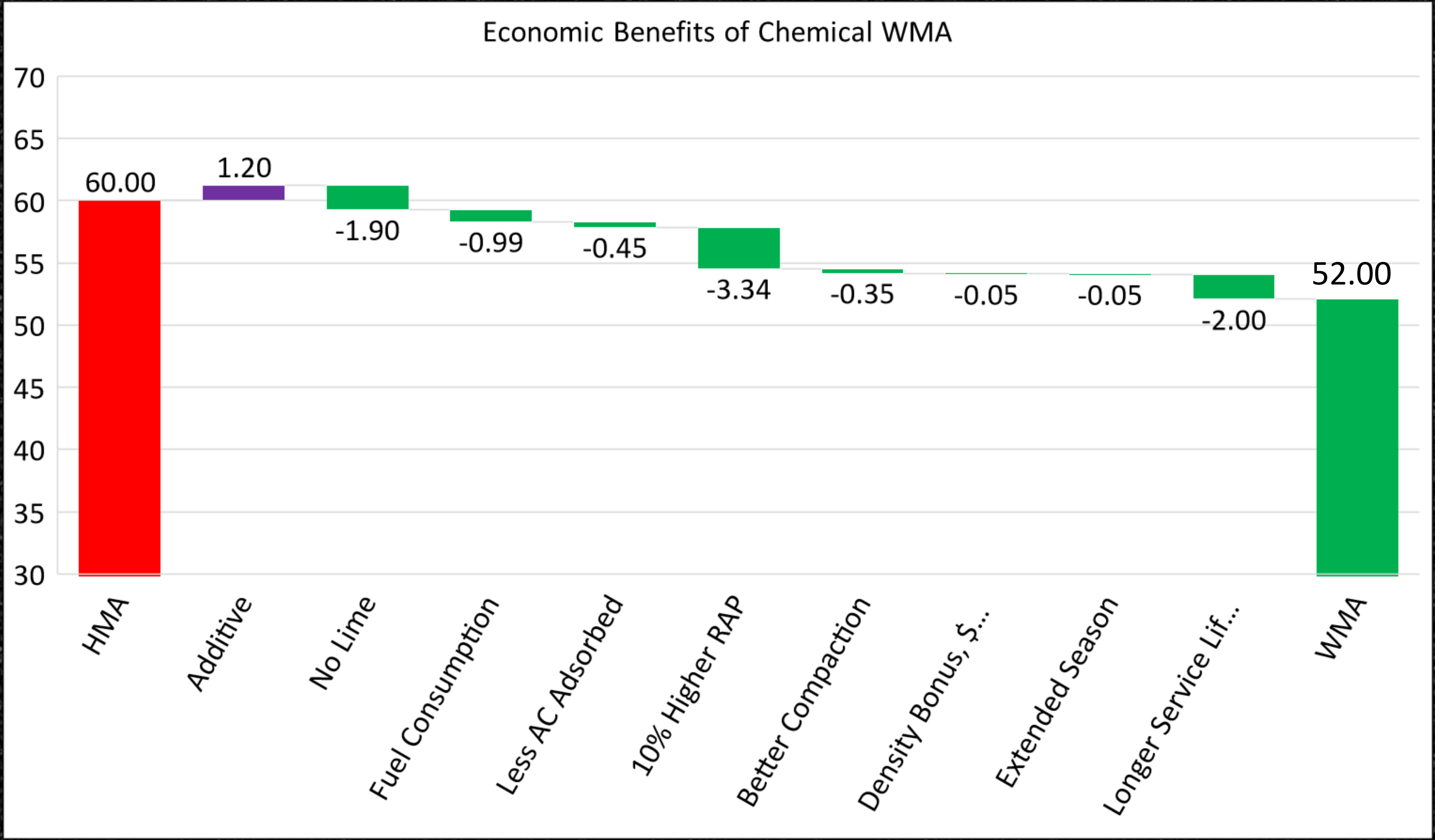
Life Cycle Assessment (LCA)

- LCA is an analytical technique for assessing potential environmental burdens and impacts throughout a product's life from raw material acquisition through production, use and disposal (ISO 2006).



http://cait.rutgers.edu/system/files/u11/LCA_Pavement_Preservation_NJDOT_Showcase.pdf by Wang, H. Rutgers University

WMA'S TOTAL ECONOMIC & ENVIRONMENTAL BENEFITS



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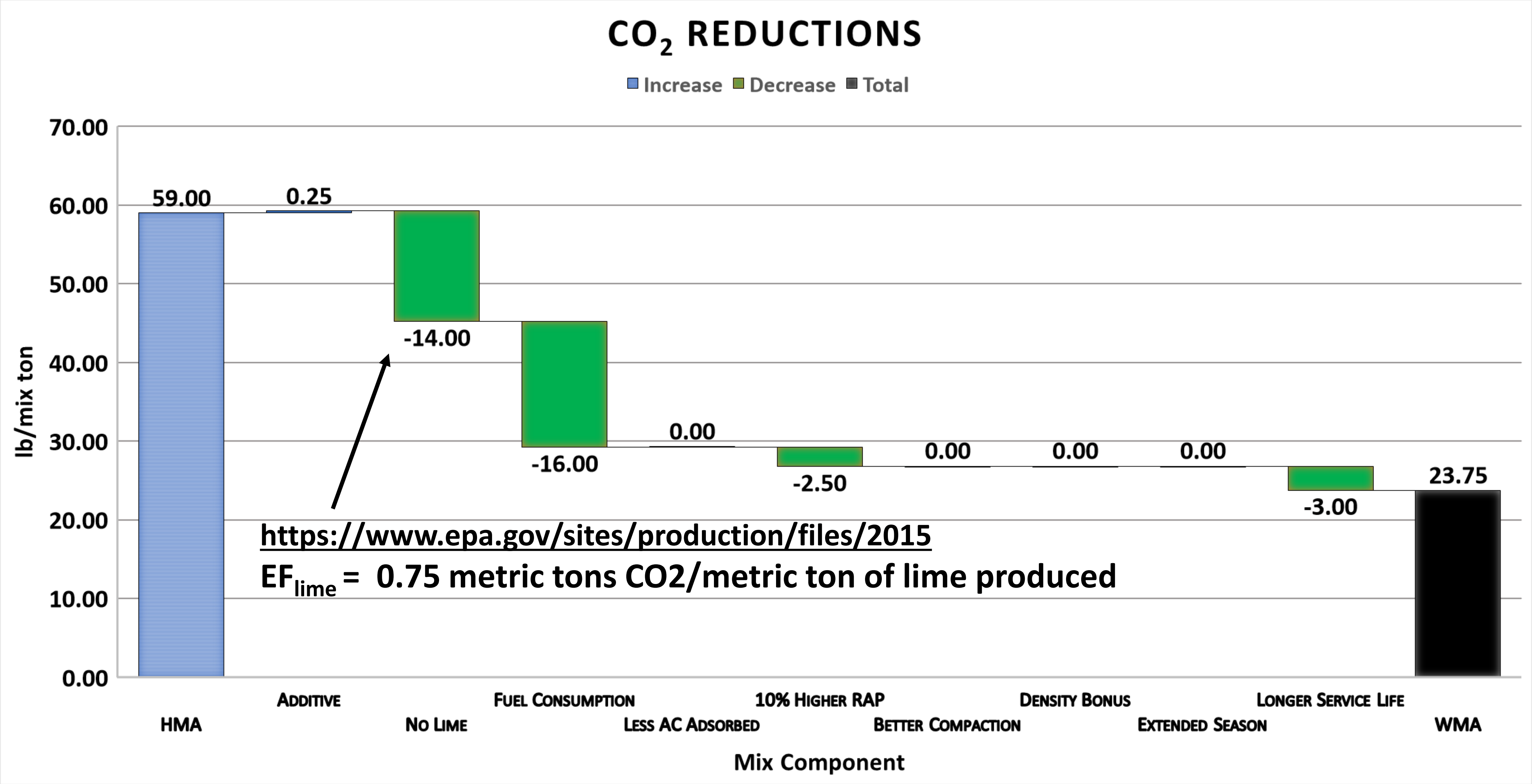

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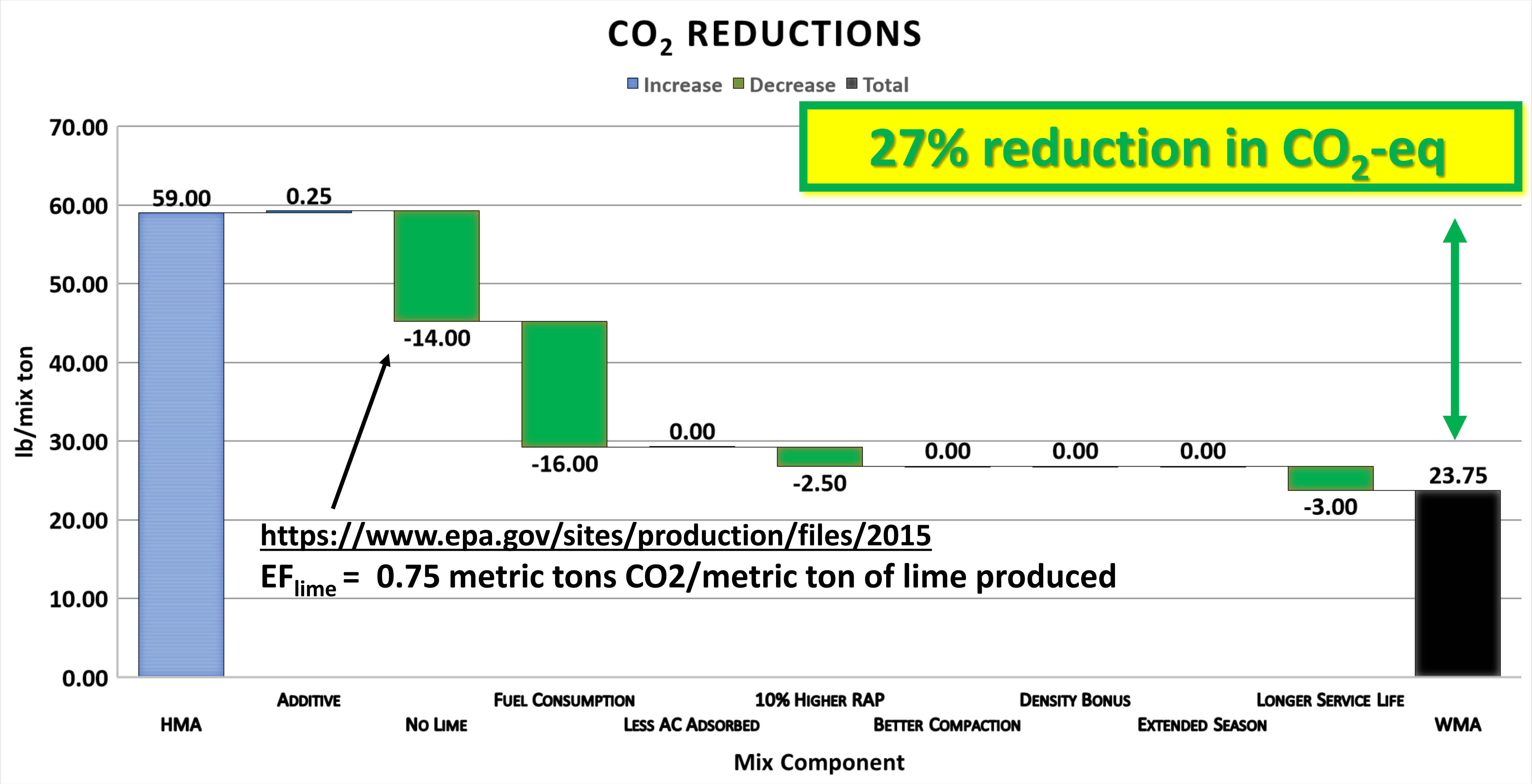
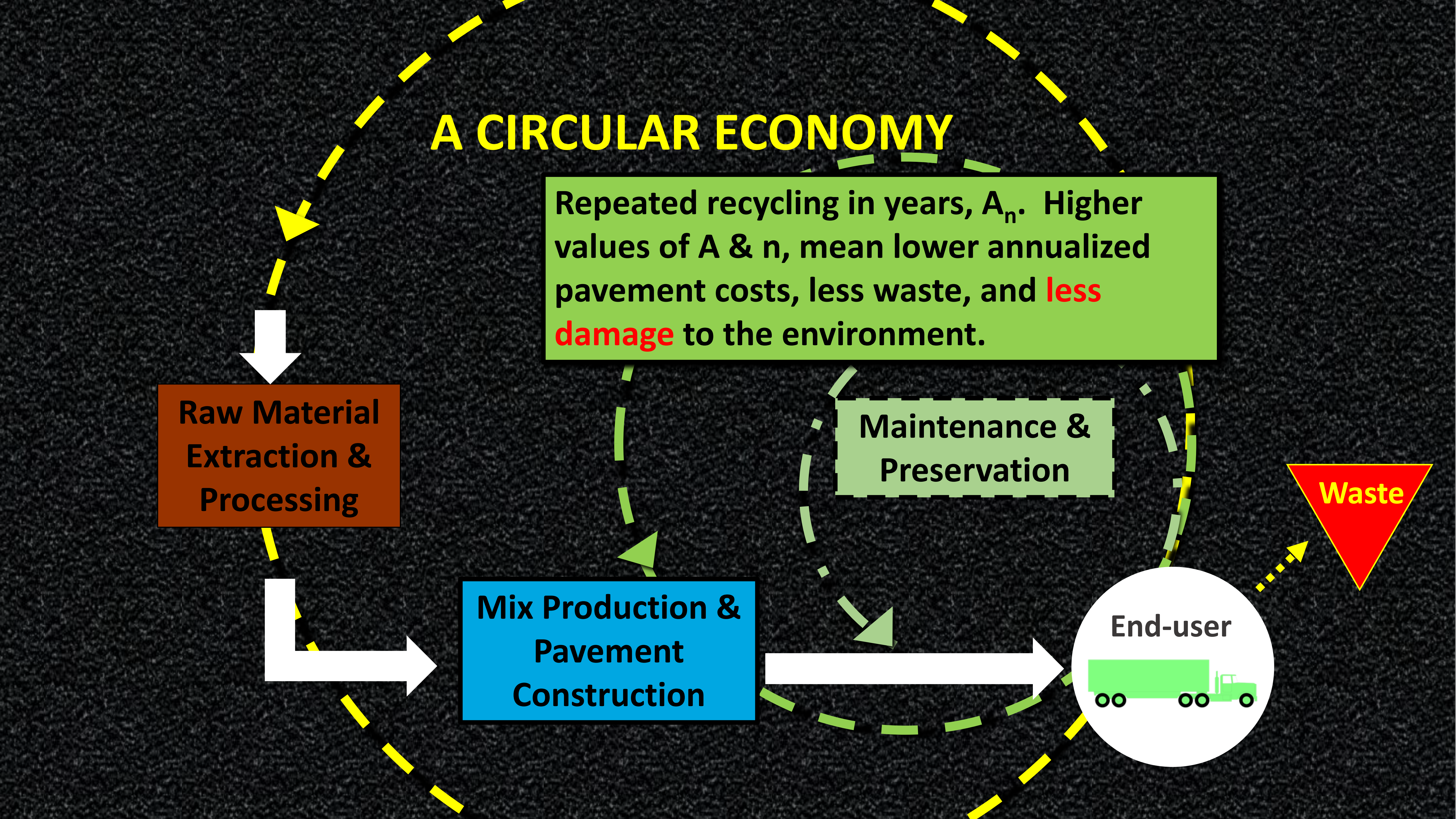


The Future of Reduced Mixing Temperatures

Can we do better than half the fuel usage, half the fumes/emissions? Can we go further?

Will lower detection limits for instrumental analysis of PAH's drive the NIOSH STEL below 0.5 mg/m^3 ?

Will "Green" environmental concerns demand even lower CO_2-equiv / ton of mixture?


A CIRCULAR ECONOMY
Repeated recycling in years, A_n. Higher values of A & n, mean lower annualized pavement costs, less waste, and less damage to the environment.
Raw Material Extraction & Processing
Maintenance & Preservation
Waste
Mix Production & Pavement Construction
End-user

QUESTIONS?

If you see something in this presentation that you want to hear more about, we have additional data available and would be happy to discuss any of the above topics in greater detail.

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