The Relationship of Binder Delta Tc (ΔTc) & Other Binder Properties to Mixture Fatigue and Relaxation

Gerald Reinke
MTE Services, Inc

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Mathy Technology and Engineering Services

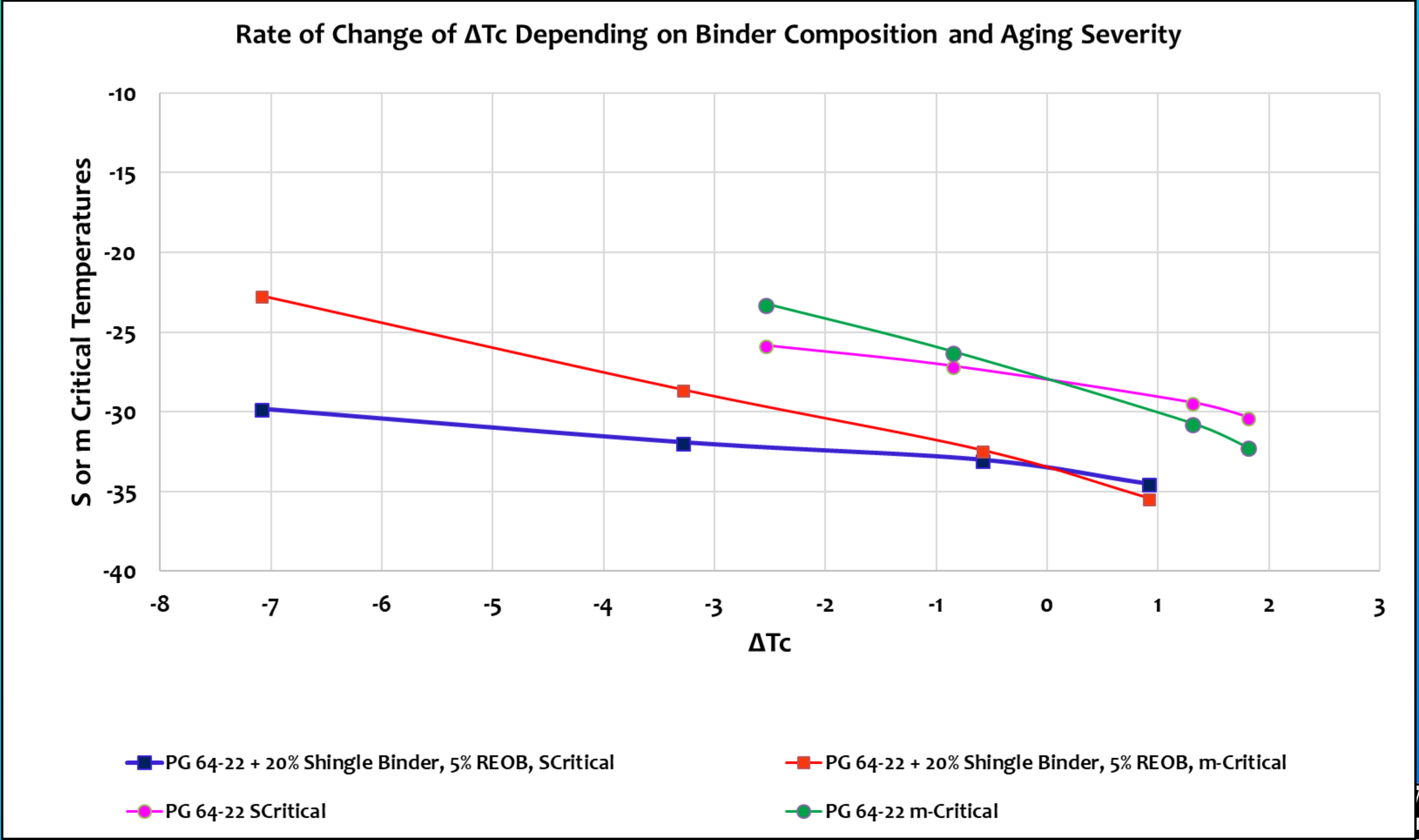
INTRODUCTION

- Great deal of information has been presented on the ΔTc parameter
- Not going to go into much detail about ΔTc or other parameters because that is not the focus of this presentation
- Goal is to show the relationship between binder and mix relaxation and measured properties of aged binders
  - R-Value, Glover-Rowe, cross over frequency, ΔTc, $T_{m\text{-Critical}}$

ΔTc Determination & Sources of Error

1. ΔTc=($T_{s\text{-critical}}$ – $T_{m\text{-critical}}$) ✓
2. To obtain an accurate value for ΔTc the BBR needs to be performed at enough temperatures so that
   a. BBR stiffness values < 300 MPa and > 300 MPa
   b. BBR m-values < 0.300 and > 0.300
   c. **Extended aging of binders , high levels of RAP and/or RAS, the use of high levels of additives such as REOB might require BBR testing at 3 or more temperatures** ✓
3. If BBR stiffness is less than ≈ 125 MPa when BBR m-value barely exceeds 0.300 then generally a 3rd BBR test temperature will be required to meet the requirements of 2.a and 2.b ✓
4. If you perform BBR at 2 temperatures where stiffness is <200 MPa so that $\mathbf{T_{m\text{-critical}}}$ will be <0.300 and >0.300 you can end up with an incorrect $T_{s\text{-critical}}$ ✓
5. **Linear extrapolations based on 2 test temperature over 100 to 150°C can result in incorrect predictions. Not all binders are linear (m value) or log linear (S value) with temperature**

When a binder exhibits a ΔTc of < -4 or -5 the S critical temperature increases at a substantially slower rate than does the m-critical temperature and this will necessitate the need for a 3rd BBR Test



Slope Ts-Critical for ΔTc of -7 is 50% that of the binder with ΔTc of -2.5

Slope of Tm-Critical for ΔTc of -7.5°C is 75% that of the binder with ΔTc of -2.5

WHY IS AN UNDERSTANDING OF ΔTc IMPORTANT?

1. Reasons that we should all know are ✓
   a. **As binders age they become more m-controlled; $T_{m\text{-critical}}$ increases more rapidly than $T_{s\text{-critical}}$ ✓**
   b. **As binders become more m-controlled they are more brittle and lose ability to relax stress ✓**
   c. **As pavements age they are more prone to cracking distress ✓**
   d. **As ΔTc becomes more negative pavements become more prone to top down fatigue cracking ✓**
   e. **It may not appear intuitively obvious that a value derived from low temperature testing should be associated with distresses that are associated with intermediate service temperatures ✓**
   f. **Based on research, some of which goes back 50+ years, research has shown the connections between pavement surface distresses and several parameters the most recent of which is ΔTc ✓**

ΔTc can quantify the aging propensity of a binder

IN THE FINAL ANALYSIS ΔTc, R-Value, GR COMES DOWN TO 1 THING

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SPECIFICALLY
BINDER
RELAXATION

TIME TO GET SERIOUS

- As with most advances in technical research developments are the result of cumulative increase in knowledge ✓
- I will briefly reference the work of three individuals, but reading their research will show many other contributors along the way
- Prithvi (Ken) Kandhal – Pennsylvania DOT Bituminous Engineer
- Dr. Charles Glover—Research Professor Texas Transportation Institute at Texas A&M
- Mike Anderson—Director of Research at the Asphalt Institute

References

1. Kandahl, Low Temperature Ductility in Relation to Pavement Performance, ASTM STP 628, Marek, Ed., 1977
2. Glover, Charles J, Davison, Richard, Domke, Chris, Ruan, Yonghong, Juristyarini, Pramitha, Knorr, Daniel, Jung, Sung, "Development Of A New Method For Assessing Asphalt Binder Durability With Field Validation", FHWA/TX-05/1872-2, August 2005
3. Anderson, R. M, King, G.N., Hanson, D.I., Blankenship, P.B. "Evaluation of the Relationship between Asphalt Binder Properties and Non-Load Related Cracking." Association of Asphalt Paving Technologists, 2011 Volume 80, pp 615-663, 2011
4. TRB papers in 2010, 2011 and 2012 by Sui and Farrar, et al from Western Research Institutre
5. EECongress in Istanbul, 2012, Farrar, et al

In the interest of time I have hidden several background slides which will be available when this presentation is provided to the ETG members

Ductility and Pavement Condition of 1961 and 1962 Pennsylvania Pavements Reported by Kandhal (**Kandhal 1977**)

Ductility value at 60°F (15.5°C), 5 cm/min, cm	**Pavement Condition Observed**
More than 10	**Satisfactory**
8 to 10	**Loss of fines (matrix)**
5 to 8	**Raveling**
3 to 5	**Cracking, needs resurfacing**
Less than 3	**Very poor, extensive cracking**

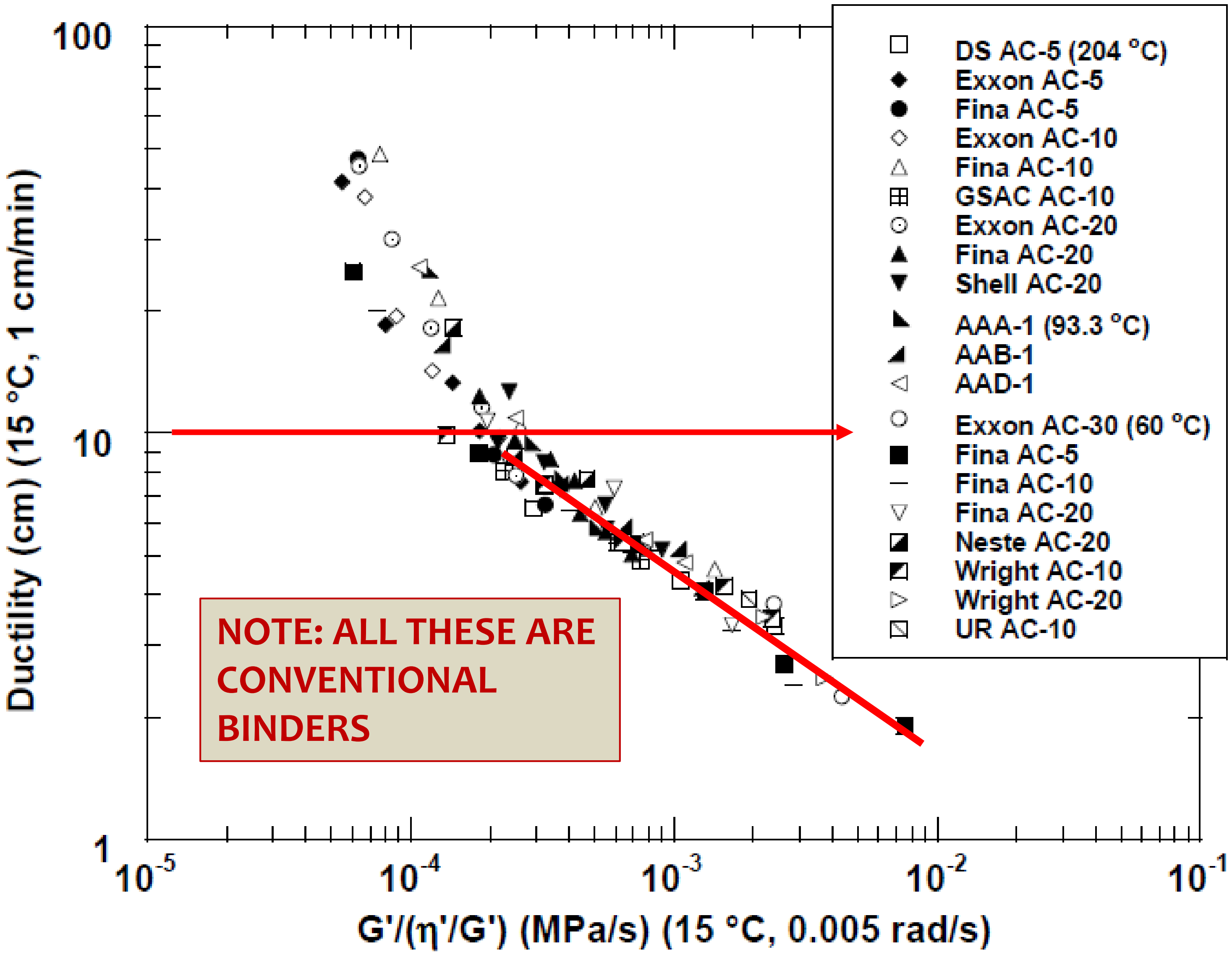
SOME COMMENTS REGARDING KANDHAL'S WORK

1. **At 10 cm ductility there is no cracking reported, however when it takes longer than 3 years to reach 10 cm loss of fines and some raveling is noted**
2. **Regardless of the time it takes to reach less than 5 cm of ductility that ductility value is associated with the onset of cracking ✓**

***Extent* of binder aging is the key factor and not the *time* of binder aging**

What Can We Infer From This Data?

- There is a point in the aging of a binder when cracking begins to develop
- Binder aging rate is not the same for every binder *(crude source impacts performance)* or perhaps it is not the same time point for the same binder depending on the conditions of the job
  - Time of year constructed
  - % bitumen in the mix
  - Air voids
  - Aggregate type and/or gradation
  - Other factors e.g. RAP, RAS, polymer or ???
- Extent of Binder Aging is the Key Driver
- **How can we age binders and mixtures sufficiently in the lab to tell us something useful about long term performance?**



NOTE: ALL THESE ARE CONVENTIONAL BINDERS

Figure 4-11. Ductility versus DSR Parameter G′/(η′/G′), All Ductilities.

Taken from Glover, et al 2005, plot shows

1. Linear correlation between G'/ η'/G' and 15°C ductility for ductility values < 10 cm✓
2. Based on Kandhal's data when ductility drops below 10 pavement distress begins ✓
3. Glover used this data to develop relationship between ductility and binder rheology at 15°C ✓
4. Glover used time temperature superposition principles to adjust the DSR test to 44.7°C and 10 rad/sec ✓

Moving from Ductility to ΔTc

- Mike Anderson, et al AAPT 2011—**introduced ΔTc concept** ✓
- Rheological & ductility of PAV binders and binders recovered from aged airfield mixtures
- Established Relationship of ΔTc to non-load associated distress
- Key findings ✓
  1) Glover @ Texas A&M had shown ductility @ 15°C & 1 mm/min correlated to long term pavement distress ✓
  2) G'/(η'/G') correlated to ductility @ 15°C & 1 mm/min ✓
  3) Also showed G'/(η'/G') correlated to ΔTc (difference between the BBR $T_{m\text{-critical}}$ – BBR $T_{s\text{-critical}}$ ✓
  4) ΔTc of 2.5°C = cracking warning limit, ΔTc = 5°C point where binder durability lost ✓

ΔTc and 4 mm DSR Testing

- Much of the data to be discussed next was generated at MTE using a 4 mm DSR test developed at Western Research Institute (see reference list)
- Requires very little material to perform test ✓
- Results correlate well to BBR, but there is a learning curve ✓
- Provides a broader temperature range (-36°C to +30°C or +40°C) of data collection in less time than BBR test at 3 temperatures ✓

The size advantages are obvious for performing tests on field samples and other forensic work

When the main mixture layer that needs testing is binder recovered from the top ½ inch of a 6 inch diameter core very little binder is obtained and the 4 mm test requires only one core to provide sufficient binder for a 25 mm and 4 mm test

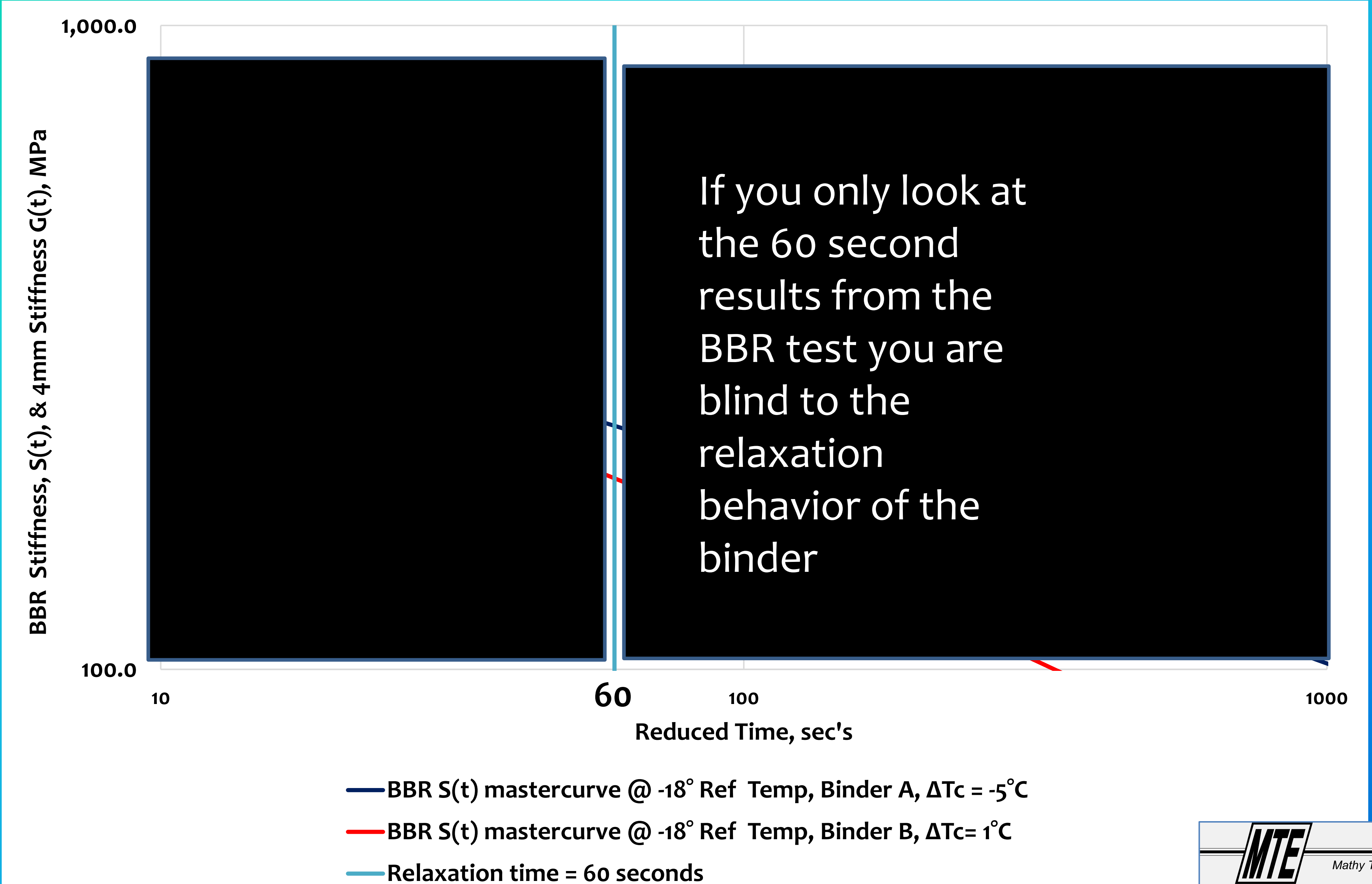
Just How Does ΔTc Relate to Mix Performance?

- Need to get back to RELAXATION
- As binders age their ability to relax stress diminishes ∴ BBR result becomes increasingly m-controlled (poor relaxation) ✓
- Some binders have inherently poor relaxation properties, BBR will show this and ΔTc can quantify impact of poor relaxation✓
- Relaxation is not just a low temperature (i.e. sub 0°C) problem
  - Ductility decreases when binder cannot relax fast enough to prevent the binder thread from breaking (Kandhal & Glover at 15°C)
  - The DSR data shows similar behavior (Glover's DSR vs Ductility Plot another test performed at 15°C)

Just How Does ΔTc Relate to Binder Relaxation and Ultimately Mix Performance?

- How many of you have really looked at or compared the BBR data plot for different binders?
- BBR test is not just a single data point at 60 seconds
- In that plot is the story of how the binder relaxes (or doesn’t) due to the imposition of load

COMPARISON OF BBR MASTERCURVES @ -18°C FOR TWO DIFFERENT BINDERS



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If you only look at the 60 second results from the BBR test you are blind to the relaxation behavior of the binder

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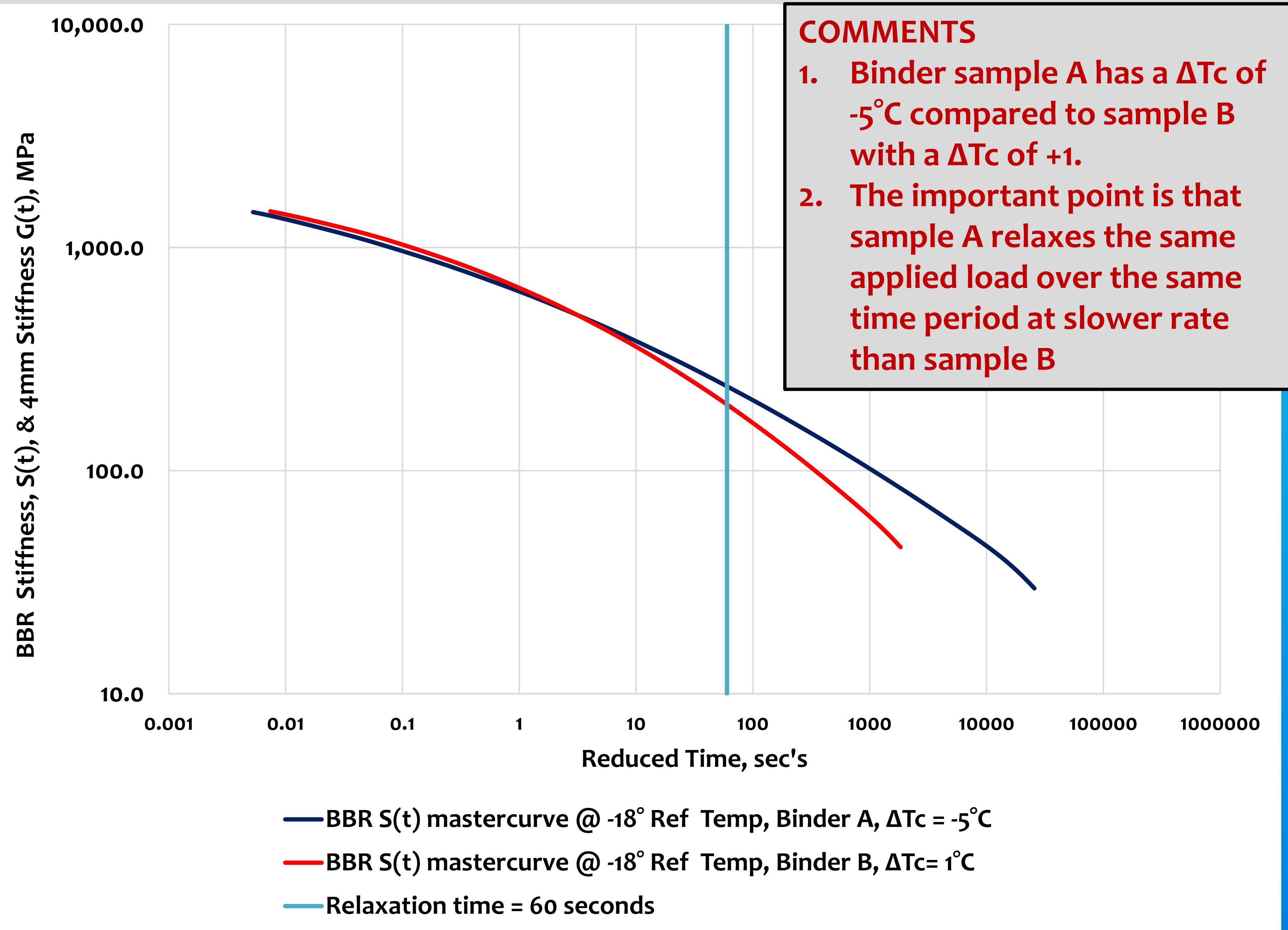
COMPARISON OF BBR MASTERCURVES @ -18°C FOR TWO DIFFERENT BINDERS

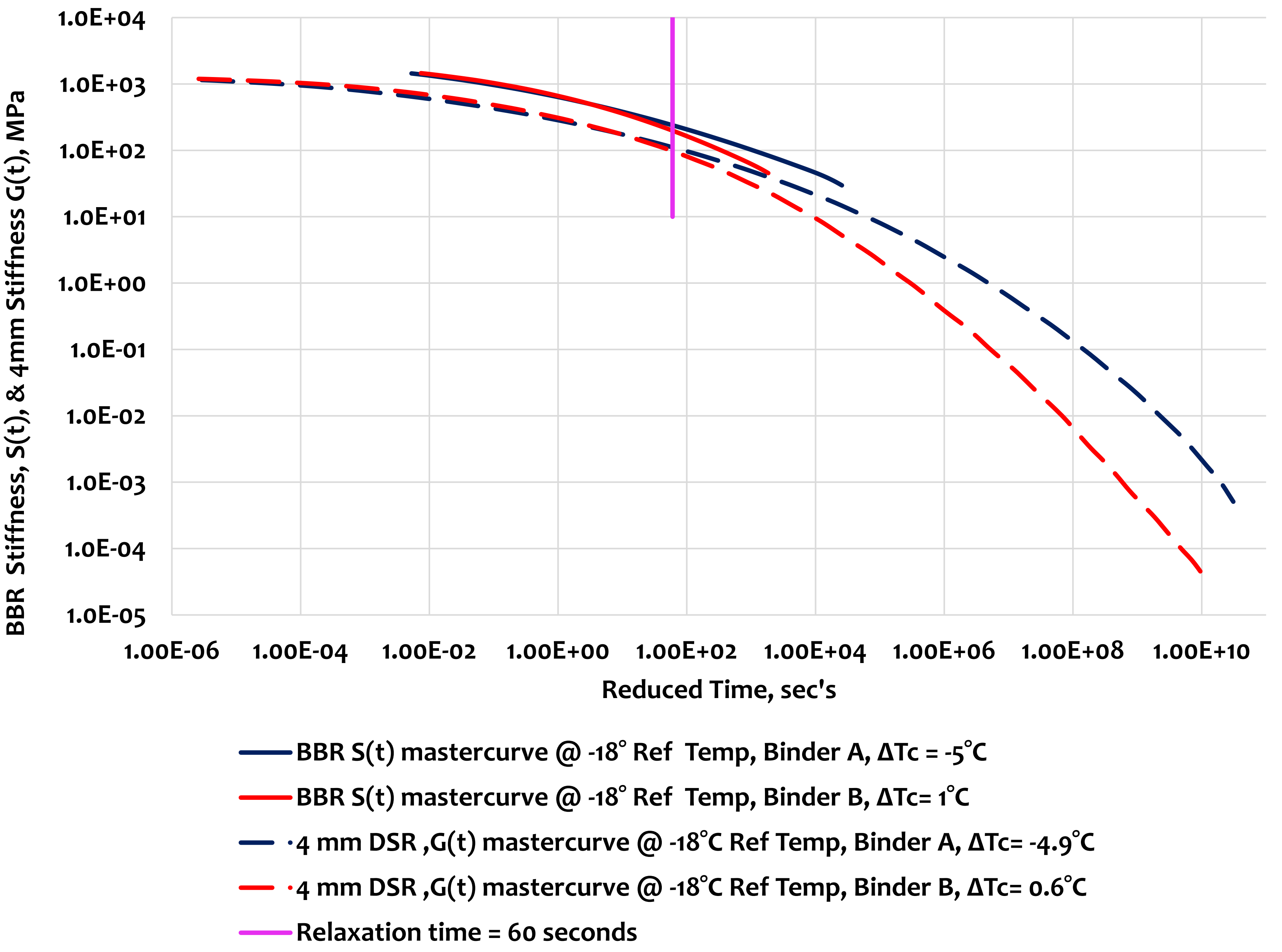


COMMENTS

1. Binder sample A has a ΔTc of -5°C compared to sample B with a ΔTc of +1.
2. The important point is that sample A relaxes the same applied load over the same time period at slower rate than sample B

1. If you only focus on the slope at 60 seconds you will see a difference, but it is just a comparison of 2 numbers
2. When you look at the complete BBR mastercurve you see how much more readily the binder with a ΔTc of 1°C relaxes stress compared to the binder with a ΔTc of -5°C

COMPARISON OF BBR & 4 mm MASTERCURVES @ -18°C FOR TWO DIFFERENT BINDERS



1. When you incorporate the 4 mm data for the same binders similar ΔTc results are obtained, but you also observe how the relaxation disparity carries over to longer relaxation times
2. Longer relaxation times are a surrogate for relaxation behavior at warmer temperatures

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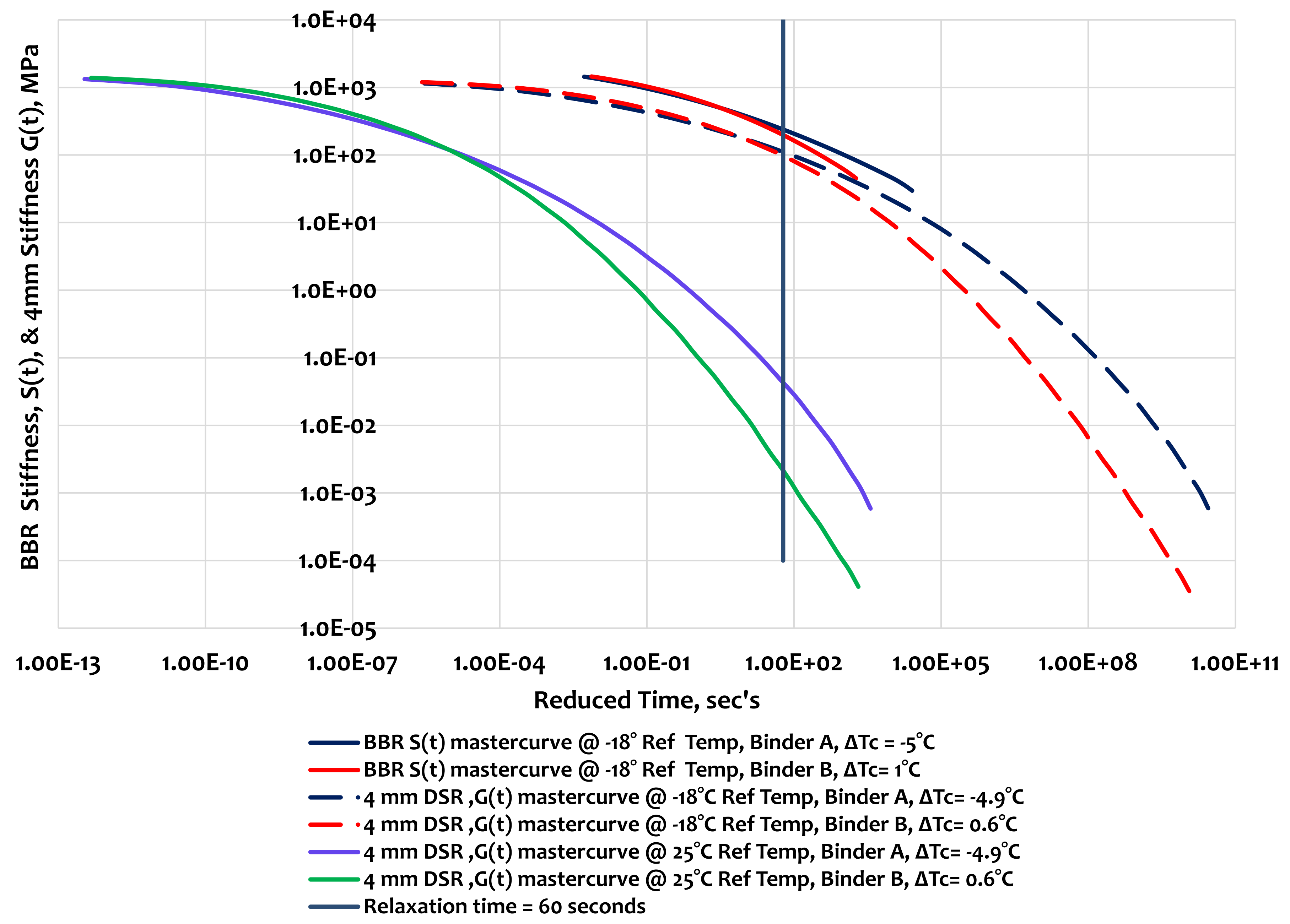
COMPARISON OF BBR & 4 mm MASTERCURVES @ -18°C & 25°C FOR TWO DIFFERENT BINDERS



If binders have a relaxation disparity at low temperatures they also have a relaxation disparity at warmer temperatures

An additional benefit of the 4 mm test is the ability to examine the binder's behavior at temperatures beyond those capable by the BBR

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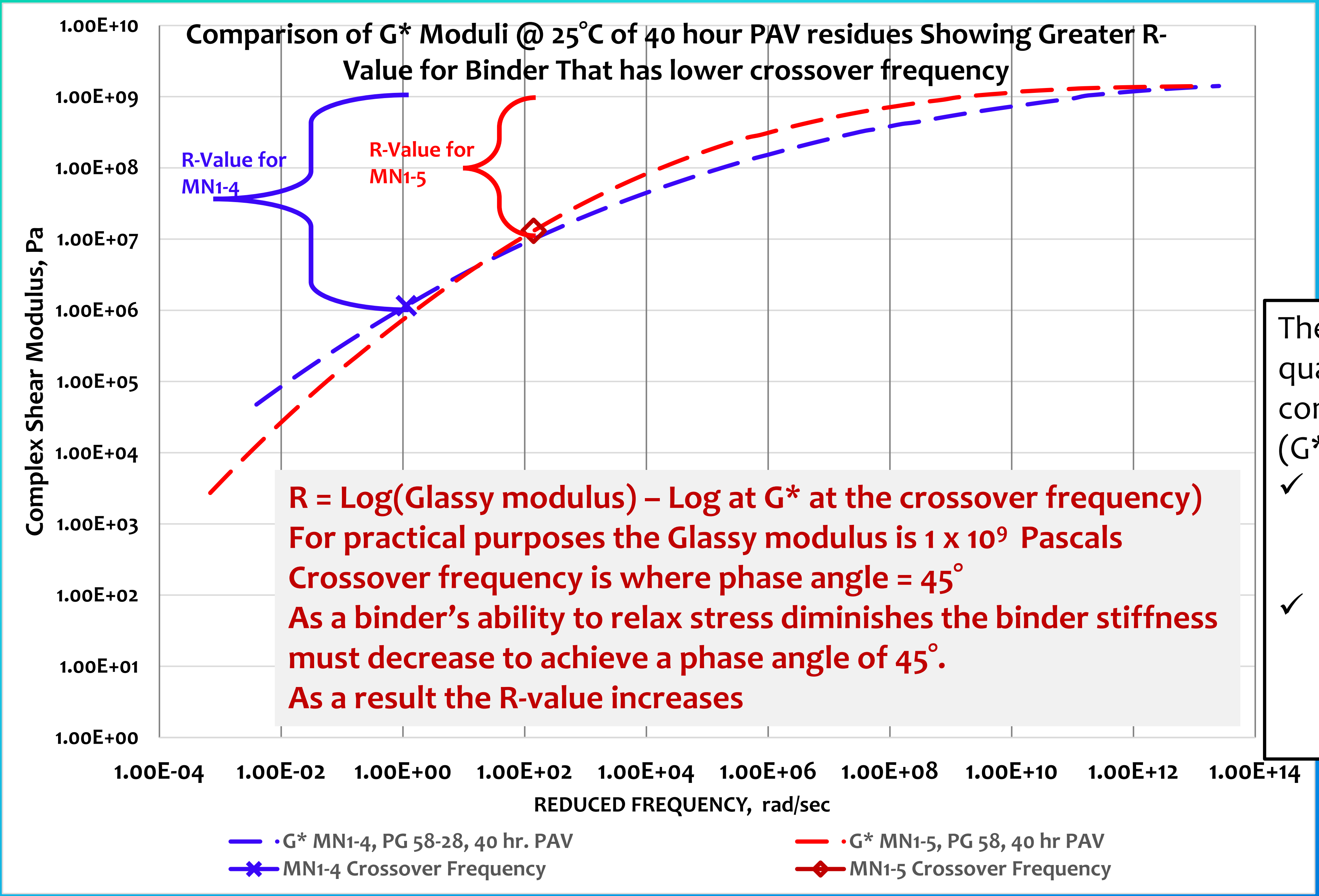
Illustration of Determination of R-Value (Rheological Index)



R = Log(Glassy modulus) – Log at G* at the crossover frequency)
For practical purposes the Glassy modulus is 1×10^9 Pascals
Crossover frequency is where phase angle = 45°
As a binder's ability to relax stress diminishes the binder stiffness must decrease to achieve a phase angle of 45°.
As a result the R-value increases

1. MN1-5 binder performed the best and has the lowest R-value
2. MN1-4 performed the worst and has the highest R-value

The R-Value is another way to quantify binder relaxation by comparing the shear modulus (G*) mastercurves

- ✓ The method of determining the R-value from rheological data is summarized at the left
- ✓ A graphical presentation of R-Value is shown in the difference in length for the 2 sets of brackets

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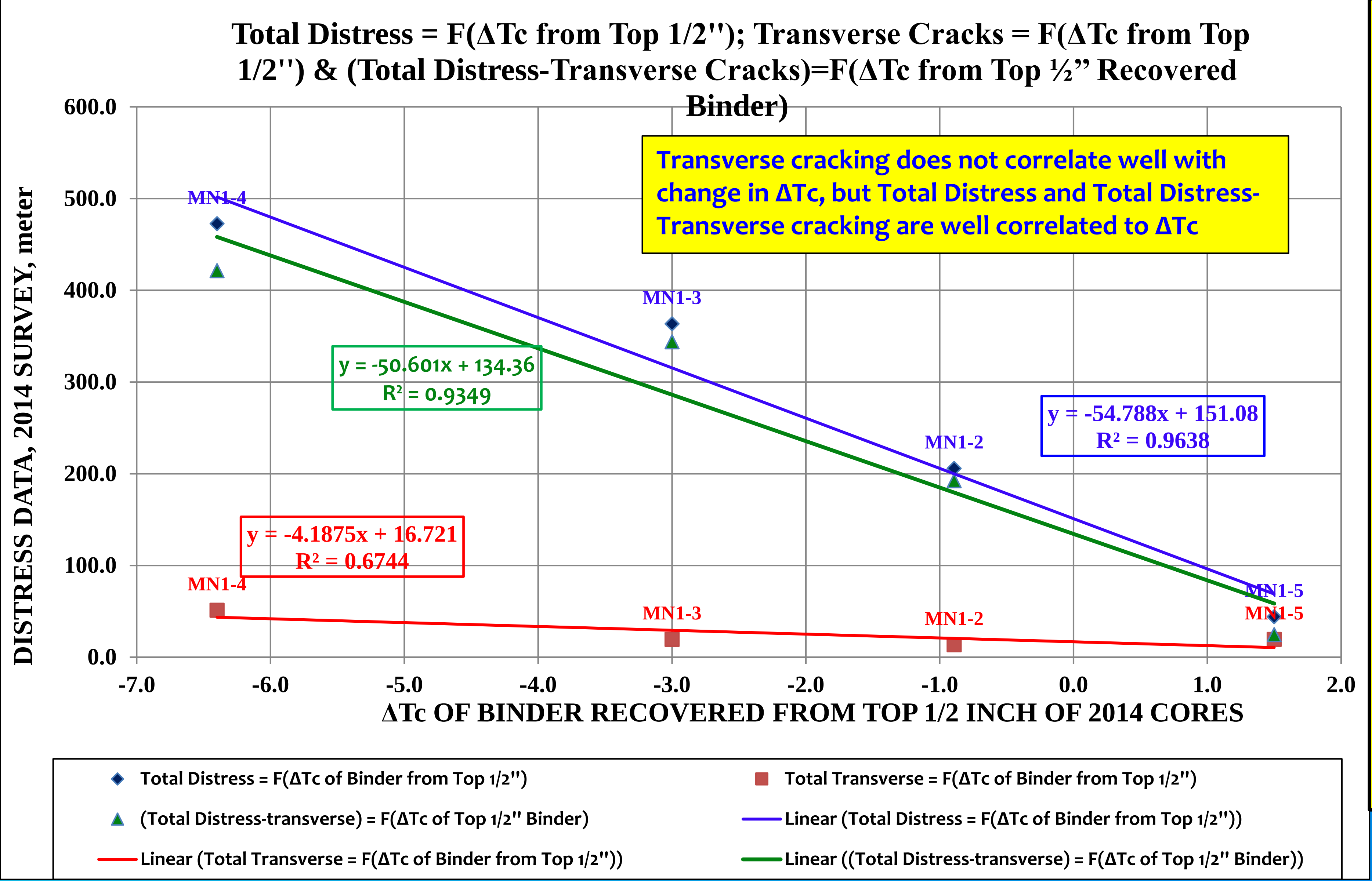
SOME FIELD EXAMPLES

- I’ve presented this information at AI and other places such as ETG meetings, ∴ I will only provide a couple brief comments

COMPARATIVE CRUDE SOURCE STUDY

- CTH 112 Olmsted Cty, MN; 2006 construction
- 3 virgin test sections to compare 3 different crude sources of PG 58-28 binder (MN1-3, MN1-4, MN1-5)
- 1 virgin PG 58-34 PMA binder (MN1-2)
- Project specified mix of a PG 58-34 + 20% RAP (MN1-1)
- Substantial surface cracking began to show up between years 4 and 5

Olmsted County, MN CTH 112, 2014 (8 yrs)



Total Distress = F(ΔTc from Top 1/2''); Transverse Cracks = F(ΔTc from Top 1/2'') & (Total Distress-Transverse Cracks)=F(ΔTc from Top ½” Recovered Binder)

Transverse cracking does not correlate well with change in ΔTc, but Total Distress and Total Distress-Transverse cracking are well correlated to ΔTc

COMMENTS

1. ΔTc does not correlate well with transverse cracking
2. transverse cracking level is similar for all mixes, but ΔTc varies widely
3. Substantial difference in top down cracking in the test sections does correlate well with ΔTc

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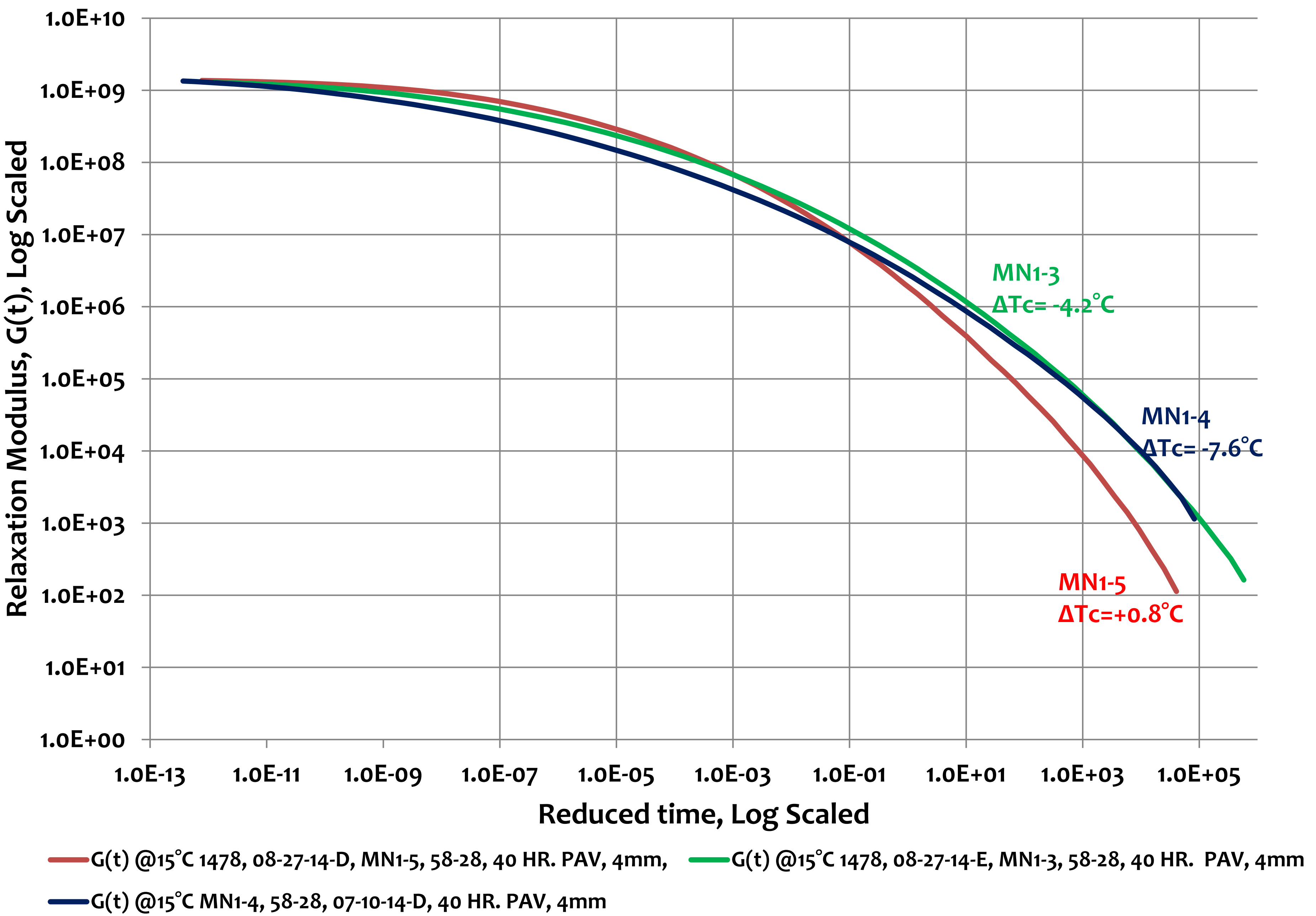
Relationship of Cracking to Binder Relaxation

- For purposes of my objective in this discussion the next few slides are more important than looking at ΔTc plots correlated to cracking

Reduced Time VS Relaxation Modulus @ 15°C for MN1-3, MN1-4, MN1-5 of 40 hour PAV Residue



COMMENTS

1. MN1-3 & MN1-5 have greater relaxation moduli than MN1-4 at short relaxation times
2. **HOWEVER**
3. MN1-4 relaxes stiffness so slowly that at extended time it intersects MN1-3

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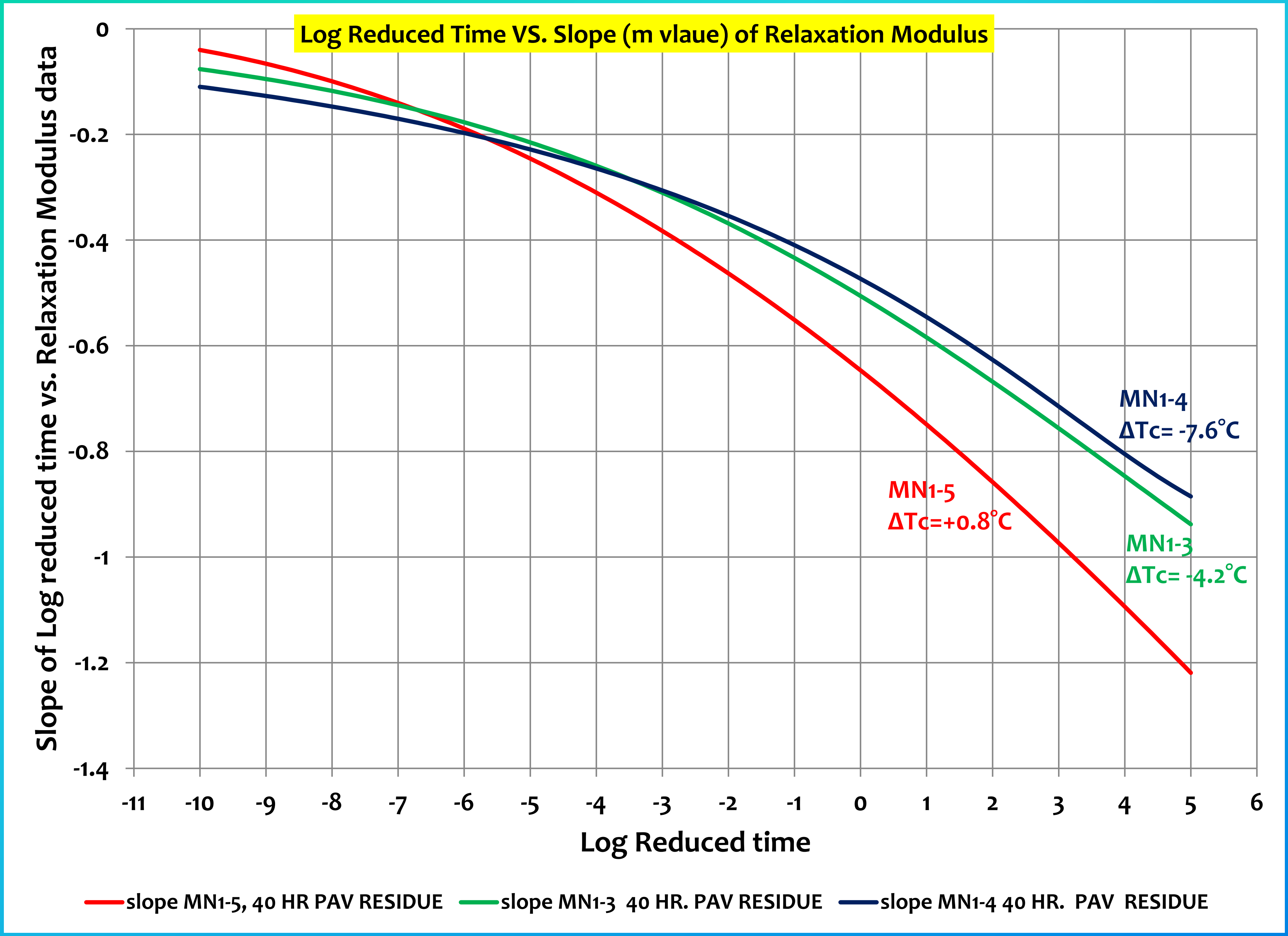

Log Reduced Time VS. Slope (m vlaue) of Relaxation Modulus

COMMENTS

1. The first derivative of relaxation modulus curves show more clearly what is happening
2. The 1st derivative plot is the same as determining the m-value at every point along the relaxation modulus mastercurve
3. The slope of MN1-3 decreases at a faster rate than the slope of MN1-4 and the slope of MN1-5 decreases at the fastest rate of all.
4. This rate of relaxation emphasizes the interrelation of relaxation slope and level of ΔTc

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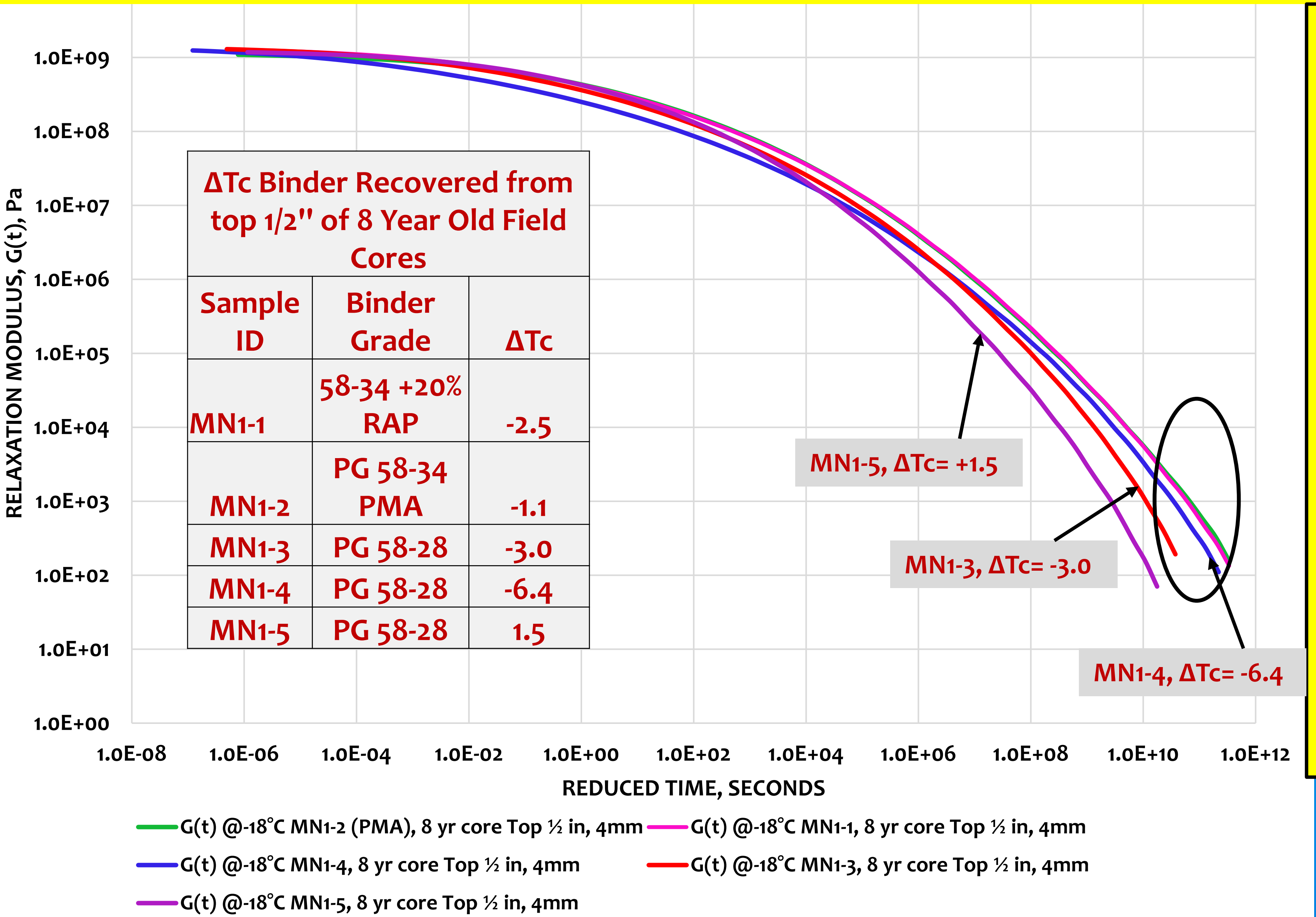
Reduced Time VS Relaxation Modulus @ -18°C of Recovered Binder from Top ½ inch of 8 year Field Cores of MN1-1, MN1-2, MN1-3, MN1-4, MN1-5



ΔTc Binder Recovered from top 1/2" of 8 Year Old Field Cores

Sample ID	Binder Grade	ΔTc
MN1-1	58-34 +20% RAP	-2.5
MN1-2	PG 58-34 PMA	-1.1
MN1-3	PG 58-28	-3.0
MN1-4	PG 58-28	-6.4
MN1-5	PG 58-28	1.5

COMMENTS

1. Plot is of relaxation moduli of binders recovered from the top ½ inch of 8 year field cores
2. The 3 PG 58-28 binders have relaxation moduli plots that reflect their ΔTc values;
3. The plots of MN1-1 and MN1-2 (PMA binder) appear to have worse relaxation moduli even though they have the 2nd & 3rd best ΔTc values

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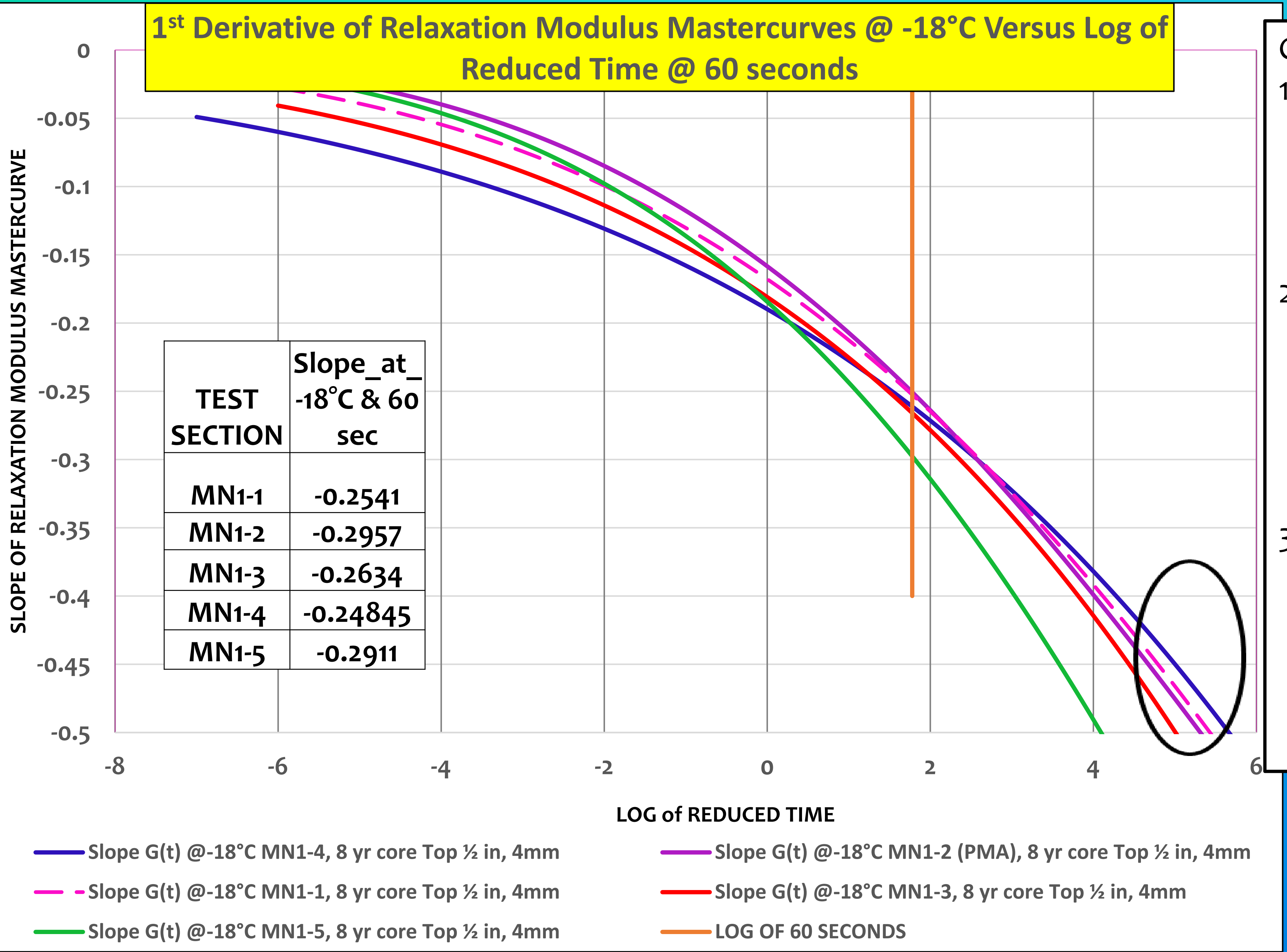
1st Derivative of Relaxation Modulus Mastercurves @ -18°C Versus Log of Reduced Time @ 60 seconds



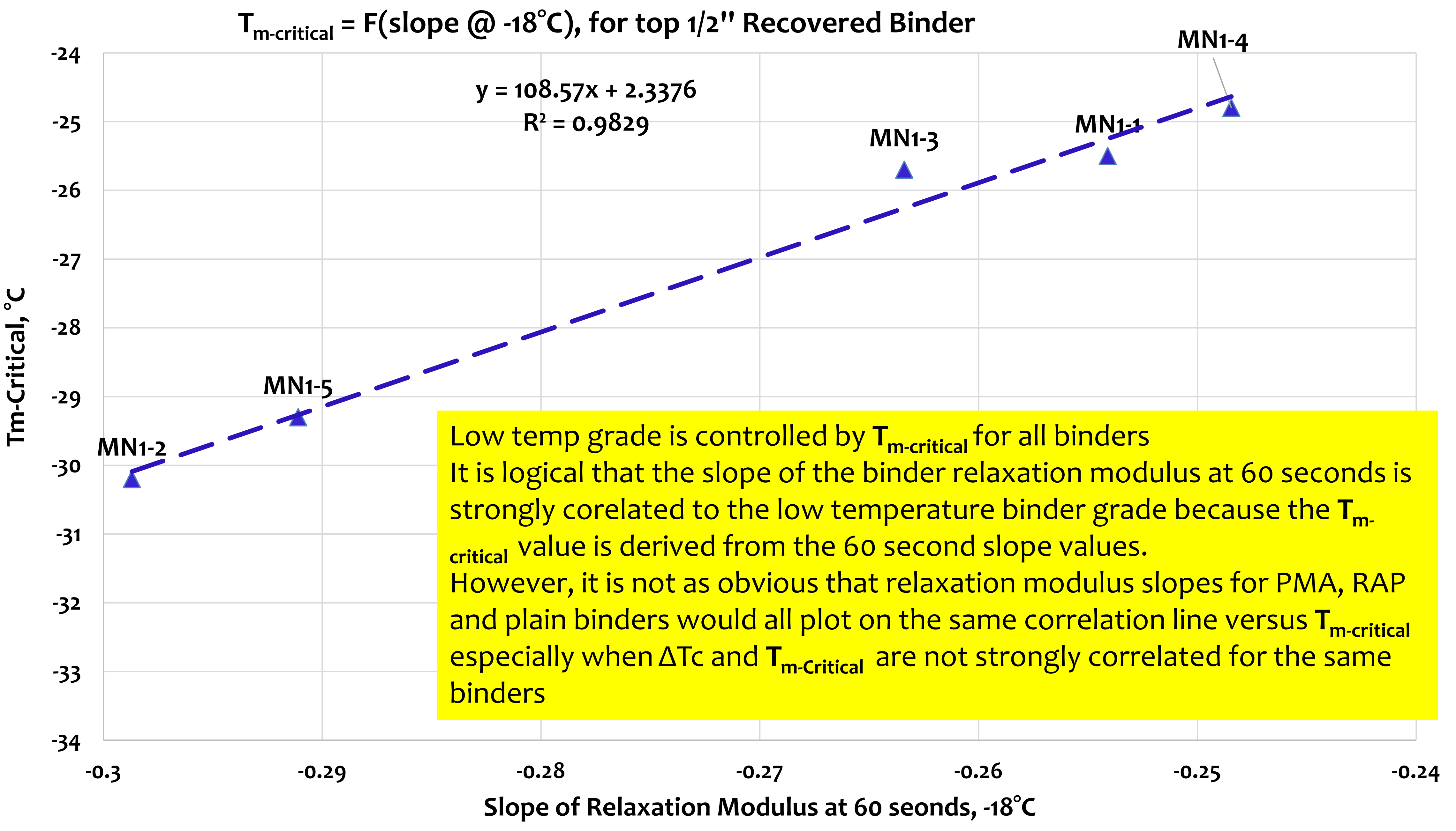
TEST SECTION	Slope_at_-18°C & 60 sec
MN1-1	-0.2541
MN1-2	-0.2957
MN1-3	-0.2634
MN1-4	-0.24845
MN1-5	-0.2911

COMMENTS

1. This is a zoomed plot of the slope of the relaxation modulus mastercurve vs log of reduced time for all 5 CTH 112 binders
2. MN1-1 starts out at a slightly lower relaxation modulus than MN1-5, but relaxes more slowly and by 60 seconds is relaxing at a slower rate than MN1-2
3. MN1-4 which has the lowest relaxation modulus at short times relaxes so slowly that it eventually crosses over all of the other binders and has the worst slope of all materials

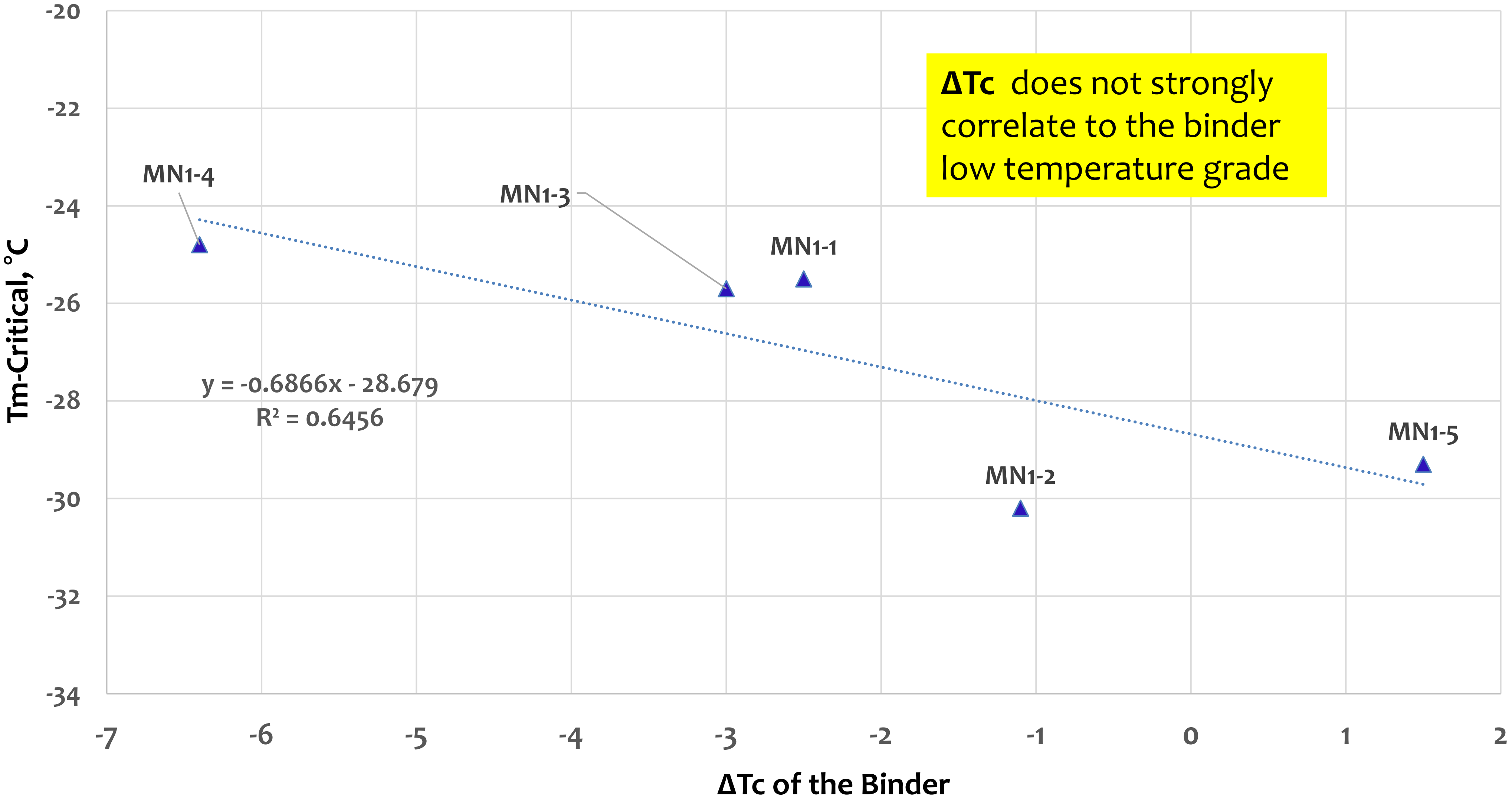
Relationship of $T_{m\text{-}Critical}$ to Several Parameters

$T_{m\text{-critical}}$ = F(slope @ -18°C), for top 1/2" Recovered Binder



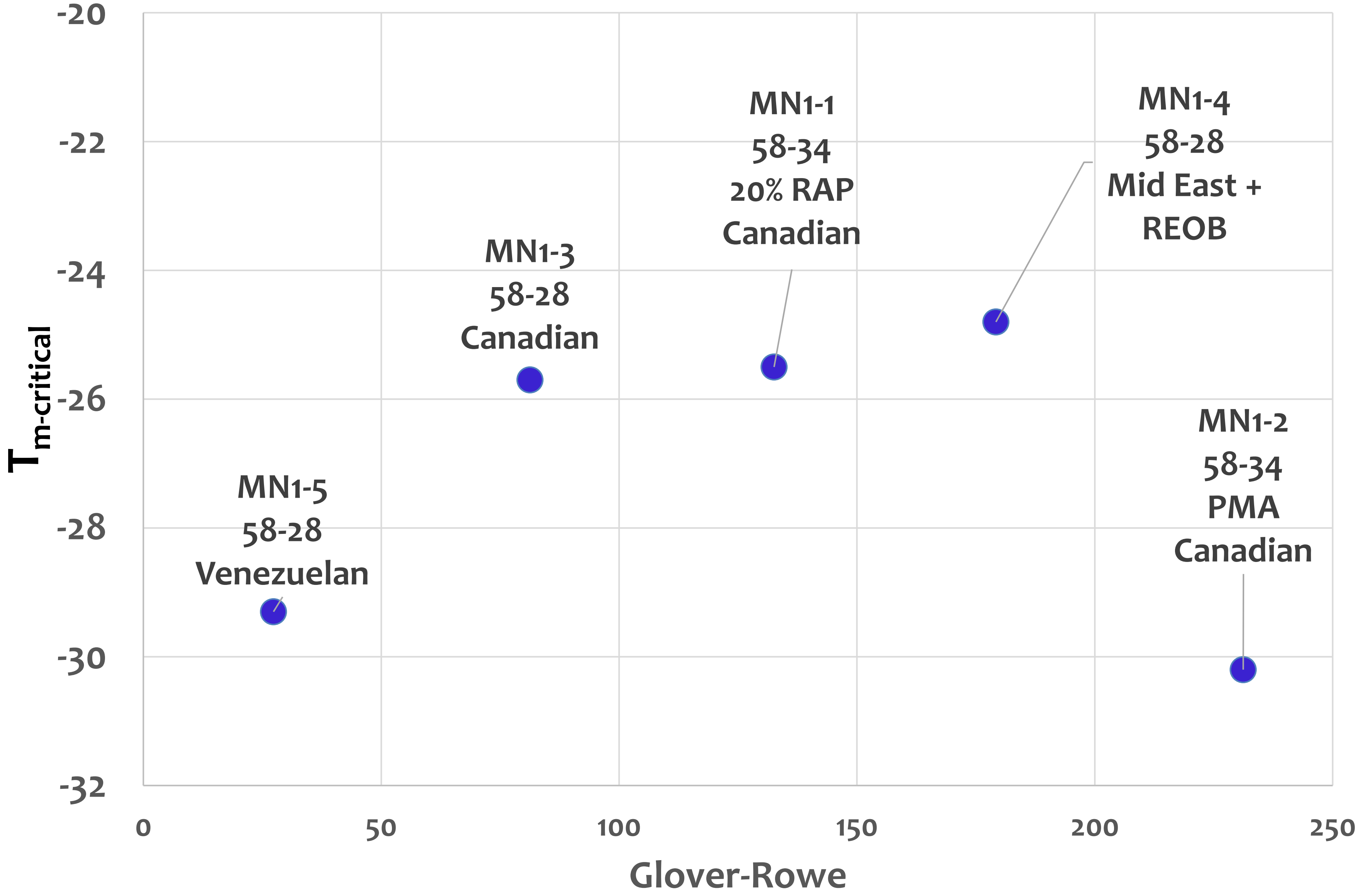
Low temp grade is controlled by **$T_{m\text{-critical}}$** for all binders
It is logical that the slope of the binder relaxation modulus at 60 seconds is strongly corelated to the low temperature binder grade because the **$T_{m\text{-critical}}$** value is derived from the 60 second slope values.
However, it is not as obvious that relaxation modulus slopes for PMA, RAP and plain binders would all plot on the same correlation line versus **$T_{m\text{-critical}}$** especially when ΔTc and **$T_{m\text{-Critical}}$** are not strongly correlated for the same binders

$T_{m\text{-}critical}$ = F(ΔTc), for top 1/2" Recovered Binder

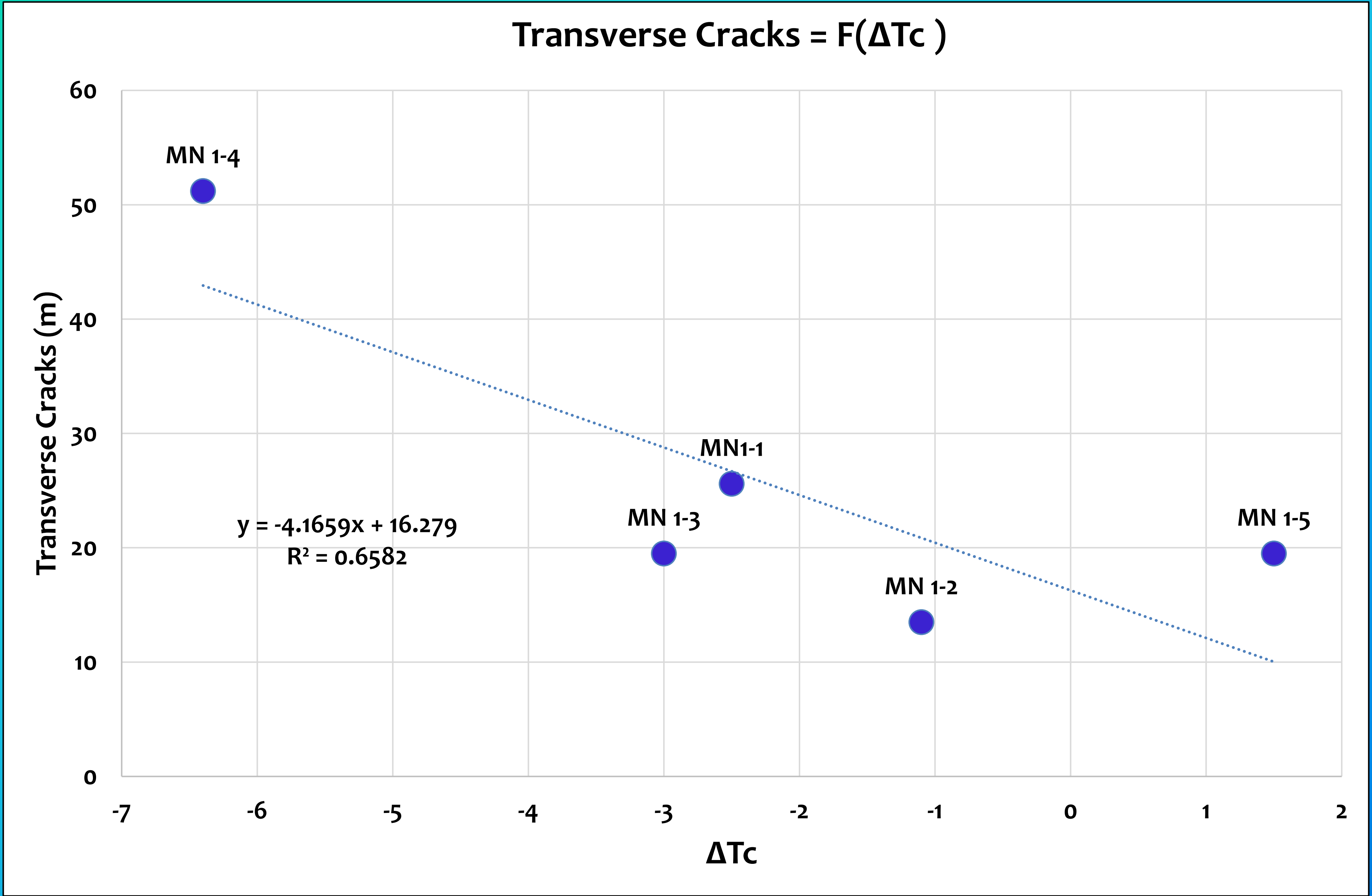


ΔTc does not strongly correlate to the binder low temperature grade

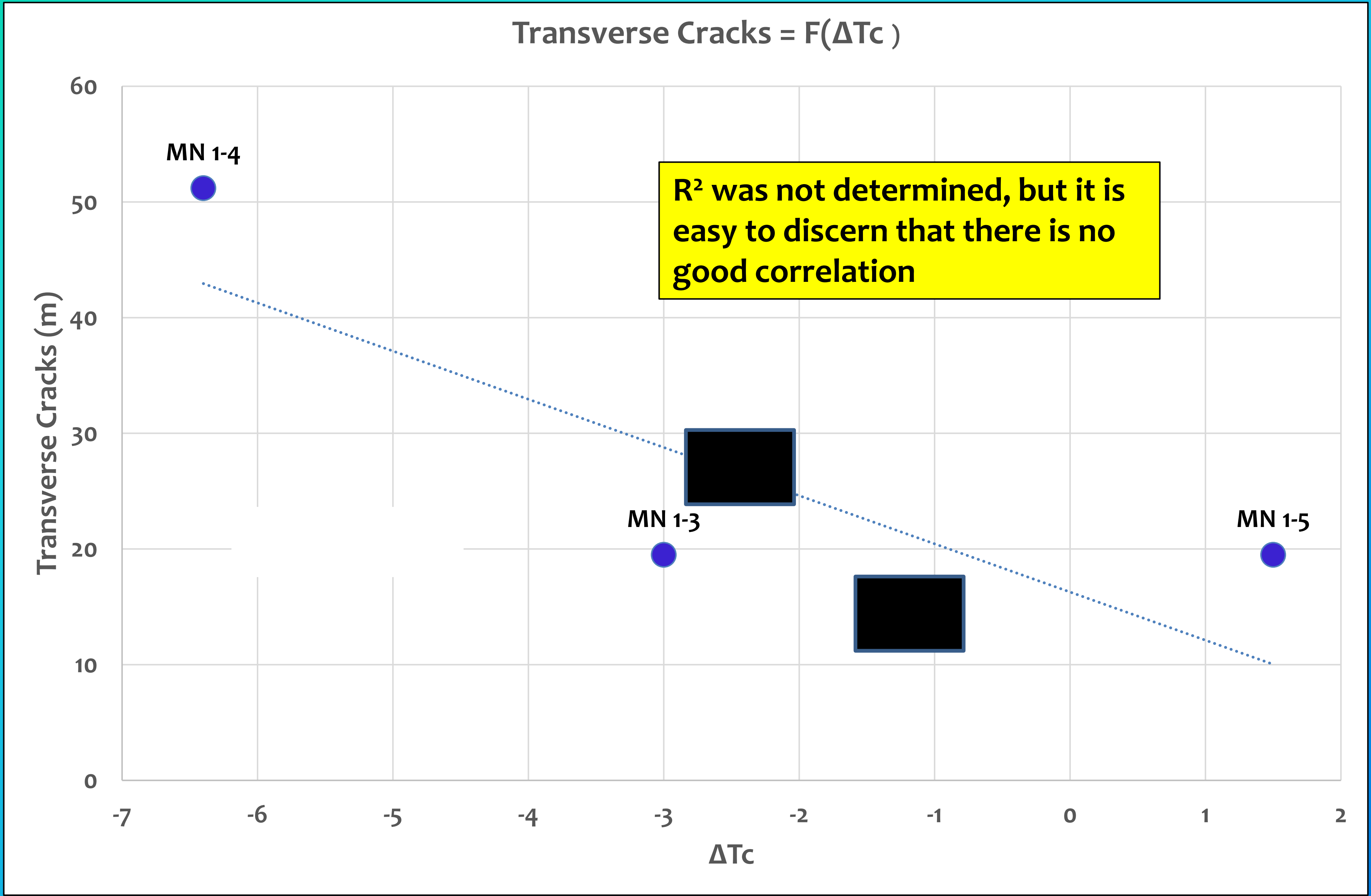
$T_{m\text{-critical}}$=F(Glover-Rowe)



Transverse Cracks = F(ΔTc) Olmsted CTH 112 Crude Source Study



Transverse Cracks = F(ΔTc) Olmsted CTH 112 Crude Source Study



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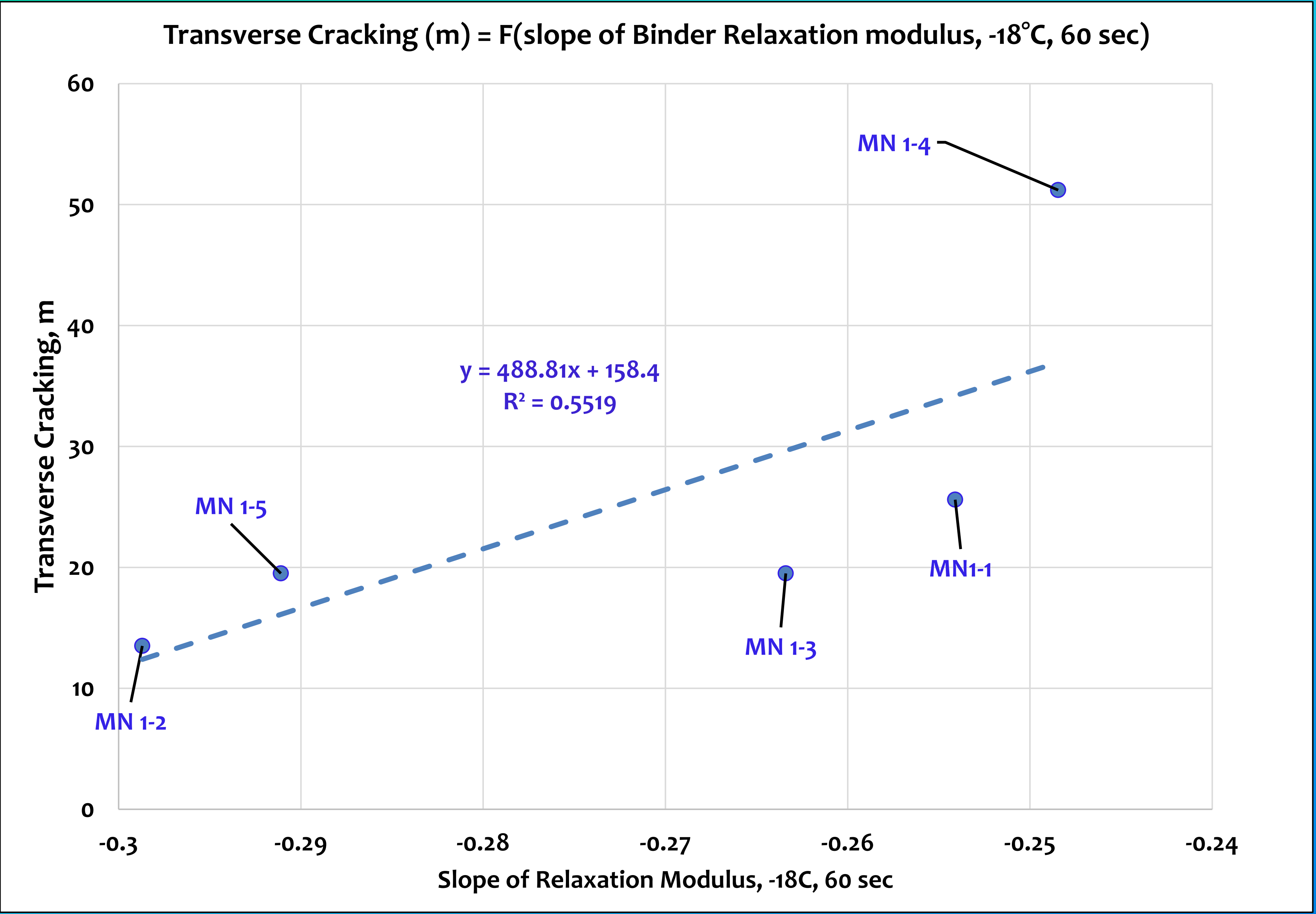
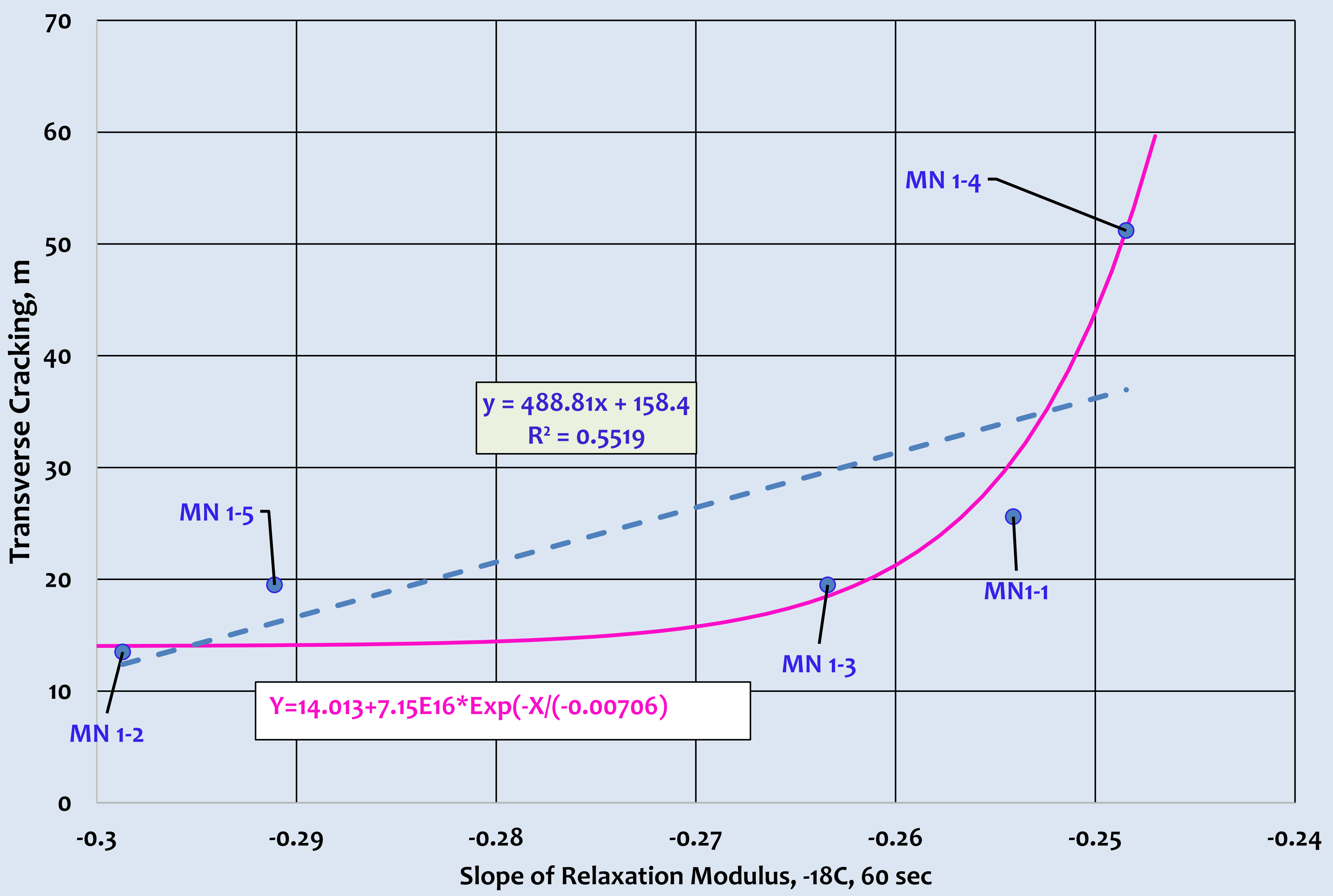
R^2 was not determined, but it is easy to discern that there is no good correlation

Even if you eliminate the polymer only (MN1-2) & polymer + RAP (MN1-1) data there is still not a linear correlation of transverse cracking with **ΔTc**



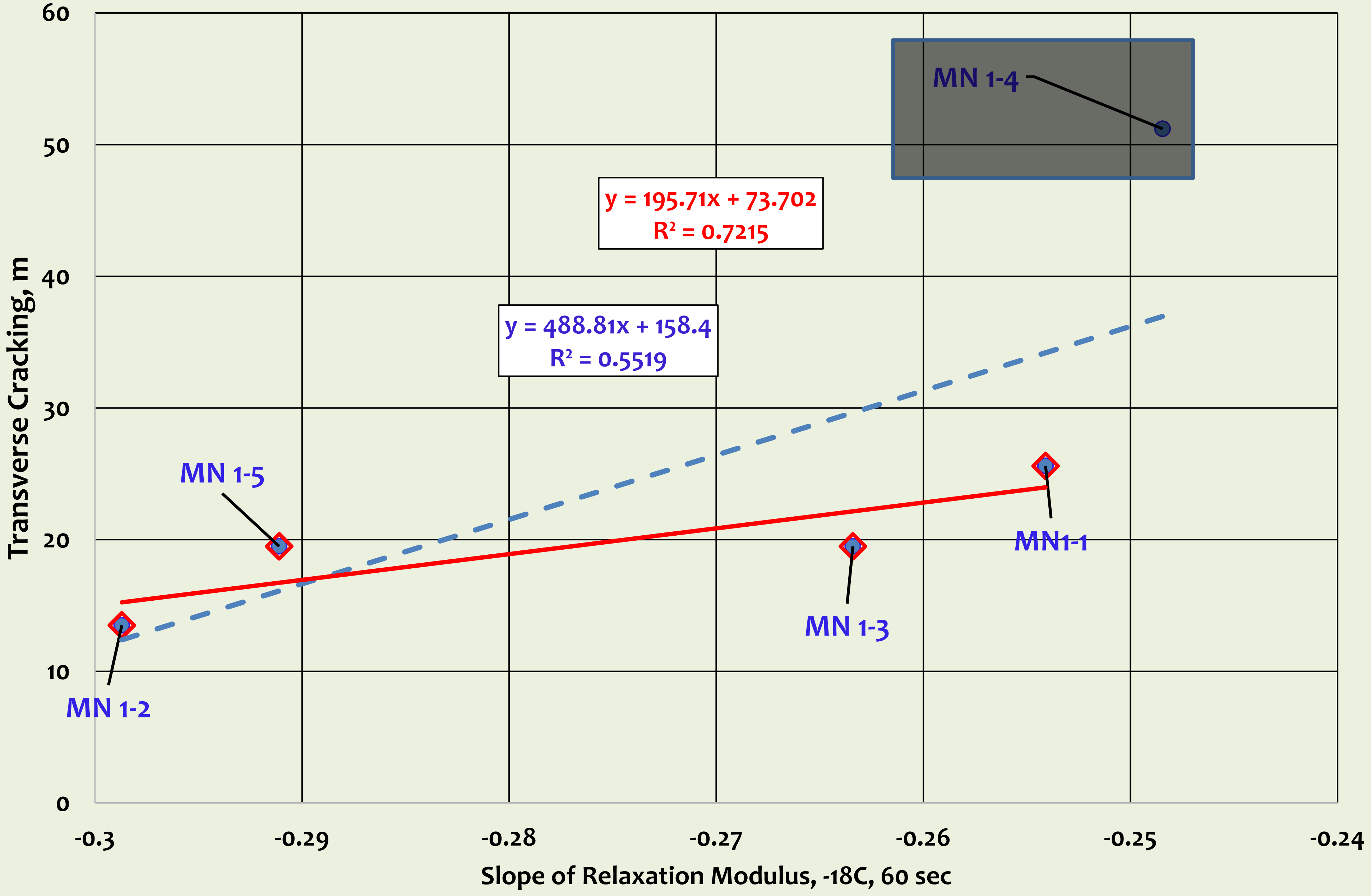
There is not a linear relationship between the slope of the binder relaxation modulus and the level of transverse cracking

Transverse Cracking (m) = F(slope of Binder Relaxation modulus, -18°C, 60 sec)



The exponential relationship fits the data, but I suspect that this function really fits the physical reality of transverse cracking as a function of binder relaxation modulus

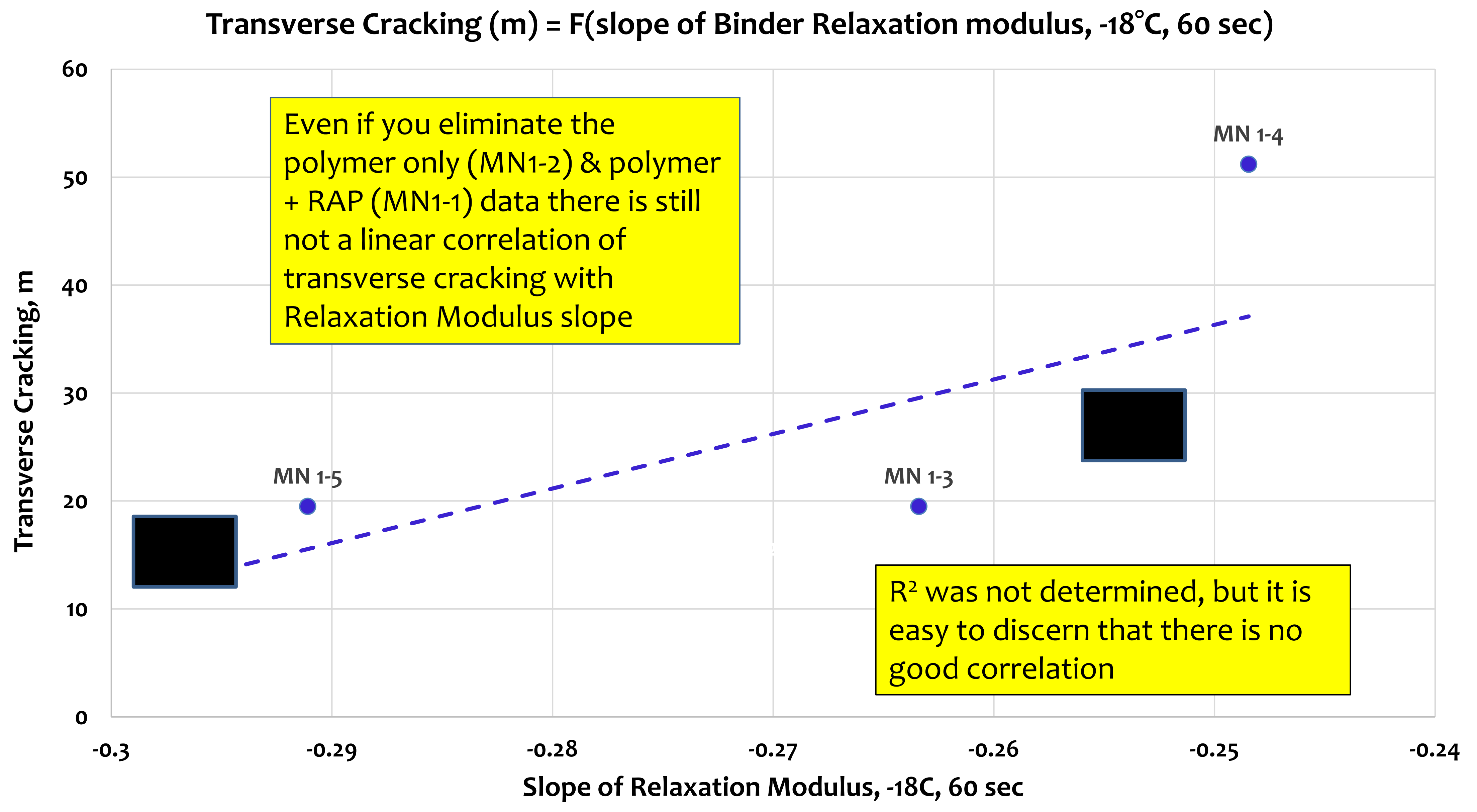
Transverse Cracking (m) = F(slope of Binder Relaxation modulus, -18°C, 60 sec)



For the non-REOB binders the linear correlation between slope of the binder relaxation modulus and transverse cracking is reasonable. Keep in mind that MN1-2 was a virgin PMA PG 58-34 mix and MN1-1 was a 20% RAP mix with PG 58-34 binder. MN1-5 and MN1-3 were virgin PG 58-28 mixes.

I think the most we can conclude from this data is that binder relaxation plays a role in transverse cracking, but is certainly not the whole story

Transverse Cracks = F(Slope of Binder Relaxation Modulus) Olmsted CTH 112 Crude Source Study



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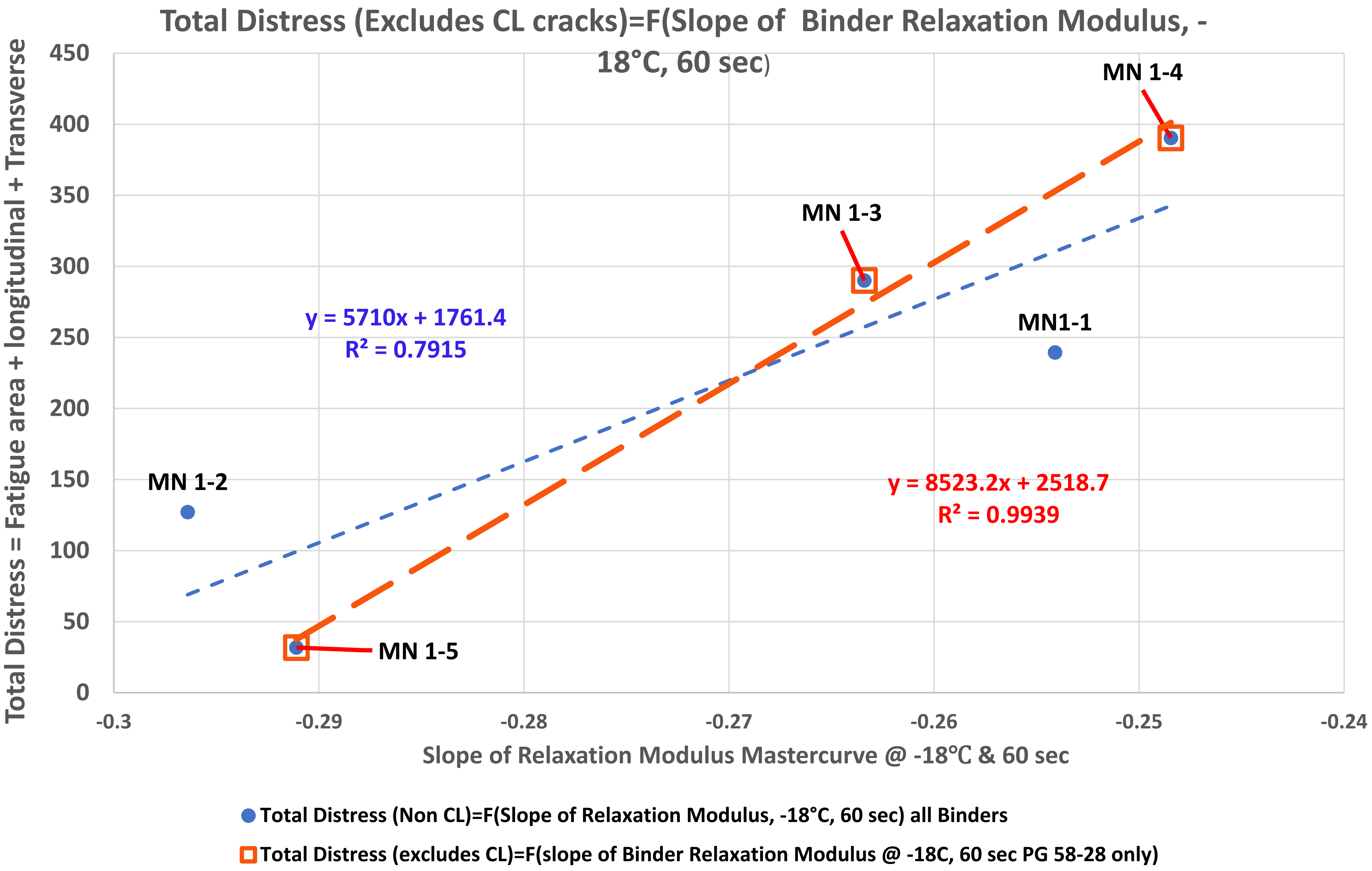
Even if you eliminate the polymer only (MN1-2) & polymer + RAP (MN1-1) data there is still not a linear correlation of transverse cracking with Relaxation Modulus slope

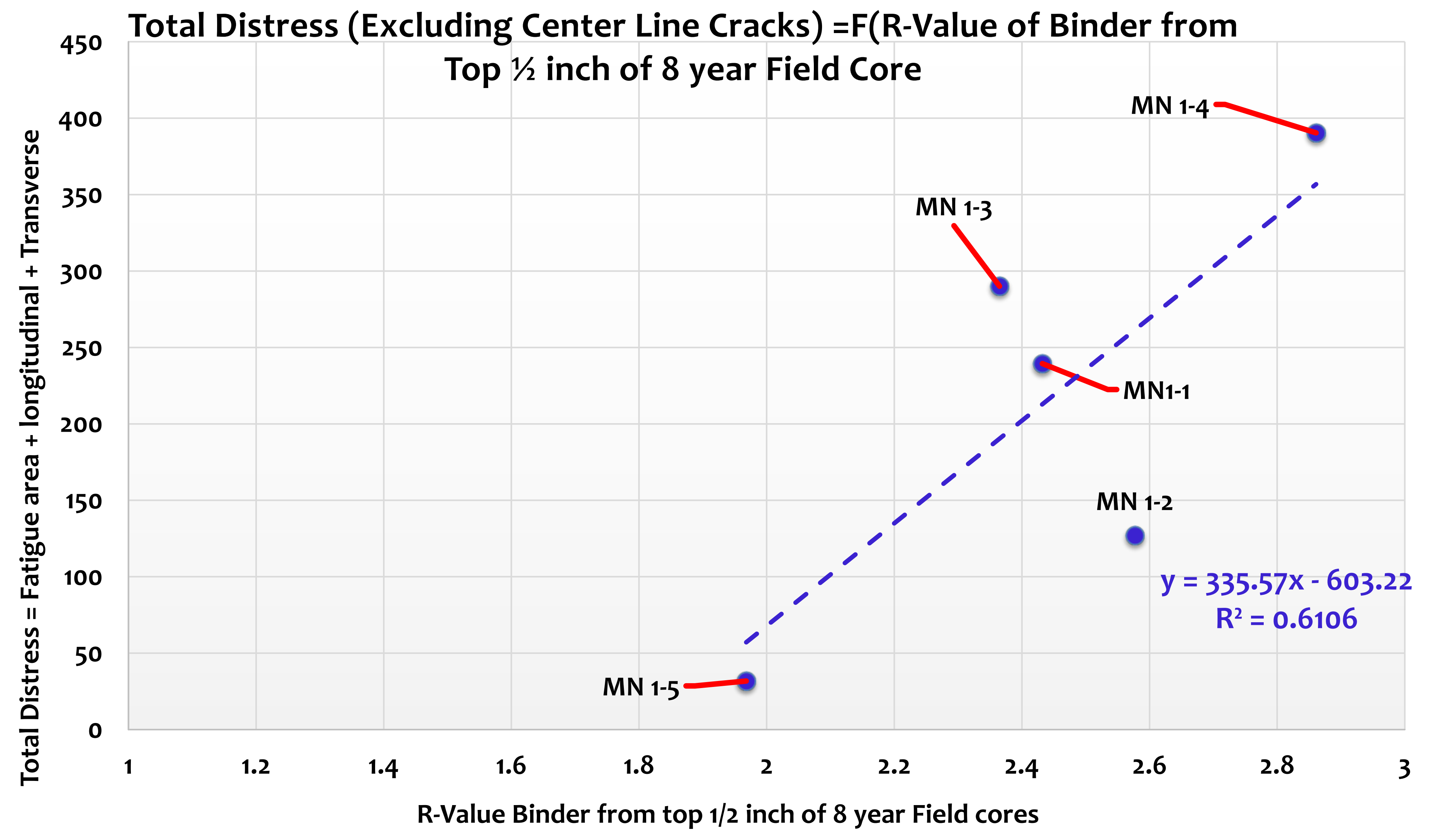
R^2 was not determined, but it is easy to discern that there is no good correlation

Total Distress = F(Slope Binder Relaxation Modulus) Olmsted CTH 112 Crude Source Study



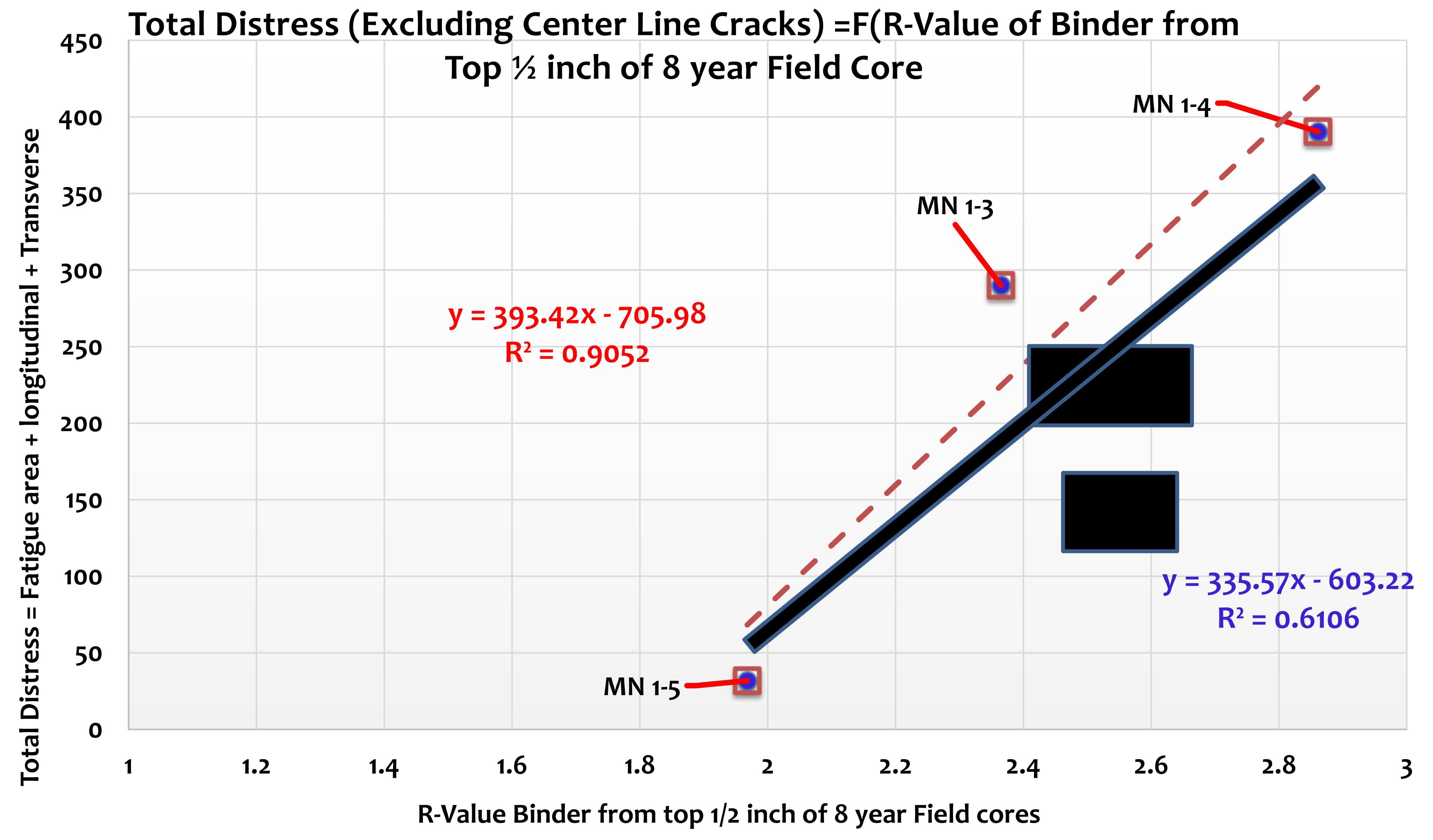
The relationship between total fatigue distress and the slope of the binder relaxation modulus master curve has a R^2 value of 0.79 for all binders, including the REOB binder mix MN1-4. Considering that this relationship includes the virgin PMA mix (MN1-2) and the 20% RAP containing PMA mix (MN1-1) this is a good result. When the PMA mixes are removed the relationship is nearly perfect. Both relationships indicate that binder relaxation plays a greater role in fatigue cracking than in transverse cracking

Total Distress = F(R-Value) Olmsted CTH 112 Crude Source Study



There is not a good correlation of Total Distress as a function of Binder R-Value when the data for all mixes are evaluated

Total Distress = F(R-Value) Olmsted CTH 112 Crude Source Study



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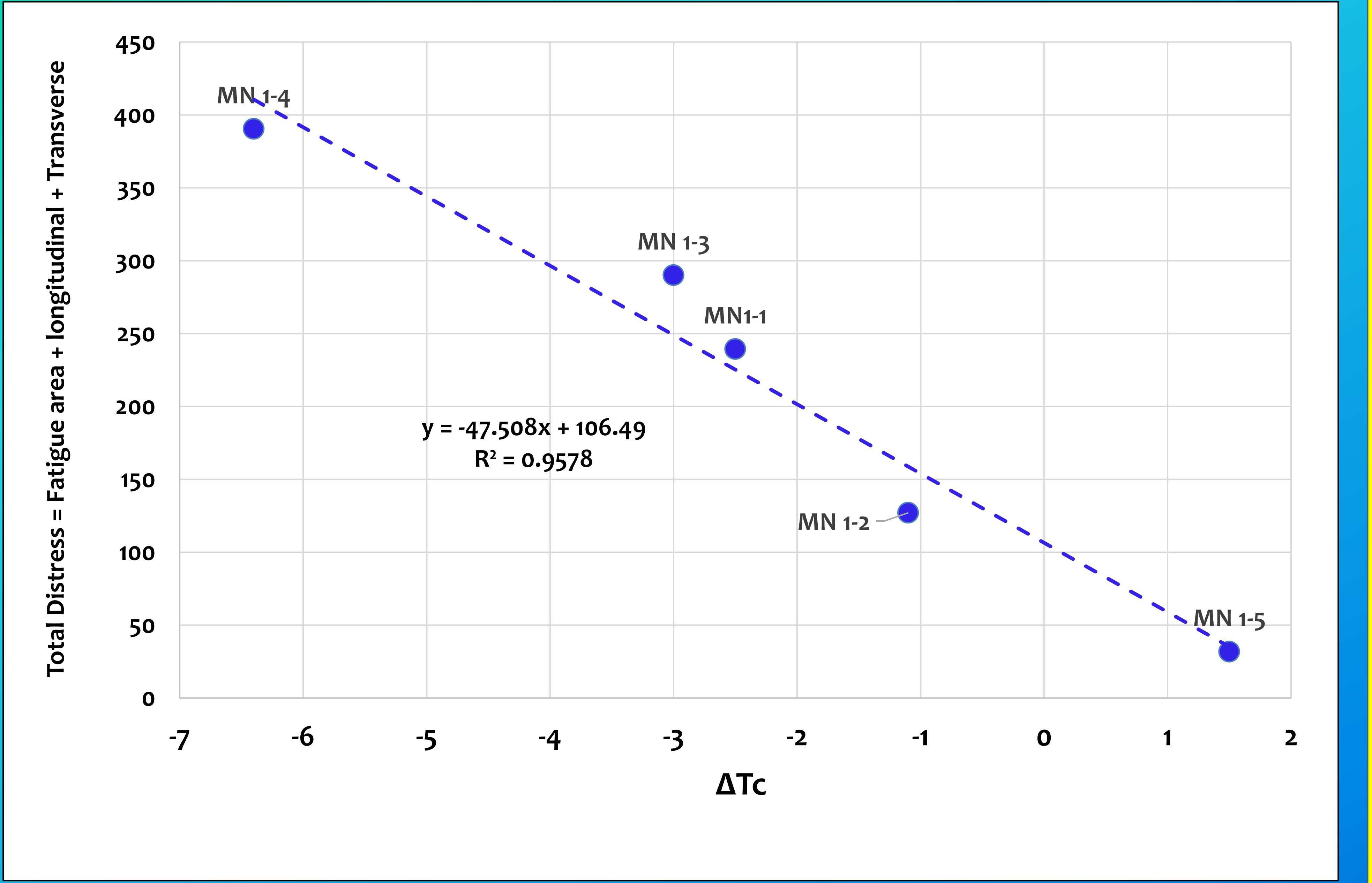
There is not a good correlation of Total Distress as a function of Binder R-Value; however when the polymer mix (MN1-2) and the polymer + RAP mix (MN1-1) data are removed there is a linear correlation with the non modified PG 58-28. Binder R-Values differ when polymer and/or reclaimed binders are included in the mix.

The base binder for MN1-1 and MN1-2 are from the same crude source as MN1-3

Total Distress = F(ΔTc) Olmsted CTH 112 Crude Source Study



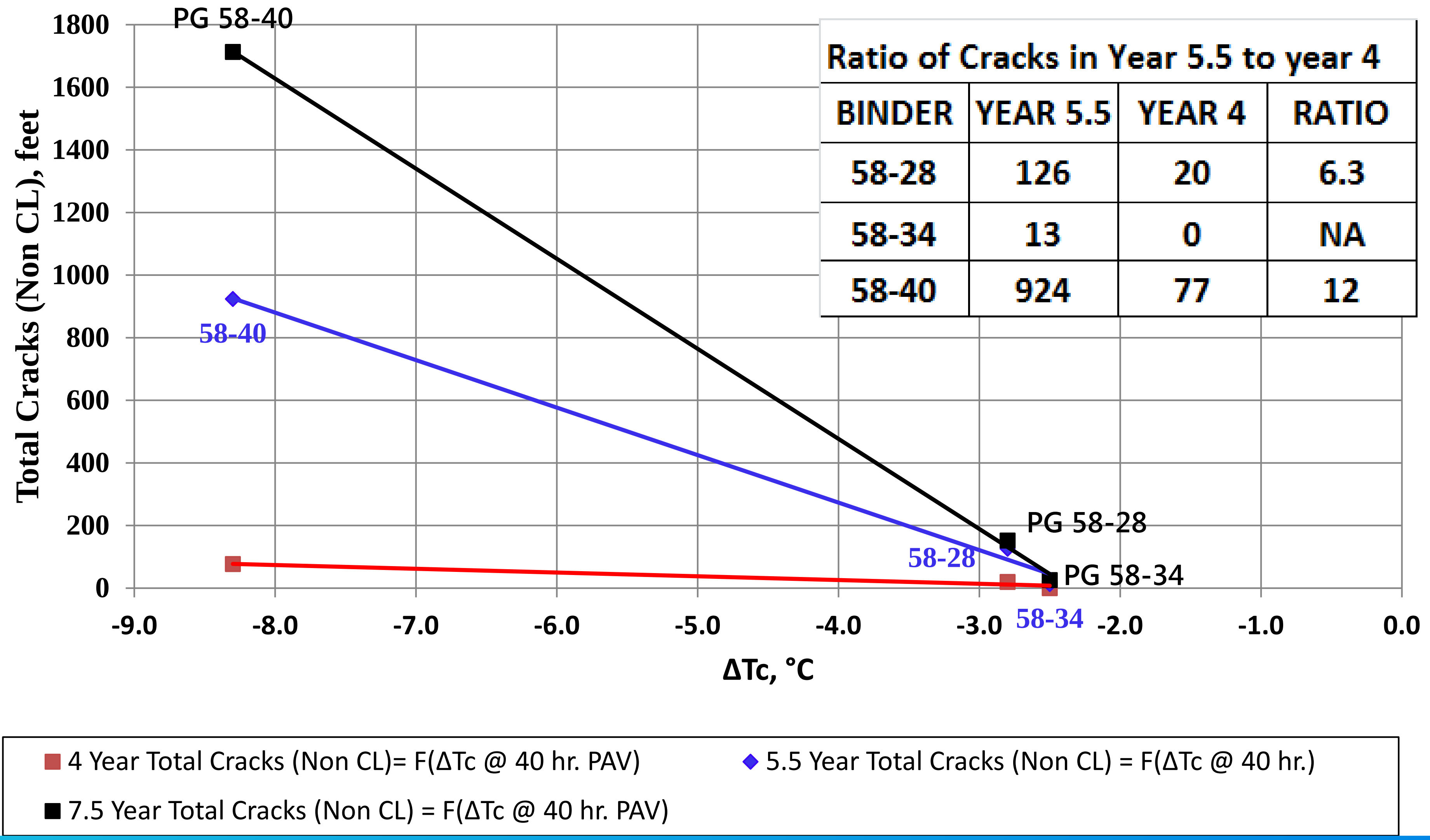
Unlike relaxation modulus or other parameters such as R-Value, crossover frequency and Glover Rowe which are impacted by binder additives or crude source and therefore do not correlate well with pavement distress the ΔTc parameter appears to be blind to the presence of polymer or RAP when looking at the correlation to pavement performance.

ΔTc may not correlate this well for all mixtures with a wide variety of binder types, but it appears it will always correlate better than other parameters.

MnROAD TEST OF 3 BINDERS

1. CONSTRUCTED IN SEPT 1999
2. 3 BINDERS
   a. PG 58-28
   b. PG 58-34
   c. PG 58-40
3. TRAFFICED UNTIL APRIL 2007
4. ANNUAL OR NEARLY ANNUAL PAVEMENT DISTRESS SURVEYS CONDUCTED

Total Crack Length (Non CL) @ years 4, 5.5 & 7.5 =F(ΔTc 40 hr PAV)



Ratio of Cracks in Year 5.5 to year 4

BINDER	YEAR 5.5	YEAR 4	RATIO
58-28	126	20	6.3
58-34	13	0	NA
58-40	924	77	12

COMMENTS

1. Between years 4 and 5.5 a substantial increase in cracking took place for the PG 58-40 section. While the increases for the other 2 sections were not as severe they also showed an increase after 5.5 years
2. Regardless of the years in service, the cracking trended with the ΔTc of the 40 hour PAV residue.
3. No binder was recovered from field cores over the course of the project.

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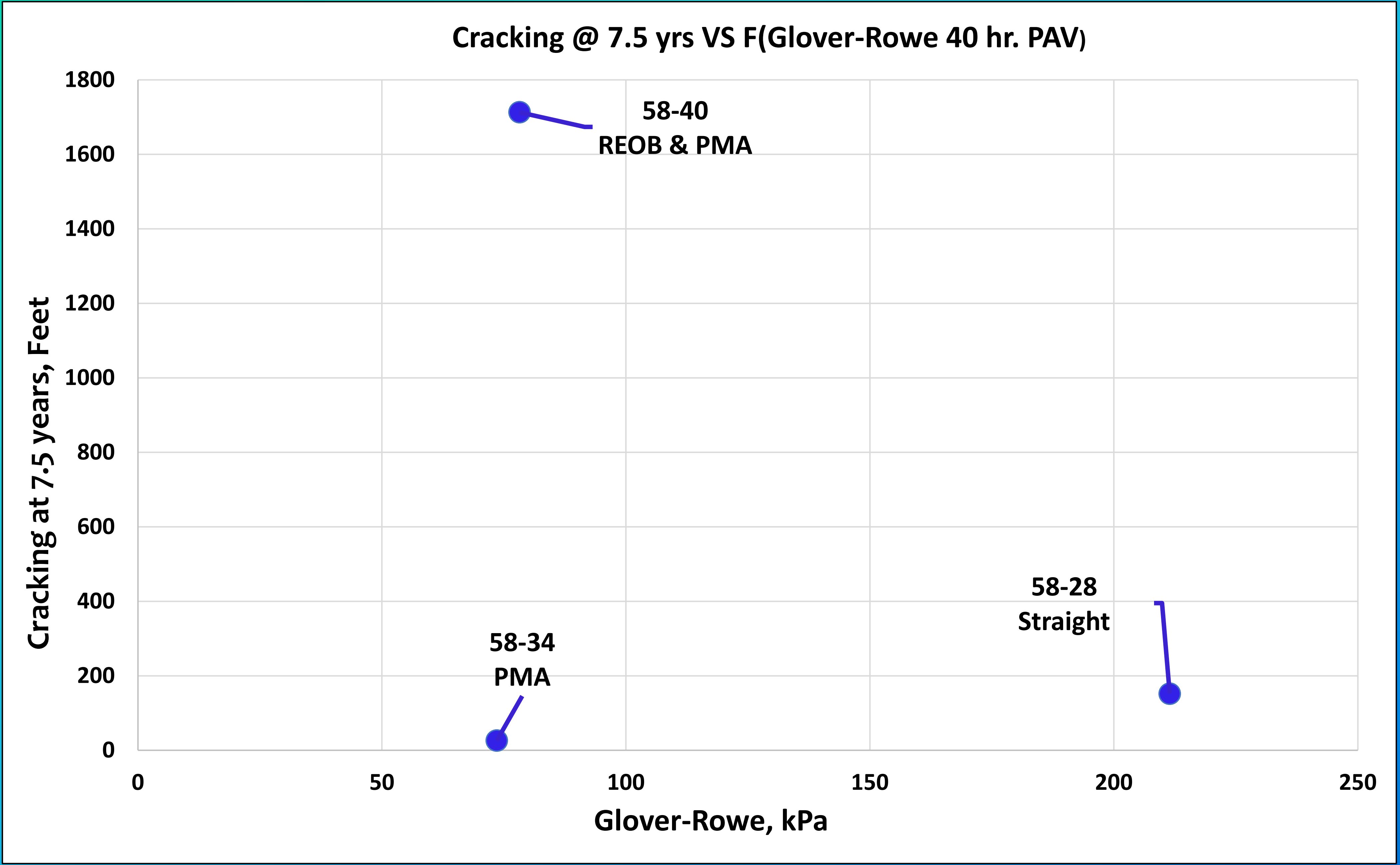
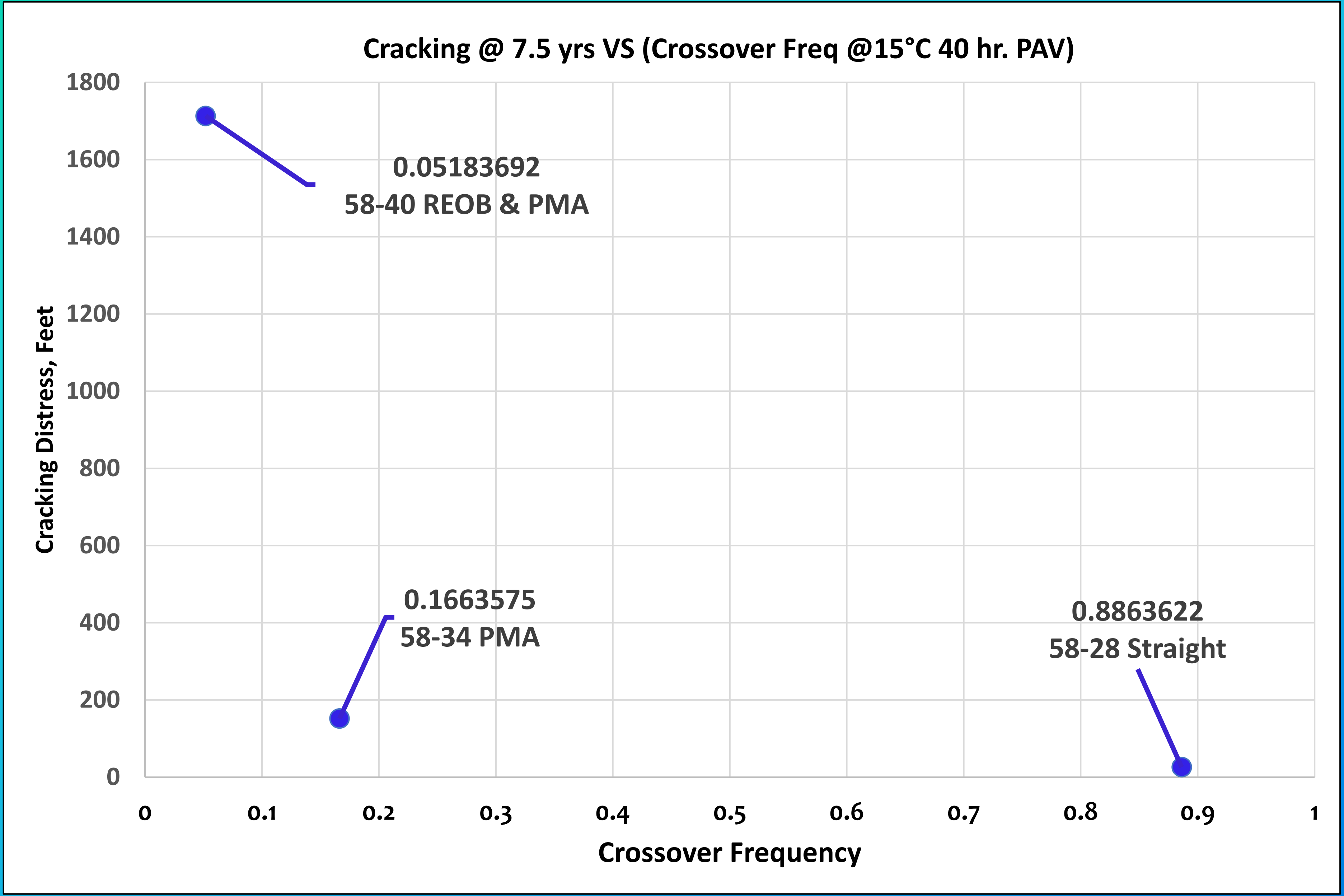
MnRoad Comparative Binder Study

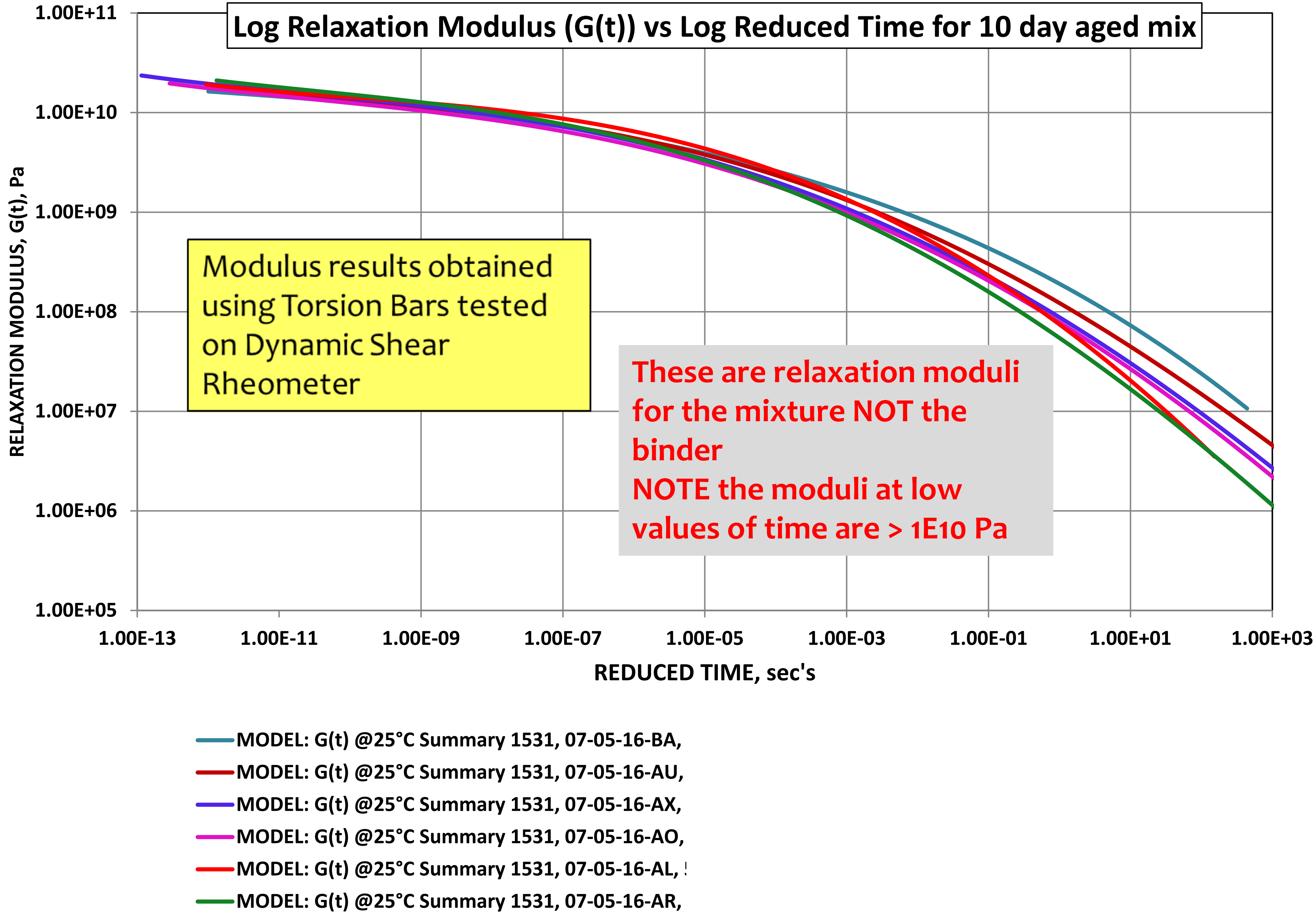


MnRoad Comparative Binder Study



Evaluation of Relaxation of Mixes Aged for 10 and 20 Days @ 85°C

1. **Six Mixtures**
   a) **PG 52-34 + 5% RAS, PG 52-34 + 5% ADD#1+5% RAS, PG 52-34 + 5% ADD#1, 2.5% ADD#2 +5% RAS**
   b) **PG 58-28 +5% RAS, PG 58-28 + 5% ADD#2 +5% RAS, PG 58-28 + 5% ADD#3 +5% RAS**
2. Binders recovered from aged mixes and characterized
3. Relaxation modulus determined for mixes and binders
4. Relationship between mixes and binders evaluated



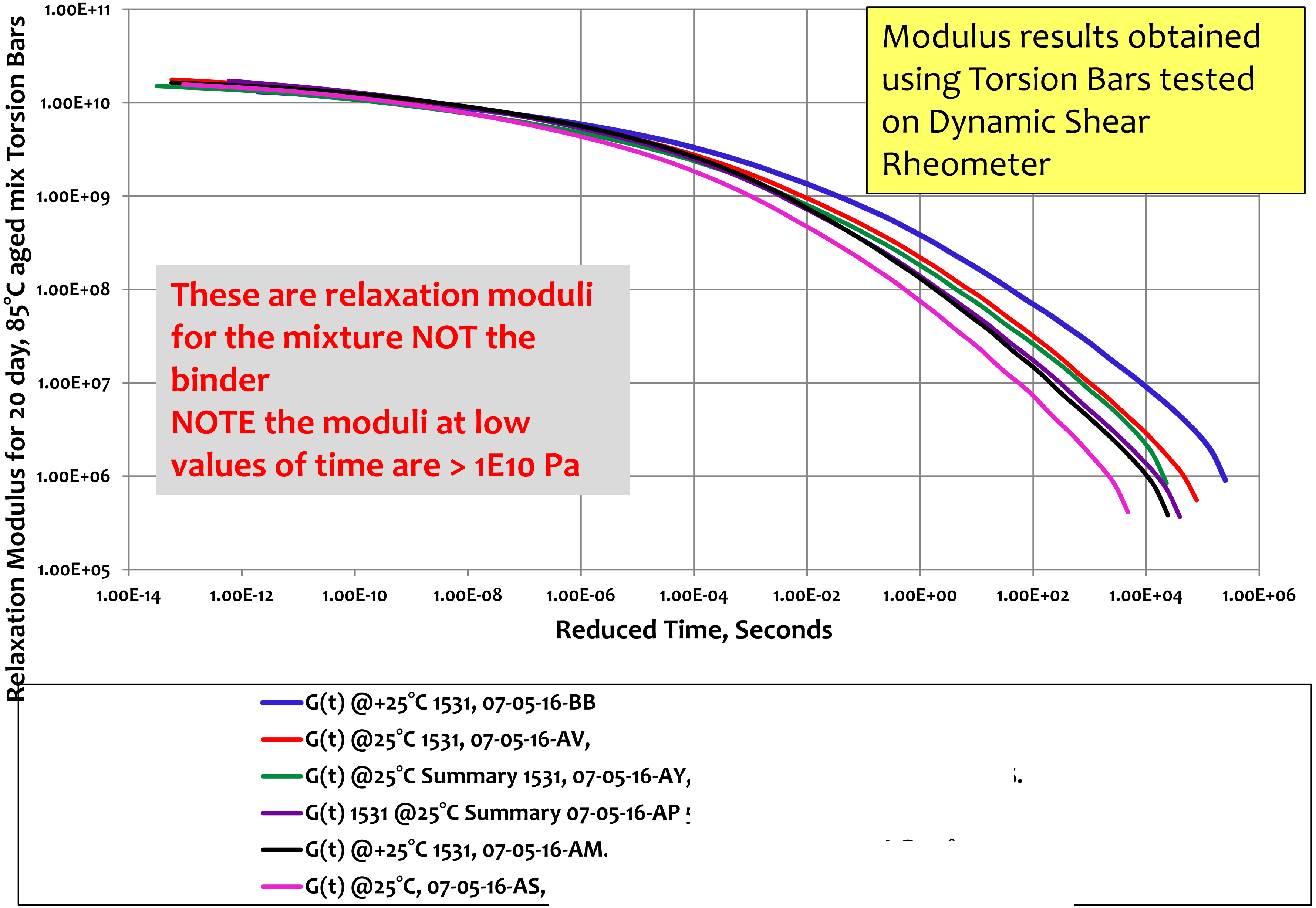
Log Relaxation Modulus (G(t)) vs Log Reduced Time for 10 day aged mix

Modulus results obtained using Torsion Bars tested on Dynamic Shear Rheometer

These are relaxation moduli for the mixture NOT the binder
NOTE the moduli at low values of time are > 1E10 Pa

AO & AP	**PG 52-34 + 5% RAS**
AL & AM	**PG 52-34 + 5% ADD#1+5% RAS**
AR & AS	**PG 52-34 + 5% ADD#1, 2.5% ADD#2 +5% RAS**
BA & BB	**PG 58-28 +5% RAS**
AX & AY	**PG 58-28 + 5% ADD#2 +5% RAS**
AU & AV	**PG 58-28 + 5% ADD#3 +5% RAS**

Relaxation Modulus of Commpacted Mix aged 20 days @ 85°C
all mixes contained 5% RAS, different Binders and Additives were employed



Modulus results obtained using Torsion Bars tested on Dynamic Shear Rheometer

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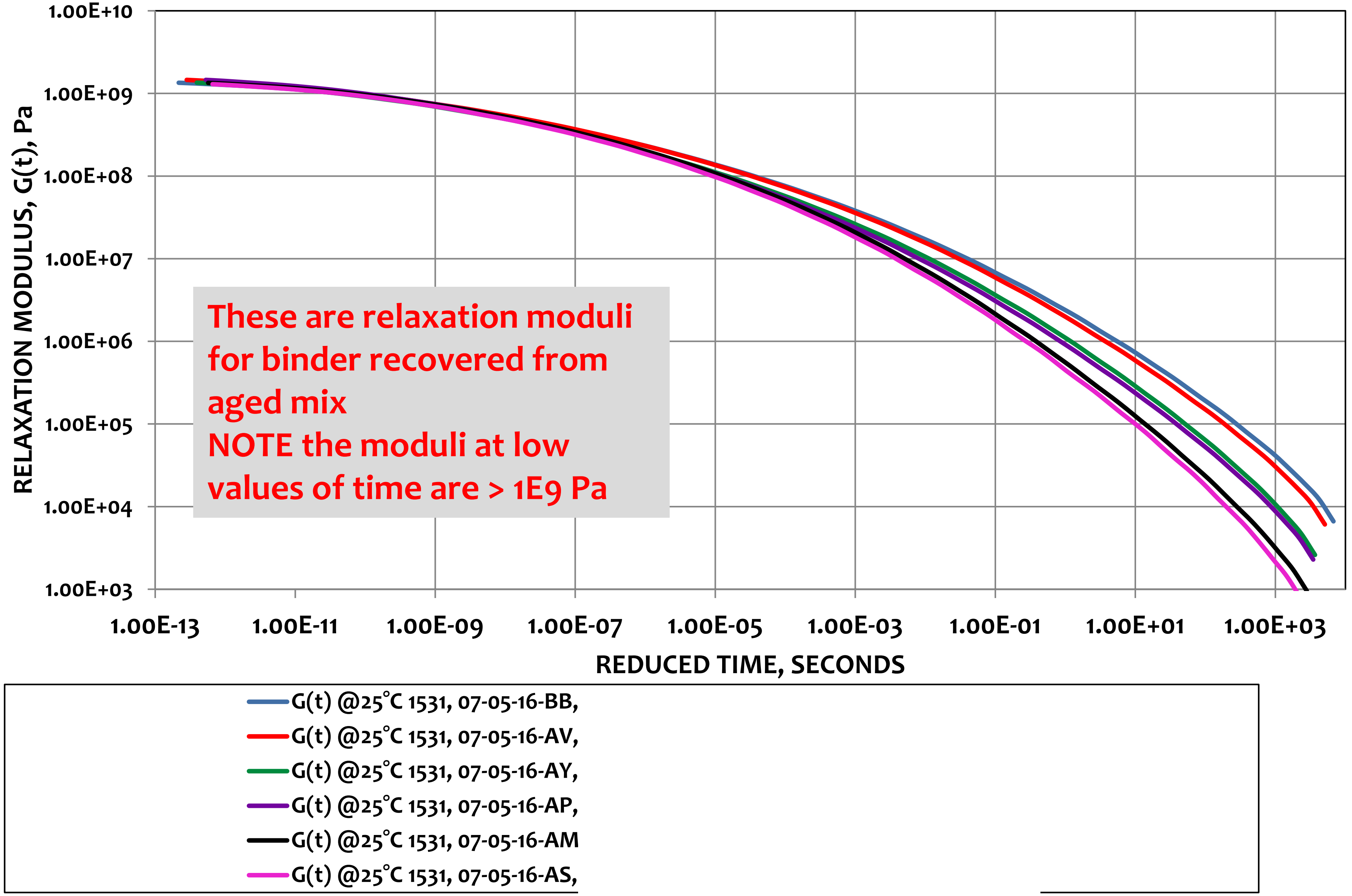
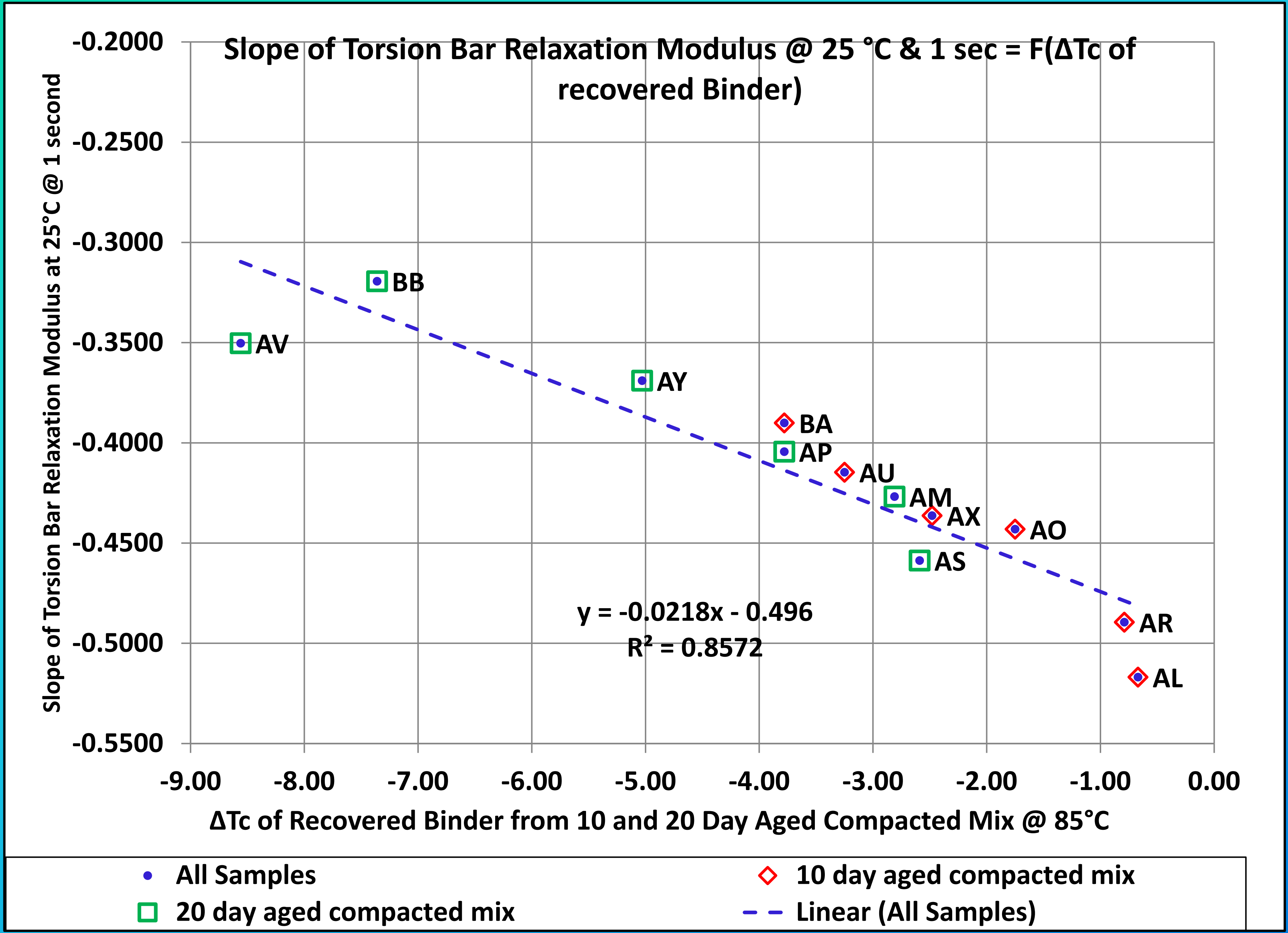
BA & BB	PG 58-28 +5% RAS
AX & AY	PG 58-28 + 5% ADD#2 +5% RAS
AU & AV	PG 58-28 + 5% ADD#3 +5% RAS

Relaxation Modulus of Binder Recovered from 20 day, 85°C Compacted Mix with 5% RAS and Different Binders



These are relaxation moduli for binder recovered from aged mix
NOTE the moduli at low values of time are > 1E9 Pa

AO & AP	PG 52-34 + 5% RAS
AL & AM	PG 52-34 + 5% ADD#1+5% RAS
AR & AS	PG 52-34 + 5% ADD#1, 2.5% ADD#2 +5% RAS
BA & BB	PG 58-28 +5% RAS
AX & AY	PG 58-28 + 5% ADD#2 +5% RAS
AU & AV	PG 58-28 + 5% ADD#3 +5% RAS



AO & AP	PG 52-34 + 5% RAS
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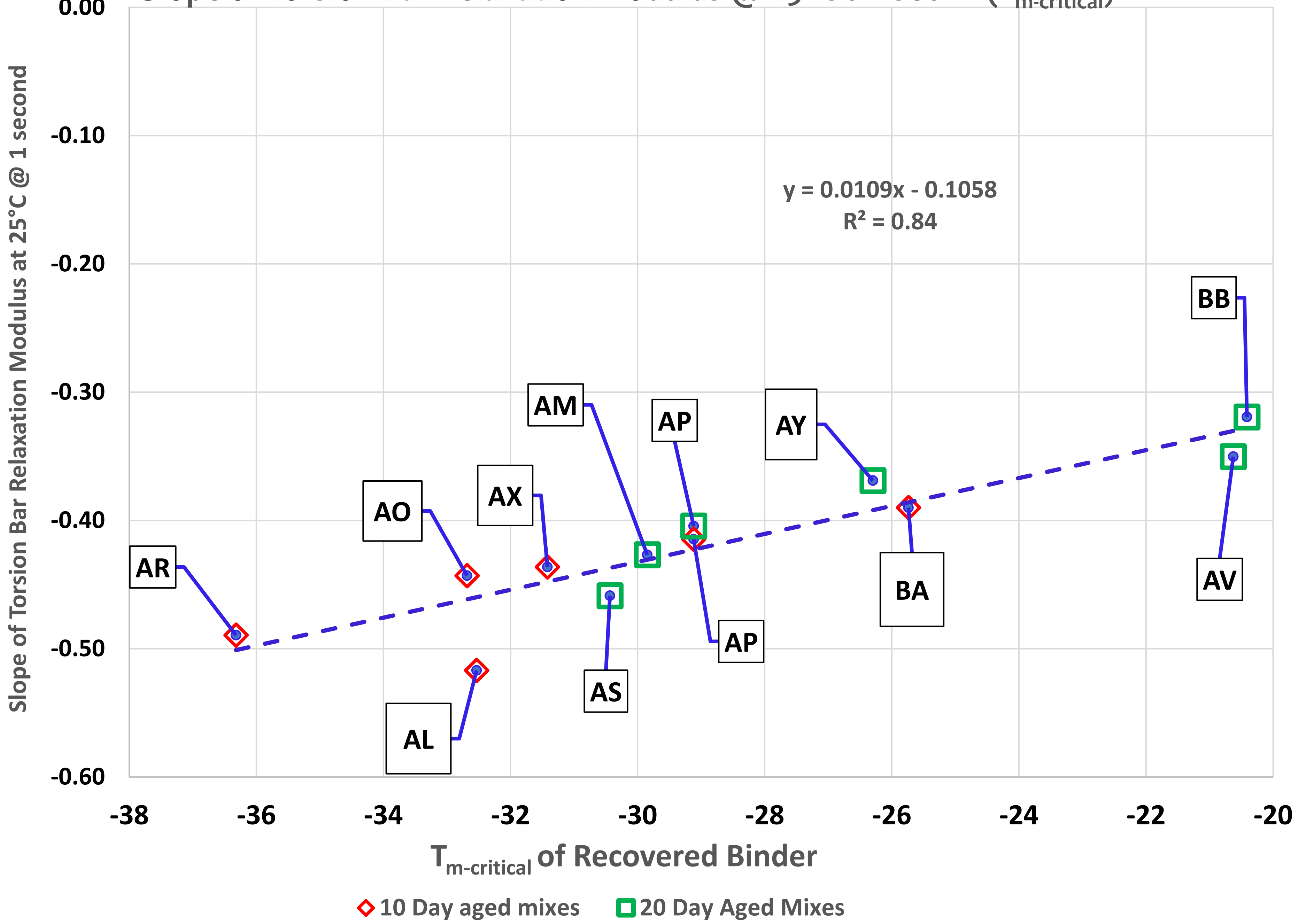
BA & BB	PG 58-28 +5% RAS
AX & AY	PG 58-28 + 5% ADD#2 +5% RAS
AU & AV	PG 58-28 + 5% ADD#3 +5% RAS

Recovered Binder ΔTc correlates well with the slope of the mixture relaxation modulus

Slope of Torsion Bar Relaxation Modulus @ 25 °C & 1 sec = F($T_{m\text{-critical}}$)



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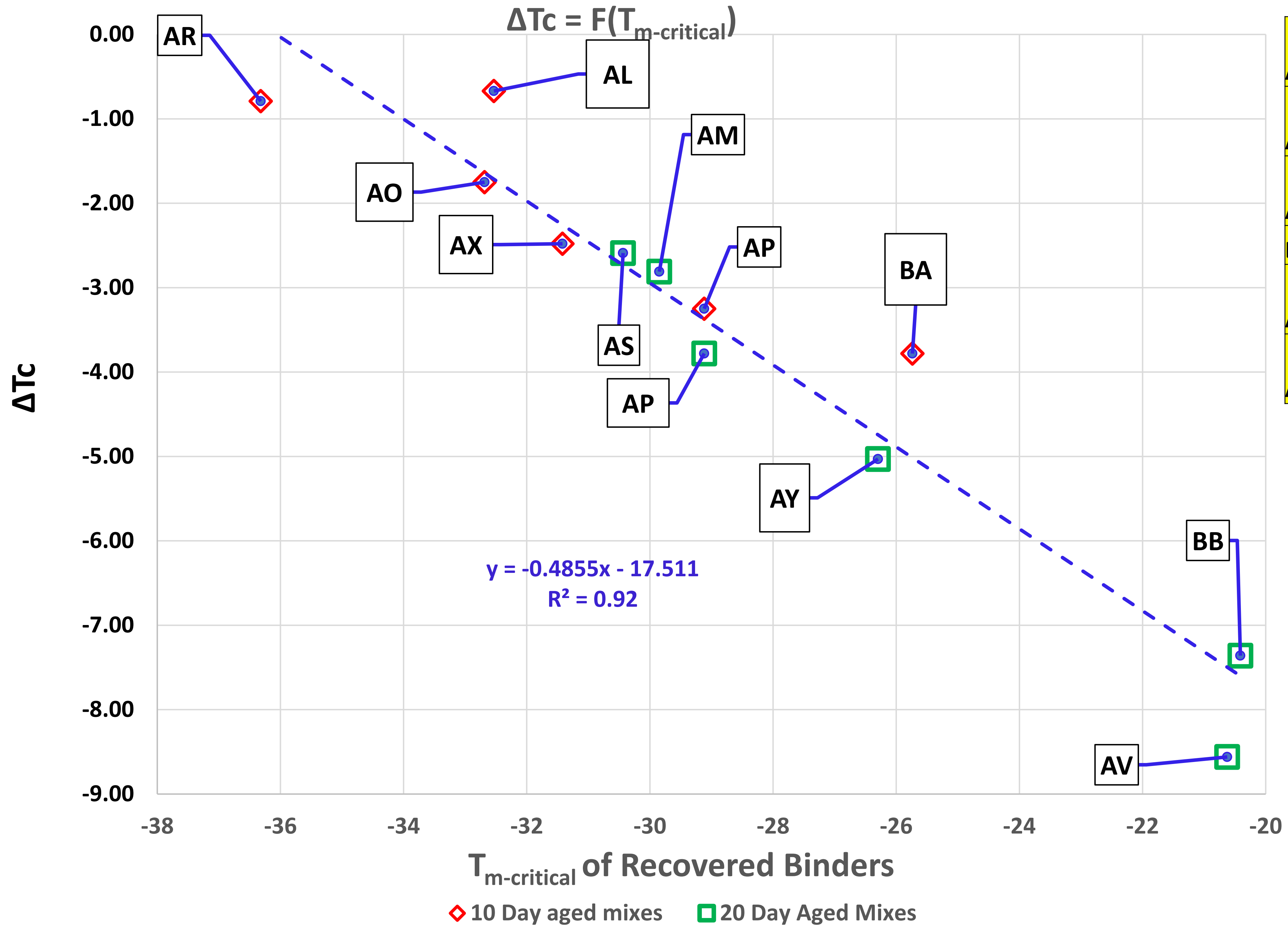
In addition the low temperature Tm-Critical value of the recovered binder also correlates well with the slope of the mixture relaxation modulus



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SUMMARY COMMENTS

- Parameters such as ΔTc, Glover-Rowe, R-Value, crossover frequency are manifestations of binder relaxation
- Binder relaxation largely drives mix relaxation for the aged mixes we studied
- $T_{m\text{-Critical}}$ and ΔTc of recovered binders correlated to mix relaxation
- Slope of relaxation modulus mastercurves appear to correlate well with ΔTc for a variety of binders
- Slope of relaxation modulus did not correlate well with transverse cracking on the Olmsted CTH 112 project

SUMMARY COMMENTS

- ΔTc did not correlate well with transverse cracking on CTH 112, but did correlate well with total cracking
- Slope of binder relaxation modulus at -18C correlated reasonably well (R^2 =0.79) with total cracking on CTH 112 for all 5 test sections including virgin PMA (MN1-2) and PG 58-34 + 20% RAP (MN1-1)
- ΔTc correlated well with the project cracking even when modified binders were used
- Glover-Rowe, crossover frequency and R-value did not correlate well when evaluating mixtures produced with straight run and modified binders

WI STH 33 @ 4 years of age

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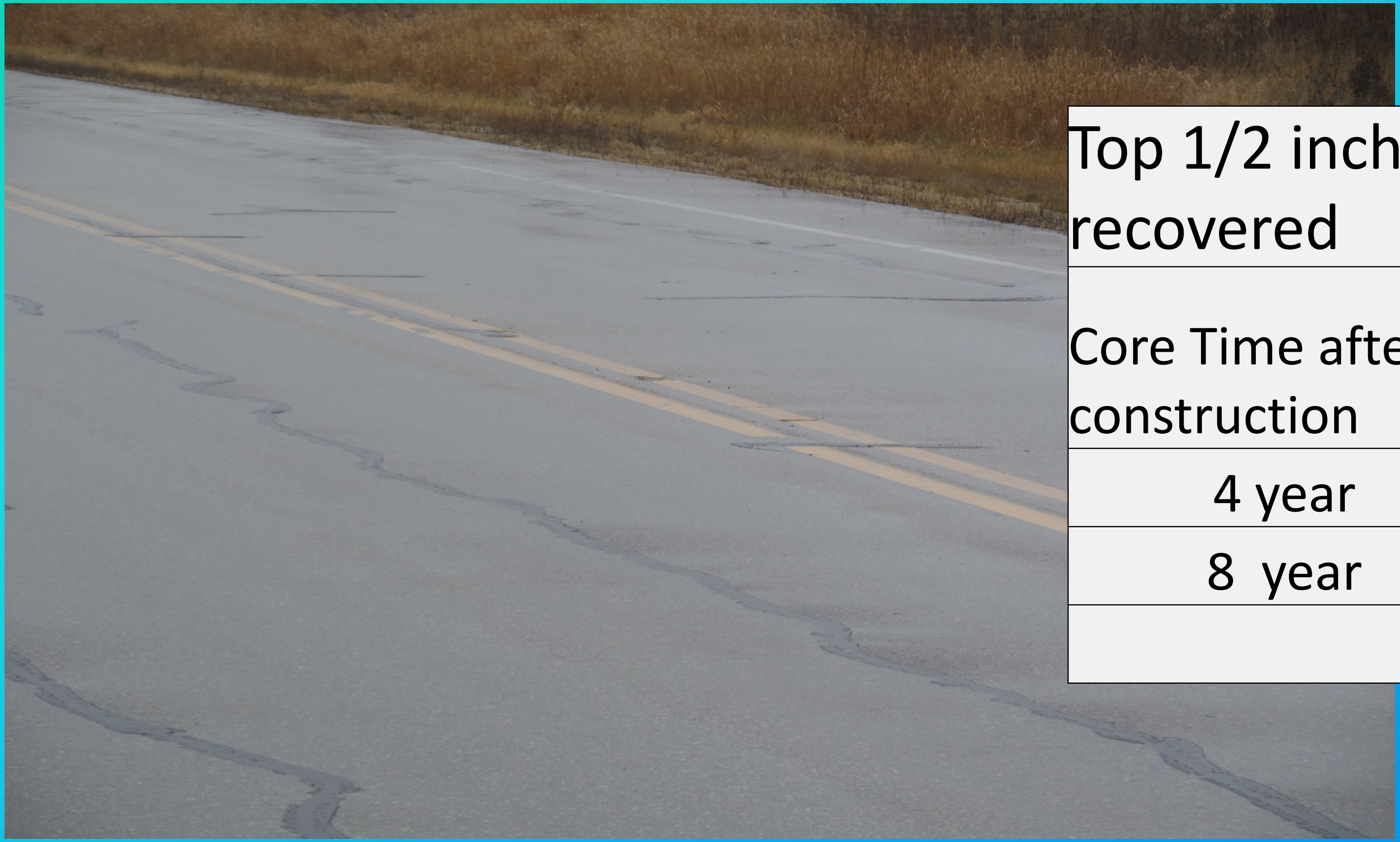
WI STH 33 @ 8 years of age



Top 1/2 inch of core extracted and recovered			
Core Time after construction	S critical,°C	m critical, °C	ΔTc, °C
4 year	-30.2	-30.9	0.7
8 year	-28.9	-26.6	-2.3

At 8 years cracking has started, some transverse, some wheel path. This is more consistent with the onset of distress than the pervasive deterioration seen on some sections of CTH 112 and MnROAD

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