JOINT TRANSPORTATION RESEARCH PROGRAM
INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

Investigation of Delta T_c for Implementation in Indiana

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SPR-4115 • Report Number: FHWA/IN/JTRP-2019/14 • DOI: 10.5703/1288284316923

RECOMMENDED CITATION

McDaniel, R. S., & Shah, A. (2019). *Investigation of delta T_c for implementation in Indiana* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2019/14). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284316923

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ACKNOWLEDGEMENTS

The support and guidance of the Study Advisory Committee members is gratefully acknowledged. Thanks too to the contractors and binder suppliers who provided materials for the study.

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Published reports of the Joint Transportation Research Program are available at http://docs.lib.purdue.edu/jtrp/.

NOTICE

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA/IN/JTRP-2019/14	**2. Government Accession No.**	**3. Recipient's Catalog No.**

4. Title and Subtitle Investigation of Delta T_c for Implementation in Indiana	**5. Report Date** July 2019
	6. Performing Organization Code
7. Author(s) Rebecca S. McDaniel, Ayesha Shah	**8. Performing Organization Report No.** FHWA/IN/JTRP-2019/14
9. Performing Organization Name and Address Joint Transportation Research Program Hall for Discovery and Learning Research (DLR), Suite 204 207 S. Martin Jischke Drive West Lafayette, IN 47907	**10. Work Unit No.**
	11. Contract or Grant No. SPR-4115
12. Sponsoring Agency Name and Address Indiana Department of Transportation (SPR) State Office Building 100 North Senate Avenue Indianapolis, IN 46204	**13. Type of Report and Period Covered** Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

The current Superpave asphalt binder specifications do not address durability issues and do not adequately address fatigue. Several approaches have been proposed by different researchers to address both these durability issues. Some of the proposed refinements are quite complex, but one, ΔT_c (delta Tc), is gaining favor because it is computationally simple and uses the existing BBR test method and data. This research explored the possible advantages and disadvantages of implementing a ΔT_c limit in Indiana as one means to control binder-related durability cracking issues. This was accomplished by performing a detailed literature review, analyzing data for commonly used binders in the state as well as RAP stockpile data, and conducting laboratory testing on a range of asphalt binders with varying reclaimed asphalt pavement (RAP) and recycled asphalt shingle (RAS) contents.

At this time, it is not recommended that INDOT implement ΔT_c in its specifications. This recommendation is based in large part on several remaining issues. One primary consideration is the caution against using ΔT_c for polymer modified binders. The results of testing unmodified binders seem to be more meaningful but would require identifying or assuming which binders are unmodified and handling them differently in the lab, which could be problematic. Another consideration is that the need for 40-h PAV aging is still being debated. INDOT could consider ΔT_c a characterization or research tool for forensic studies, for certain applications like high recycled material contents, or other investigations. As research continues on a national level, future implementation in a purchase specification or quality acceptance process may become advisable.

17. Key Words binder, cracking, delta Tc, rheology	**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 25	**22. Price**

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

EXECUTIVE SUMMARY

INVESTIGATION OF DELTA T_C FOR IMPLEMENTATION IN INDIANA

Introduction

The current Superpave asphalt binder specifications do not address durability issues and do not adequately address fatigue. Several approaches have been proposed by different researchers to address both these issues. Some of the proposed refinements are quite complex, but one, ΔT_c (delta T_c), is gaining favor because it is computationally simple and uses the existing BBR test method and data. The parameter ΔT_c is defined as the difference in the temperatures at which the stiffness (S) reaches its critical temperature, $T_{c,S}$, (that is, where it meets the specification maximum of 300 MPa) and at which the relaxation m-value reaches its critical temperature, $T_{c,m}$ (where it meets the minimum specification limit of 0.300).

This research explored the possible advantages and disadvantages of implementing a ΔT_c limit in Indiana as one means to control binder-related durability cracking issues. This was accomplished by performing a detailed literature review, analyzing data for commonly used binders in the state as well as reclaimed asphalt pavement (RAP) stockpile data, and conducting laboratory testing on a range of asphalt binders with varying RAP and recycled asphalt shingle (RAS) contents.

Findings

Based on the literature review, testing data and analysis presented here, the following conclusions can be drawn:

- The literature shows that the ΔT_c value characterizes the relaxation properties of asphalt binders and is related to the propensity of a binder to crack. In addition, ΔT_c tends to relate to other, more complex rheological parameters. However, polymer modified binders may exhibit ΔT_c values in excess of the cracking limit, despite the fact that they are typically less prone to cracking by virtue of being more elastic.
- The literature also shows fair to good correlations of ΔT_c to mixture cracking test results in most cases.
- Addition of recovered RAP binder increased the stiffness of the blended binders, thereby raising (warming) the pass/fail temperature (T_c) based on the $S = 300$ MPa criterion. Correspondingly, it also resulted in a decrease in the binder's ability to relax thermal stresses, as evidenced by a warming trend in T_c obtained at m-value $= 0.300$, in general.
- Estimation of the S-based critical temperature, ($T_{c,S}$), by extrapolating beyond the test temperature range did not always agree with the value obtained from testing at an extra temperature and interpolating, particularly for binders exposed to extended aging in the pressure aging vessel (designated 40-hr PAV or 2PAV binders).
- Two recovered RAP binders were used for blending purposes in this study, one of which (RAP1) had ΔT_c above -5 (less negative) and the other (RAP2) was greater than -5 (more negative).
- Addition of 20% and 40% RAP1 binder to PG 64-22 and PG 76-22 resulted in larger changes in $T_{c,S}$ compared with the changes due to the addition of RAP2.
- The effects of RAP2 on $T_{c,m}$ of PG 76-22 were not as clear cut as that seen with RAP1. Perhaps there may be some chemical interaction with the polymer modified binder.
- As in the case of recovered RAP binder, addition of recovered RAS binder also increased the stiffness of the blended binder and raised the $T_{c,S}$. But unlike the recovered RAP binder, addition of RAS appeared to improve the blended binder's thermal relaxation ability. Difficulties in blending the RAS binder into the base or some sort of interaction may explain these counterintuitive results.
- As other researchers have indicated, ΔT_c of highly oxidized binders can be very difficult, if not impossible, to obtain via BBR testing.

Implementation

At this time, it is not recommended that INDOT implement ΔT_c in its specifications. This recommendation is based in large part on several remaining issues. One primary consideration is the caution against using ΔT_c for polymer modified binders. The results of testing unmodified binders seem to be more meaningful but would require identifying or assuming which binders are unmodified and handling them differently in the lab, which could be problematic. Another consideration is that the need for 40-h PAV aging is still being debated.

INDOT could consider ΔT_c a characterization or research tool for forensic studies, for certain applications like high recycled material contents, or other investigations. As research continues on a national level, future implementation in a purchase specification or quality acceptance process may become advisable.

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LIST OF ABBREVIATIONS

BBR	bending beam rheometer
ΔT_c	delta T_c, difference in the temperatures at which the stiffness reaches its critical temperature, $T_{c,S}$, and that at which the m-value reaches its critical temperature, $T_{c,m}$
CCT	critical cracking temperatures
DSR	dynamic shear rheometer
HMA	hot mix asphalt
m	m-value, slope of the binder relaxation curve from the BBR
PAV	pressure aging vessel
PG	performance graded
PMB	polymer modified binder
RAP	reclaimed asphalt pavement
RAS	recycled asphalt shingles
REOB	re-refined engine oil bottoms (also called VTAE, vacuum tower asphalt extender)
RTFO	rolling thin film oven
S	binder stiffness, MPa
SCB	semi-circular bend test
$T_{c,m}$	critical temperature at which the m-value reaches the specification limit of 0.300
$T_{c,S}$	critical temperature at which the stiffness reaches the specification limit of 300 MPa
WMA	warm mix asphalt

1. INTRODUCTION

When the Superpave Performance Graded (PG) asphalt binder specifications were implemented in the 1990's, a new suite of binder tests was also implemented to help identify binders that would be resistant to permanent deformation at high temperatures, fatigue cracking at intermediate temperatures, and thermal cracking at low temperatures. Fatigue resistance was to be controlled by dynamic shear rheometer (DSR) testing of aged binder, while thermal cracking resistance was evaluated using the bending beam rheometer (BBR).

Over the course of more than 20 years of PG specification use, the asphalt community has recognized that the current PG criterion for fatigue cracking is not very reliable. In addition, problems with asphalt mixture durability have apparently increased. (It could be argued that we did not recognize as many durability problems before Superpave because early-age rutting failures meant many pavements did not last long enough to exhibit durability problems.) Researchers across the country have been seeking improved methods to control binder-related fatigue and durability issues.

Fatigue distress is caused by the repeated deflection of the pavement under traffic loads. It typically manifests itself in the form of longitudinal wheel path cracking that continues to grow, leading to many interconnected cracks, as shown in Figure 1.1. Fatigue cracks typically form at the bottom of the asphalt layer and progress up to the surface. The development of fatigue cracking is largely dependent on factors related to the pavement structure—in simplistic terms, thicker pavements or pavements constructed on stronger subgrades deflect less and are less likely to crack. The brittleness of the binder can affect fatigue performance; as binders age and become more brittle, they are more prone to cracking.

Figure 1.1 Advanced fatigue cracking (photo courtesy of G. Huber).

Durability is not explicitly addressed by the current PG specifications. Like fatigue cracking, durability issues are also exacerbated by binder aging, which is caused by oxidation of the binder. A viscoelastic binder has the ability to relax when strained; this can be illustrated by the way a rubber band can deform when it is held in a stretched position for a long time. Relaxation allows a binder to undergo deformation (strain) without cracking. As binders age, they lose this ability to relax (become less viscous and more brittle) to different extents, making them more susceptible to cracking. Durability cracking typically appears as block cracking and is non-load associated, being caused by binder aging; see Figure 1.2. Durability problems can also be seen as raveling (loss of aggregate at the surface), again related to embrittlement of the binder. Low temperature cracking is also non-load associated and is exhibited by transverse cracking.

Several approaches have been proposed by different researchers to address both fatigue and durability issues. Some of the proposed refinements are quite complex, but one, ΔT_c (delta T_c), is gaining favor because it is computationally simple and uses the existing BBR test method and data.

In the conventional BBR test, two parameters are determined at low temperature; the binder stiffness, S, and the slope of the stiffness vs. time plot, m, as illustrated in Figure 1.3. The m-value is related to the binder's ability to relax when strained; a higher slope indicates more ability to relax.

The parameter ΔT_c is defined as the difference in the temperatures at which the stiffness reaches its critical temperature, $T_{c,S}$, (that is, where it meets the specification maximum of 300 MPa) and that at which the m-value reaches its critical temperature, $T_{c,m}$ (the minimum specification limit of 0.300). In conventional PG grading, the higher (less negative) of these two critical temperatures determines the binder grade. The calculation of ΔT_c is shown in Equation 1.1.

$$\Delta T_c = T_{c,S} - T_{c,m} \qquad \text{(Eq. 1.1)}$$

As a binder ages, its ΔT_c becomes more negative, which indicates a loss of relaxation properties and an increased susceptibility to cracking. Currently, the most common limits being applied to this parameter are a warning level at -2.5°C, indicating that the binder is approaching the point where cracking will occur, and a limit at -5.0°C, which is where the binder will presumably crack. Anderson, King, Hanson, and Blankenship (2011) suggested the warning be at 2.5°C and limit at 5°C, but they calculated ΔT_c as $T_{c,m} - T_{c,S}$—the reverse of what has become the accepted calculation.)

Figure 1.2 Block cracking.

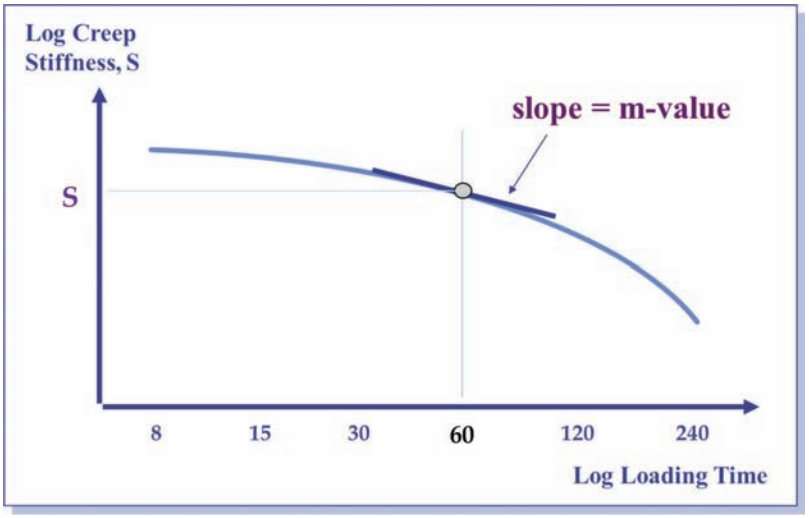

Figure 1.3 Stiffness (S) and m-values from BBR test.

While the calculation of ΔT_c is quite simple, it has been correlated by previous researchers with more complex and more theoretical approaches (Anderson et al., 2011; Rowe, 2016; Corrigan & Golalipour, 2016; Mensching, Rowe, Daniel, & Bennert, 2015; D'Angelo, 2016; Reinke, 2017). The parameter has also been shown to relate well to various types of mixture cracking tests, such as the Texas overlay tester, double edged notch test (DENT), as well as field performance (Rowe, 2016). It has even been correlated with low temperature cracking test results, such as the thermal stress restrained specimen test (TSRST) (Mensching et al., 2015). This suggests that the simple approach has a sound basis and can be used as a surrogate for more rigorous, rheological approaches.

1.1 Problem Statement

This research explored the possible advantages and disadvantages of implementing a ΔT_c limit in Indiana as one means to control binder-related durability cracking issues.

1.2 Objectives

The objectives of this project are to:

- Examine historical binder acceptance testing data to determine if typical binders in Indiana meet the proposed ΔT_c limits.
- Obtain or fabricate and test samples of binders/mixtures containing additives such as RAS, RAP and possibly recycled engine oil bottoms (REOB) to determine if these additives have an effect on the ΔT_c values for typical Indiana binders.
- If possible, obtain binder data or binder/mix samples from projects that have exhibited cracking or durability problems to examine the correlation between ΔT_c and distress.
    - No such projects were identified by the Study Advisory Committee (SAC Minutes, 7-6-17), so this objective was dropped.
- Perform limited laboratory mixture testing on selected binders to explore the relationship between binder and mixture performance.

    - This objective was also dropped by the SAC members, who felt adequate mix testing had been performed by others (SAC Minutes, 9-19-18).

1.3 Work Plan

Achieving the modified objectives of this project, as outlined above, involved completion of the following tasks.

- *Literature review*. Use of ΔT_c is rapidly evolving, so the research team continued to review the literature and relevant presentations throughout the project.
- *Analyze historical binder data*. The INDOT Office of Materials Management (OMM) started conducting the BBR test on binder acceptance samples at two temperatures, which is needed to determine the critical temperatures, in 2016. (Standard grade verification only requires testing at the binder low temperature grade plus 10°C.) Data from 2016–2017 was provided to the research team by OMM. This data was analyzed to examine any trends in the data and assess how well currently used binders in the state meet (or do not meet) the proposed limits on ΔT_c. In addition, the research team examined data from a previous study on characterizing RAP stockpiles around the state (Beeson, Prather, & Huber, 2011).
- *Develop experimental design.* In consultation with the Business Owner, Project Advisor and SAC, an experimental design was developed early in the project to determine the variables of interest. The experimental design is detailed in Chapter 3. The following tests were performed:
    - BBR low temperature grade determination; test at two to three temperatures to determine $T_{c,S}$ and $T_{c,m}$. This was performed after rolling thin film oven (RTFO) and 20 hours of pressure aging vessel (PAV) conditioning of the original binders (for comparison) and the blended binders; the 100% recycled binder would be considered fully aged. Some 40-h PAV (2PAV) testing was also conducted for comparison to the standard 20-h.
    - High temperature binder testing was performed to verify the binder grade.
- *Conduct laboratory testing* according to the approved experimental design.
- *Data analysis and reporting*. The amassed data was analyzed and this final report prepared. Statistical analysis of the data was conducted. This task also involved periodic progress reports and SAC meetings.

2. LITERATURE REVIEW

Anderson et al. (2011) proposed the concept of using the difference in the temperatures at which the BBR m-value and stiffness meet the specification limits to identify binders that would be prone to block cracking after aging (oxidation). Block cracking has been shown to be related to durability, which is in turn a function of binder ductility. The m-value, or slope of the time versus displacement curve, is an indication of the relaxation properties of the binder. A binder that can relax stresses more readily (has a steeper slope) is less likely to crack. As a binder ages, the temperatures at which the stiffness and m-value reach the specification limits both increase (become warmer), but the m-value increases faster. In other words, the binder becomes more strongly m-controlled, and its relaxation properties decrease.

Anderson et al. evaluated three asphalt binders in the lab using a variety of tests and analysis techniques after 20, 40, and 80 hours of PAV aging. They determined that the Glover parameter $G'/(\eta'/G')$ and ΔT_c correlated best to block cracking. (They expressed ΔT_c as $T_{c,m} - T_{c,S}$; more recently, this has been reversed to $T_{c,S} - T_{c,m}$.) They proposed preliminary cracking warning and cracking limits by correlation of the ΔT_c values to the critical cracking temperatures (CCT) determined using the BBR to estimate the development of thermal stresses and assumed direct tension values to estimate the tensile strength of the binders. That is, the CCT is the temperature at which the stresses induced in the binder by thermal contraction exceed the tensile strength of the binder. The concept was validated based on a comparison of ΔT_c values for binders extracted from four pavements at three airfields to observed field cracking. It should be noted, however, that none of the pavements exhibited severe block cracking (Anderson et al., 2011).

The ΔT_c parameter has been included in AASHTO PP 78-17, *Design Considerations When Using Reclaimed Asphalt Shingles (RAS) in Asphalt Mixtures*, to assess embrittlement of the blended binder caused by the incorporation of heavily oxidized shingle binder. A value of -5.0°C is suggested in PP 78 as the limit below which (more negative) significant cracking could be expected, but it is noted that this limit could be adjusted. A 40-h PAV aging time is called for in PP 78.

In addition to being used to evaluate embrittlement caused by RAS binder, ΔT_c has also been suggested by some researchers as a tool to detect the presence of re-refined engine oil bottoms (REOB) (Arnold, 2017; Bennert et al., 2015; Li, Gibson, Andriescu, & Arnold, 2017; You et al., 2018). REOB is also called vacuum tower asphalt extender (VTAE) by refiners (REOB Task Force, 2016). REOB is the black, sticky residue left after waste engine oils are distilled, or re-refined, to produce new lubricating oil. It contains petroleum products as well as engine oil additives (like heat stabilizers and others) and metals from engine wear (Arnold, 2017). REOB is used to extend asphalt and soften it. Many states have banned the use of REOB because of concerns about its effects on long-term pavement performance (Arnold, 2017). Research in Canada suggested REOB was to blame for significant cracking after nine years of service (Hesp, Genin, Scafe, Shurvell, & Subramani, 2009). Because REOB tends to affect the stiffness more than the m-value (Youtcheff, 2016), it yields a greater difference in ΔT_c, therefore ΔT_c has been used by some researchers to detect the presence of REOB in a binder.

A 2016 position paper by the Asphalt Institute summarizes relevant literature regarding REOB/VTAE. The paper recommends further evaluation of ΔT_c after extended (40-h) PAV aging as a possible test method to evaluate the effects of REOB on binder durability and performance. However, it cautioned against using this as a purchase specification, citing the need for more research and the impacts of such extended testing time on testing operations and logistics. (REOB Task Force, 2016) Extended PAV aging has been suggested by many researchers to better differentiate between binders (Corrigan & Golalipour, 2016) and to fully characterize embrittlement. D'Angelo suggests that 20-h PAV aging and the change between the original binder and 20-h-aged binder are sufficient to predict if the binder would fail after 40-h aging (D'Angelo, 2016).

All binders become more m-controlled as they age, demonstrating the loss of relaxation properties as the binder oxidizes. The presence of RAP, RAS, REOB, waxes and paraffinic oils are associated with more negative values of ΔT_c (REOB Task Force, 2016; Cascione, 2018).

Rahbar-Rastegar, Daniel, & Reinke (2017) compared asphalt binder and mixture cracking test results for 14 plant-produced mixtures in New Hampshire. The binder tests were conducted on binder extracted from the mixtures then PAV-aged for 20 hours. They found that the ΔT_c value correlated well with the more complex (in terms of analysis techniques) Glover-Rowe parameter and rheological index, R. Mixture tests—including dynamic modulus, phase angle, mixture Glover-Rowe, dynamic cyclic fatigue and disk-shaped compact tension fracture energy—did not correlate well amongst themselves. The researchers also did not see good correlations between the binder cracking indices and mixture fatigue or low-temperature cracking test results.

Reinke (2017) reported on comparisons of ΔT_c and other rheological properties to field performance of some projects in Minnesota. The comparison established a good correlation between ΔT_c and field cracking after six years; the correlation was slightly better for 40-h PAV aging. He also postulated a relationship between ΔT_c and mixture fatigue; although ΔT_c is a low temperature test and fatigue is an intermediate temperature distress, both are related to binder relaxation.

Arshadi et al. (2017) used the ΔT_c parameter, among other binder and mixture parameters, to evaluate rutting, cracking and durability of four plant-produced mixtures in Oklahoma that incorporated 12% RAP and 3% RAS with different warm mix technologies plus an HMA control with the same recycled materials. They found a fair correlation of ΔT_c with the critical strain energy release rate (J_c) from the SCB test. Two mixes with a WMA chemical additive plus either a two PG grade drop or a rejuvenator and a one PG grade drop performed better in terms of ΔT_c and J_c than the HMA control, the foamed WMA and the chemical WMA additive alone.

Karki and Zhou (2018) tested a range of asphalt binders from Texas in terms of ΔT_c among other parameters. They found that the ΔT_c value (20-h PAV) for the same grade from the same source from different days of production could vary markedly. Four samples of PG 64-22 from one source had values ranging from -1.6 to -4.6. Values from a second source of PG 64-22 varied even more; -1.7 on one day and -7.8 on another day. One PG 58-28, sampled once, also exceeded the -5 limit with a ΔT_c of -7.2.

When Karki and Zhou (2018) blended the PG 58-28 (ΔT_c = -7.2) and PG 64-22 (ΔT_c = -4.6) with 30% RAP binder (PG 94-xx) or 30% RAP+RAS binder (PG 106-xx), the ΔT_c became more negative. The PG 64-22 with 30% RAP had a ΔT_c slightly more negative than that of the 64-22 with 30% RAP+RAS binder. The PG 58-28 with 8% RAP binder had a ΔT_c slightly less negative than the PG 58-28 without RAP, while the binder with 11% RAP binder was slightly more negative than the base asphalt (Karki & Zhou, 2018). These values seem somewhat counterintuitive and may reflect the complex nature of binder blending and compatibility. Reinke (2017) observed that different binders, especially from different crudes, age differently; he went on to suggest the same binder could vary depending on the construction conditions, such as time of year and others.

Karki and Zhou (2018) also looked at the effects of adding various modifiers to the PG 64-22 and PG 58-28 base asphalts. They found that aromatic extracts, bio-based rejuvenators and fatty acids improved the ΔT_c. REOB, a softener, and PPA, a stiffener, both worsened the ΔT_c.

There are indications that ΔT_c does not work well for polymer modified binders, especially elastomers (Anderson, 2019). The elastic nature of polymer modified binders (PMBs) imparts a lower phase angle at a given stiffness. (Phase angle is also a measure of relaxation (Arnold, 2017).) This, in turn, yields a more negative value of ΔT_c, suggesting that PMBs are more prone to cracking, when the opposite is generally true. Rowe (2016) also suggested the correlation between the Glover-Rowe parameter and ΔT_c is not as good when PMB or asphalt rubber binders are considered as when unmodified binders are tested. Also, testing binders that are very strongly m-controlled (very negative ΔT_c), like RAS binders, can be problematic (Anderson, 2019).

2.1 Summary

Since its introduction in 2011, the ΔT_c parameter has been used rather extensively to characterize the stiffness and relaxation properties of asphalt binders. Binders that are m-controlled have limited ability to relax stresses and are therefore more susceptible to cracking. A negative value of ΔT_c is associated with these binders; the more negative, the less the binder can relax without cracking. A cracking warning limit of -2.5°C and a cracking limit of -5.0°C have been suggested, though these values can be adjusted to reflect local conditions.

The ΔT_c concept has been applied most frequently to assess the potential binder embrittlement caused by modifiers such as RAP, RAS, REOB and other materials. In fact, ΔT_c is included in AASHTO's PP 78 on design of asphalt mixtures with RAS. Some unmodified binders fail to meet the suggested thresholds; adding RAP, RAS or REOB to these binders may exacerbate cracking problems. However, it has been shown that binders of the same grade from the same source may vary from day to day.

Several researchers have tried to correlate ΔT_c with different mixture cracking tests with varying degrees of success. Overall, however, the correlations have been fair to good. Correlations of ΔT_c with other binder rheological parameters, such as Glover-Rowe and rheological index R, have been more uniformly successful.

Since different binders age differently, extended aging periods (40 hours) are often recommended. This significantly increases the testing time, obviously. There may also be issues with using ΔT_c with polymer modified binders, which may demonstrate a negative ΔT_c but actually be more resistant to cracking because of their elastomeric properties.

3. RESEARCH APPROACH AND FINDINGS

This chapter describes the research approach, including the analysis of historical INDOT binder data, experimental design, factors studied, materials and test methods. Then the test results and data analysis are presented.

3.1 Historical Data Analysis

Two sets of historical binder data were provided to the research team by OMM; data from a previous analysis of RAP stockpiles around the state and BBR data from 2016–2017. The BBR data includes enough temperatures to determine the critical temperatures for S and m after 20-h PAV aging.

Figure 3.1 summarizes the 2016–2017 BBR data provided by OMM for 46 binders in use in the state. The data was collected after 20-h PAV aging. It can be seen that the sole PG 58-28 and all but one of the PG 64-22 binders passed the -2.5° warning limit. More of the PG 70-22 and PG 76-22 binders, which are more likely to be polymer modified, exceeded this limit. In fact, one PG 70-22 failed the -5.0° limit. Overall, about 39% of the binders tested (18 out of 46) exceeded the -2.5° limit and 2% (one out of 46) exceeded the -5.0° limit. This suggests that the consequences of INDOT implementing a ΔT_c requirement of $\leq$-5.0° would not be severe, but a limit of -2.5° would likely require reformulations of many of the binders with higher PG grades.

Figure 3.2 illustrates the ΔT_c values determined on binder extracted from 31 RAP stockpiles around the state (Beeson et al., 2011). The binder grades are shown on each bar. Not surprisingly, all of the binders exceeded the -5.0° cracking limit. Of the 12 RAP binders graded as PG 82-10, two exceeded a ΔT_c value of -10° including one exceeding -16. The range of ΔT_c values for the PG 82-10s was from -5.4 to -16.7. Eleven RAPs were graded PG 88-10; of these four exceeded a ΔT_c of -10. One PG 94+2 (continuous grade 94-4) had a ΔT_c of -22.9, by far the most negative. The spread of data for a given low temperature PG grade shows that the low temperature grade itself does not imply what the ΔT_c will be.

3.2 Experimental Design

For this study, initially seven asphalt binders were evaluated for low and high temperature properties, with a focus on ΔT_c after 20 h and 40 h of PAV aging. The binders selected included both unmodified and modified materials. Two RAP sources and one RAS were also selected for blending with a subset of the seven asphalts. Table 3.1 shows the binders studied and the blend proportions.

3.3 Data and Analysis

This section summarizes the test data and analysis. Results of testing the study binders, RAP binders and blends of RAP and RAS with two of the base asphalts are presented. Lastly the results of estimating ΔT_c after 40-h PAV aging based on 20-h testing are summarized.

3.3.1 Testing of Pure Binders

Original and RTFO-aged binders were tested using the DSR to determine the high temperature grade of the binders. Two replicates were tested for each binder. Table 3.2 shows the pass/fail temperatures for each binder (original and RTFO-aged condition) and the corresponding high-temperature performance grade.

The low temperature grade was determined on RTFO-PAV aged binder, subjected to both 20-h and 40-h aging, also referred to as 1PAV and 2PAV, respectively. The BBR was used to measure stiffness (S in MPa) and slope (m-value) of the binder at two or three test temperatures. As required by the test method, the average stiffness and average slope from two beams were used to determine that pass/fail temperatures. For four out of the seven binders (1PAV-aged), two test temperatures were sufficient to obtain the pass/fail temperatures from $S = 300$ MPa ($T_{c,S}$) and $m = 0.300$ ($T_{c,m}$) limits by interpolation. For the remaining three binders (i.e., SBS+PPA, PG 64-22H and PG 64-22V), a third test temperature was required to get the failure temperature at $S = 300$ MPa. For 2PAV-aged binders, additional testing at a third temperature was required to obtain $T_{c,m}$ and $T_{c,S}$.

Based on the DSR and BBR test data, the performance and continuous grades of the binders were determined and are presented in Table 3.3. These data confirm the PG of the binders, as specified by the suppliers.

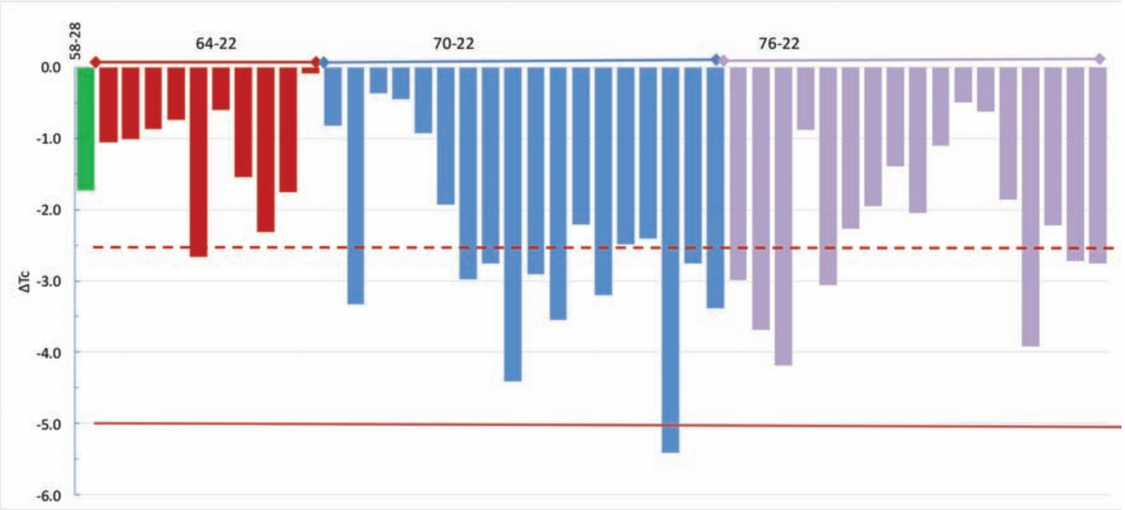

Figure 3.1 ΔT_c values for currently used Indiana binders from 2016–2017.

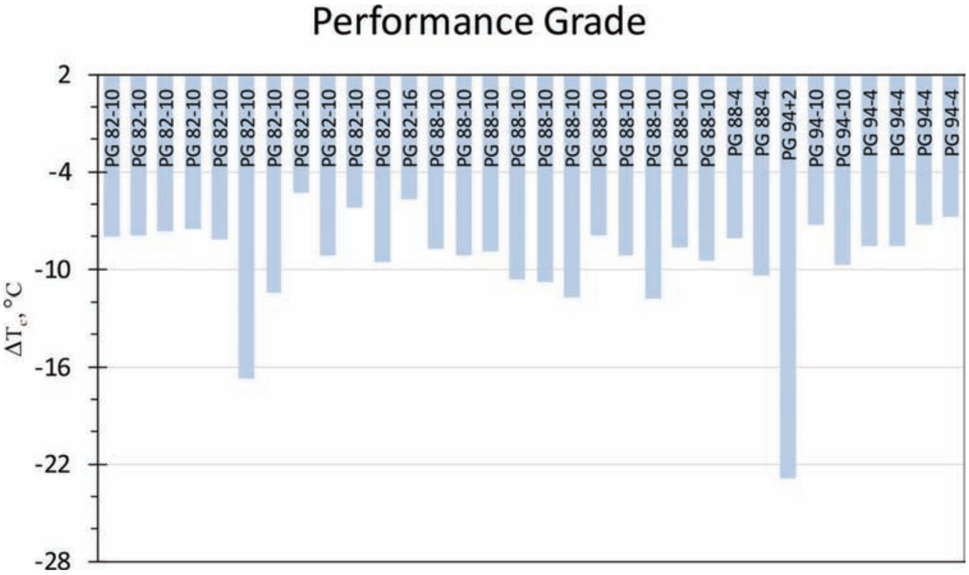

Figure 3.2 ΔT_c values for RAP stockpiles.

TABLE 3.1
Asphalts and RAP blends*

Binders	**0% RAP**	**20% RAP**	**40% RAP**	**100%**
PG 64-22*	B1	R1, R2	R1, R2	
PG 76-22*	B2	R1, R2	R1, R2	
PG 58-28	B3	—	—	
PG 70-22	B4	—	—	R1, R2
SBS+PPA	B5	—	—	
PG 64-22V	B6	—	—	
PG 64-22H	B7	—	—	

*2%, 4%, 6%, and 8% RAS blends were also tested with PG 64-22 and PG 76-22.

Measured critical pass/fail temperatures were compared with those obtained by extrapolation and are shown in Table 3.4. It was observed that in the case of 1PAV-aged binders, the extrapolated values were comparable with the measured values. For 2PAV-aged binders, the differences ranged between -2.3° and 2.0°C. This suggests that extrapolation is not reliable; testing must be conducted at enough temperatures to bracket the specification limits.

The difference between the two critical pass/fail temperatures obtained from S and m values yields ΔT_c. Table 3.5 shows the stiffness and slope data for the seven binders along with the resulting ΔT_c values, under both 1PAV and 2PAV-aging conditions. The temperature data shown in Table 3.5 reflect the interpolated BBR test temperature minus 10°C for obtaining the low temperature grade. For all of the binders tested, the m-value determined the low temperature grade. These data are also presented graphically in Figures 3.3 to 3.5. If the currently recommended "watch" and "critical" flag values are to be observed, PG 58-28,

TABLE 3.2
DSR test results on the binders

Binders	Original	RTFO-Aged	High Performance Grade	High Continuous Grade
PG 64-22	69.0	69.9	PG 64	69
PG 76-22	80.0	84.8	PG 76	80
PG 58-28	60.8	62.6	PG 58	60
PG 70-22	72.7	77.1	PG 70	72
SBS+PPA	75.4	76.1	PG 70	75
PG 64-22V	72.2	74.9	PG 70	72
PG 64-22H	69.4	72.7	PG 64	69

TABLE 3.3
Performance and continuous grades of the binders

Reported Grade	Performance Grade	Continuous Grade
PG 64-22	PG 64-22	69-25
PG 76-22	PG 76-22	80-24
PG 58-28	PG 58-28	60-30
PG 70-22	PG 70-22	72-24
SBS+PPA	PG 70-22	75-27
PG 64-22V	PG 70-22	72-25
PG 64-22H	PG 64-22	69-24

TABLE 3.4
Measured and extrapolated $T_{c,S}$

	1PAV $T_{c,S}$°C			2PAV $T_{c,S}$°C		
Binders	Measured	Extrapolated	Difference	Measured	Extrapolated	Difference
PG 64-22	-27.2	N/A	N/A	-27.1	-24.8	-2.3
PG 76-22	-27.9	N/A	N/A	-26.1	-26.5	0.4
PG 58-28	-31.2	N/A	N/A	-30.8	-32.4	1.6
PG 70-22	-27.0	N/A	N/A	-26.0	-24.7	-1.3
SBS+PPA	-29.7	-29.9	0.2	-28.5	-28.7	0.2
PG 64-22V	-29.9	-30.5	0.6	-26.0	-26.8	0.8
PG 64-22H	-28.9	-28.9	0.0	-26.2	-28.2	2.0

TABLE 3.5
Stiffness and slope data (interpolated) from BBR testing

	T_c based on $S = 300$ MPa		T_c based on $m = 0.300$		ΔT_c	
Binder	20-h PAV	40-h PAV	20-h PAV	40-h PAV	20-h PAV	40-h PAV
PG 64-22	-27.2	-27.1	-25.2	-20.8	-1.9	-6.3
PG 76-22	-27.9	-26.1	-24.1	-21.4	-3.8	-4.6
PG 58-28	-31.2	-30.8	-30.5	-26.7	-0.7	-4.0
PG 70-22	-27.0	-26.0	-24.6	-20.9	-2.4	-5.1
SBS+PPA	-29.7	-28.5	-27.2	-23.0	-2.4	-5.5
PG 64-22V	-29.9	-26.0	-25.5	-21.7	-4.4	-4.3
PG 64-22H	-28.9	-26.2	-24.3	-19.7	-4.6	-6.5

PG 76-22 and PG 64-22V would fall in the watch category with 2PAV ΔT_c between -2.5 and -5.0. The remaining four binders, PG 64-22, PG 70-22, SBS+PPA and PG 64-22H would all be in the critical category.

Examination of the data presented in Table 3.5 indicates that as the aging time is increased (doubled, in this study), the stiffness of the binder increases; accordingly, an increase (less negative) in the critical temperature was observed in all binders. The least change (negligible) was observed in PG 58-28 and PG 64-22, whereas the highly modified PG 64-22V showed the highest increase in stiffness (i.e., less negative T_c). The change in $T_{c,S}$ was in range of 0.1°C (PG 64-22) to 3.9°C (PG 64-22V). These changes are summarized in Table 3.6.

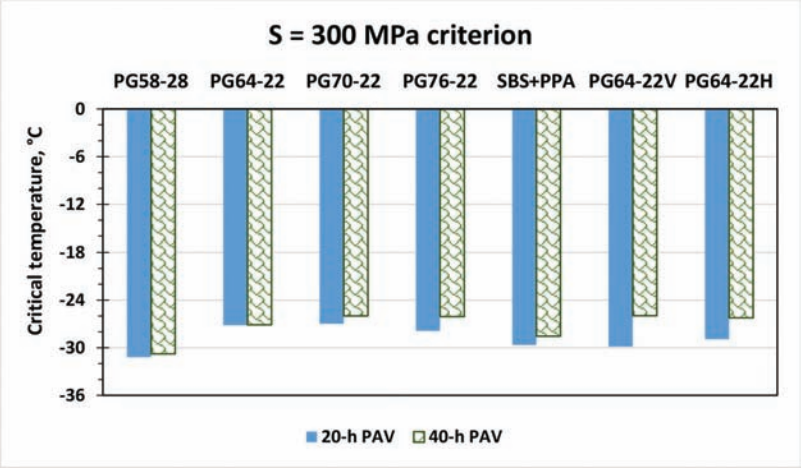

Figure 3.3 Critical temperature from stiffness criterion ($T_{c,S}$).

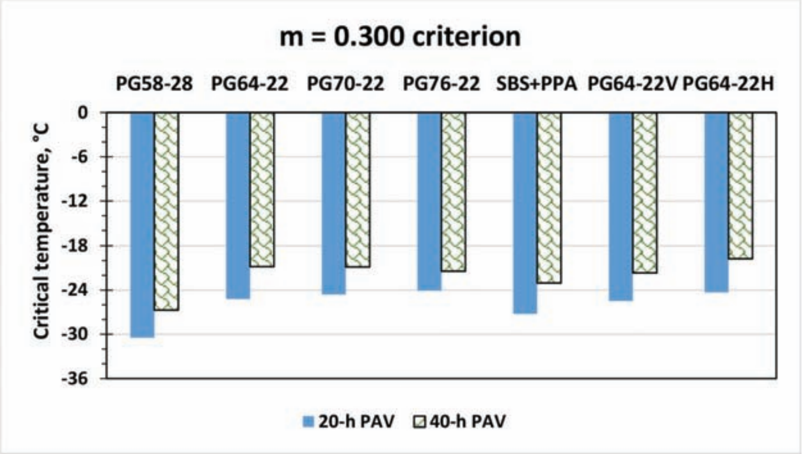

Figure 3.4 Critical temperature from slope criterion ($T_{c,m}$).

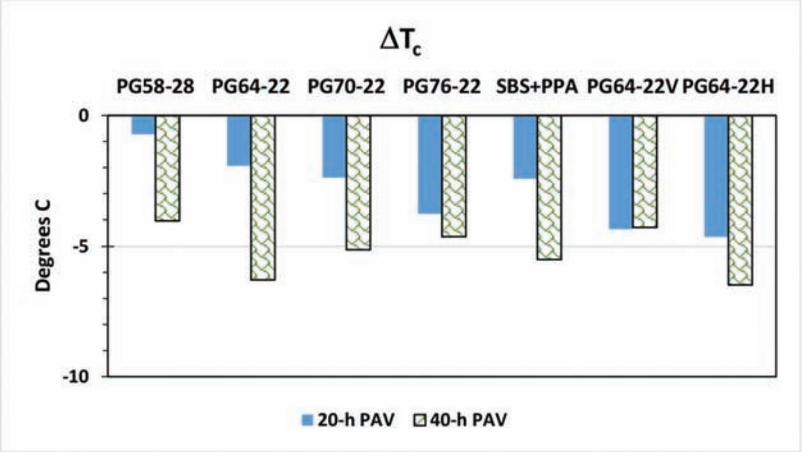

Figure 3.5 ΔT_c values for 20-h and 40-h PAV-aged binders.

Similarly, the extra aging also causes the binders to lose their ability to relax stresses as easily as unaged binders or binders aged for the standard 20-h duration. This is reflected by the change in the slope parameter (m-value) obtained from BBR testing. The change in $T_{c,m}$ was more pronounced than the change in $T_{c,S}$. All binders showed an increase (less negative) in the critical temperature $T_{c,m}$. Ironically, PG 64-22, which

TABLE 3.6

Change in T_c with aging time (40 h–20 h)

Reported Grade	Difference in $T_{c,S}$	Difference in $T_{c,m}$	Difference in ΔT_c
PG 64-22	0.1	4.4	-4.4
PG 76-22	1.8	2.7	-0.8
PG 58-28	0.4	3.8	-3.3
PG 70-22	1.0	3.7	-2.7
SBS+PPA	1.1	4.2	-3.1
PG 64-22V	3.9	3.8	+0.1
PG 64-22H	2.7	4.6	-1.8

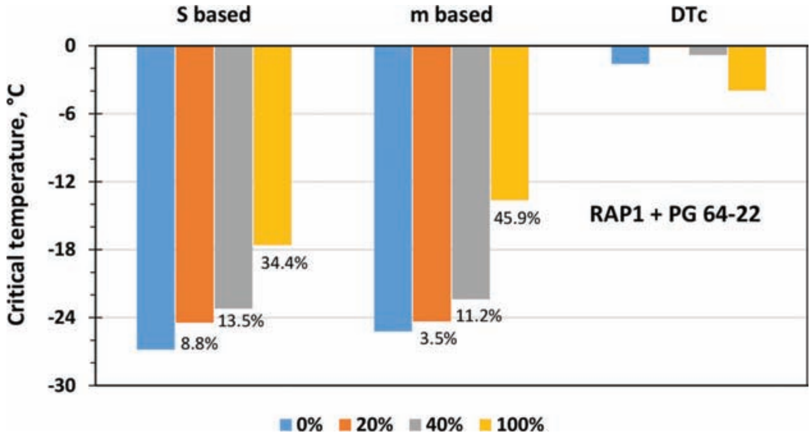

Figure 3.6 Change in critical temperature with RAP1 content in PG 64-22.

showed almost no change in stiffness with increased aging, had the highest loss in flexibility ($T_{c,m}$ change of -4.4°C). The smallest change (-2.7°C) was observed in PG 76-22.

Combining the two T_c parameters, the resultant change in ΔT_c observed by increasing the aging duration, presented in Figure 3.5, shows mixed results. PG 64-22 showed the largest change at -4.4°C, while PG 64-22V showed the smallest (or no) change, 0.1°C, followed by PG 76-22 at -0.8°C.

3.3.2 Testing of Pure RAP

Two RAP samples were used for blending purposes in this study. Both were supplied by Milestone Contractors; one from 96th St. (RAP1), Indianapolis and the other from Harding St. (RAP2), Indianapolis. RAP binders were extracted and recovered from these two sources using the AASHTO T 319 method. The solvent used in this procedure was n-propyl bromide (inhibited). Recovered RAP binders were not subjected to further aging before use in blending.

Following the recovery process, the low and high temperature grades of these binders were determined. RAP1 was graded as PG 93-22 and RAP2 was a PG 82-28. The ΔT_c values of these two recovered binders after 20-h PAV aging were -4.0° and -5.5°, respectively. Only 20-h aging was performed since the RAPs had been aged during production and service.

3.3.3 Testing of RAP-Blended Binders

To study the influence of increasing RAP binder content on the low temperature properties (ΔT_c) of the binders, 20% and 40% RAP binders were added to RTFO-PAV aged binders (20-h PAV). Only two binders out of the seven were selected for this testing in consultation with the Study Advisory Committee; PG 64-22 and PG 76-22. The aged binders were not subjected to optional vacuum degassing prior to blending and/or testing.

Figure 3.6 shows the change in critical temperatures (stiffness and slope criteria) of the binders with increasing amount of RAP1 in PG 64-22 and the resulting ΔT_c. As expected, due to the increase in binder stiffening with increasing RAP content, a warming trend in T_c was observed, using both the stiffness and slope criteria. The data for the base binder (0% RAP) and pure RAP binder (100%) are also shown for comparison. The ΔT_c of the RAP1 binder (-4.0) was over twice that of the base binder (-1.6). No difference in ΔT_c was observed between the addition of 20% and 40% RAP1 binder to PG 64-22. However, the addition of RAP1 to this binder appeared to lower the ΔT_c when compared with that of the base binder. The percentage change in $T_{c,S}$ and $T_{c,m}$ with the addition of 20% RAP was 8.8% and 3.5%, respectively, when compared with that of the base binder. The addition of 40% RAP1 changed the $T_{c,S}$ and $T_{c,m}$ by 13.5% and 11.2% respectively. It may be inferred that the addition of RAP1 binder to this PG 64-22 had a slightly higher influence on the stiffness of the blended binder than on its m-value, i.e., ability to shed thermal stress.

Figure 3.7 shows the same data for RAP2 + PG 64-22 RTFO-PAV aged for 20 hours. In general, the trends observed with this binder agree with those seen with RAP1. Increasing the RAP content increased the binder stiffness and decreased its ability to relax thermal stresses. The addition of RAP2 to PG 64-22 also had a higher influence on the m-value than on the stiffness (shown as % values in the graph). As in the case of RAP1, increasing RAP2 binder from 20% to 40% did not appear to change the ΔT_c significantly (-3.3°C vs. -2.8°C, respectively); however, unlike RAP1, it did worsen the ΔT_c of the blended binders compared to the base binder. RAP1 binder was stiffer than RAP2 and had a less negative ΔT_c than RAP2, although the difference between the two RAP binders was small, i.e., -4.0° vs. -5.5°. Nonetheless, it appears to have a more pronounced effect on the ΔT_c of the base binder, compared with that of RAP1. It should be noted that the ΔT_c value for RAP2 (-5.5) exceeded the recommended threshold value of -5.0 used to delineate binders prone to cracking when used in HMA. In reality, pure recovered RAP binder would never be used in HMA, but it is possible that the effect of ΔT_c of the RAP binders may also need to be studied.

Figure 3.8 shows the results of blending recovered RAP1 with PG 76-22. Examination of the $T_{c,S}$ indicates that the changes appear to be similar to those seen with PG 64-22 (cf. Figure 3.6), 8.8, 13.5, and 34.4% vs. 7.0, 13.5, and 36.7%, respectively. However, the m-value did not change between 20% and 40% RAP (stayed around 11.5% with respect to the base binder), unlike the behavior RAP1 + PG 64-22 blend, which had $T_{c,m}$ values to 3.5% and 11.2%, respectively.

Figure 3.9 shows the BBR results of blending recovered RAP2 with PG 76-22. While the increasing S-based critical temperature (warmer) was following the expected trend, the m-value based data appeared to be erratic. Overall, a decrease in ΔT_c was observed due to the addition of RAP2 to PG 76-22. No difference in ΔT_c was observed between the 20% and 40% RAP.

Overall, comparing T_c from S-based data, Figure 3.6 vs. Figure 3.8, and Figure 3.7 vs. Figure 3.9, it appears that addition of RAP2 (with the more negative ΔT_c) to the base binders caused small, gradual changes in stiffness with increasing RAP content, whereas the addition of RAP1 (with less negative ΔT_c) yielded larger changes.

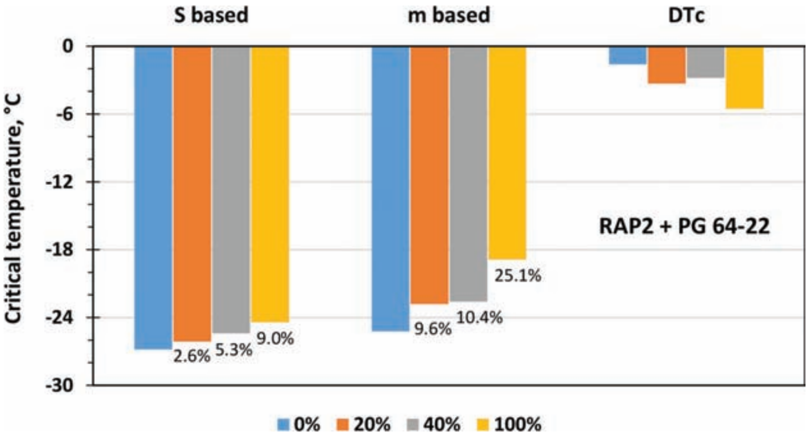

Figure 3.7 Change in critical temperature with RAP2 content in PG 64-22.

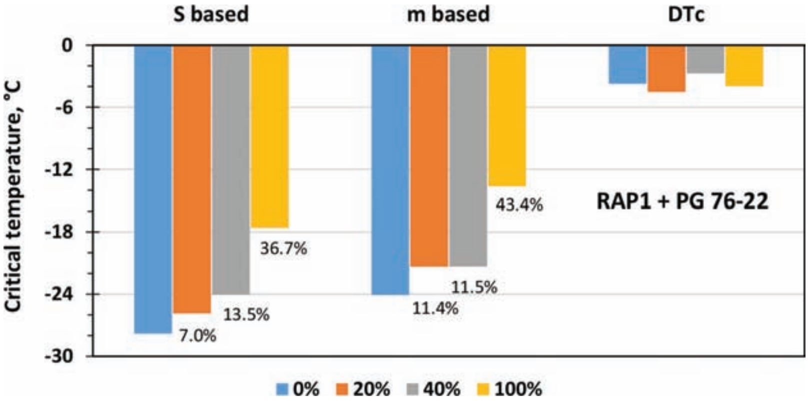

Figure 3.8 Change in critical temperature with RAP1 content in PG 76-22.

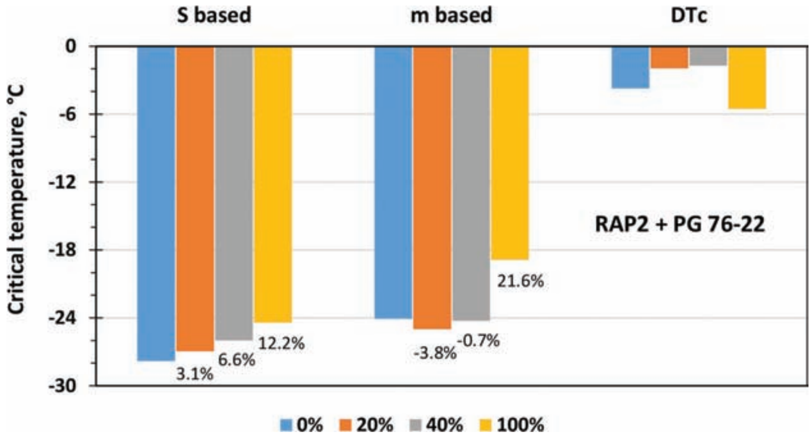

Figure 3.9 Change in critical temperature with RAP2 content in PG 76-22.

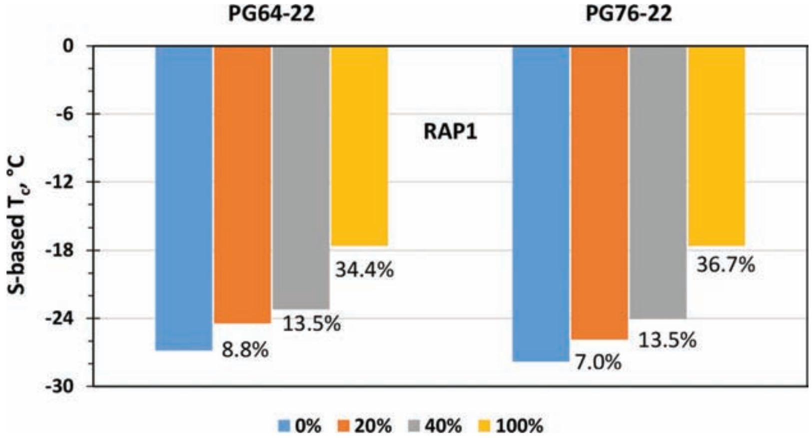

Figure 3.10 Effect of RAP1 on stiffness.

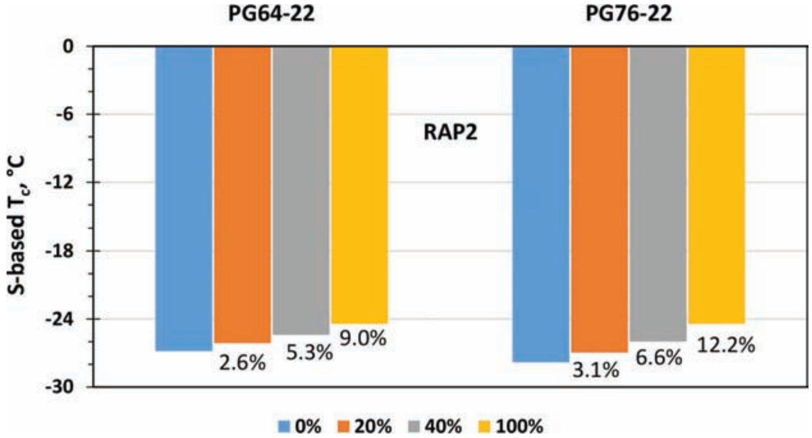

Figure 3.11 Effect on RAP2 on stiffness.

One might expect the more negative RAP to have a greater effect; these results suggest a more complex interaction is occurring between the RAP and base binder. Linear blending does not explain the results. These trends can be seen more clearly in Figures 3.10 and 3.11.

3.3.4 Testing of RAS-Blended Binders

To study the influence of increasing RAS binder content on the low temperature properties (ΔT_c) of the binders, binder was extracted from one RAS source (tear-offs) in Indiana. The recovered RAS binder was too stiff to be poured, even at elevated oven temperatures of 170°C (328°F). Hence, BBR testing of pure RAS binder could not be performed.

Different percentages of recovered RAS binder were mixed with the standard 20-h RTFO-PAV aged PG 64-22. It should be noted that it was impossible to ensure homogeneous blending of the two binders due to the difference in their stiffnesses. This resulted in a partially blended binder with clumps of RAS binder. To avoid negatively impacting the base binder, the blending temperature was limited to 150°C (302°F). BBR testing was conducted at two or three test temperatures, as needed, to obtain the critical pass/fail temperatures based on stiffness and slope criteria. Results from these tests are presented in Figure 3.12, while Figure 3.13 is an alternative representation of the same data grouped by test parameter.

Addition of RAS binder up to 8% appeared to cause only a slight increase in the overall stiffness of the blend when compared with the 2% RAS binder addition. Also, the amount of RAS added did not appear to impact the stiffness of the blended binders. (That is, the stiffness compared to the 2% RAS binder changed only 1.8% to 3.7%.)

Curiously, unlike the trends observed with the addition of RAP binder, the increase in RAS content resulted in an increase in the m-value based T_c. This indicates that the addition of RAS binder improved the ability of the binder to relax thermal stresses over that of the base binder. Addition of just 2% RAS yielded a ΔT_c greater than -5, but addition of 4%, 6%, and 8% RAS improved the ΔT_c. This is counterintuitive and again suggests a complex interaction is occurring. In the case of the RAS, these results may also be influenced by the difficulties in blending the RAS binder into the base binder in the lab.

3.3.5 ΔT_c Estimation at 2PAV

With the increasing use of various modifiers in asphalt, the original standard RTFO-PAV aging introduced with the Strategic Highway Research Program (SHRP) has proven to be inadequate in fully capturing the benefits of the modifiers on long-term aging of pavements. Some researchers have proposed the need for doubling the PAV-aging time for binders (aka, 2PAV) to better address this gap (inadequacy). While this has caused some push back

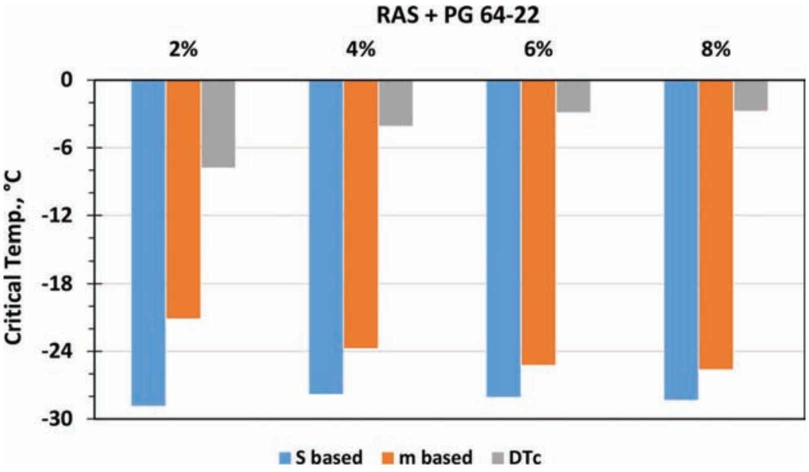

Figure 3.12 Change in ΔT_c with increasing RAS binder.

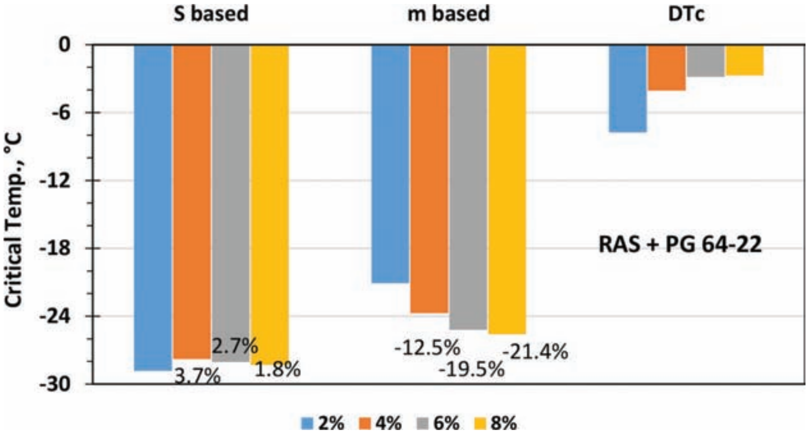

Figure 3.13 Change in low temperature properties with increasing RAS binder.

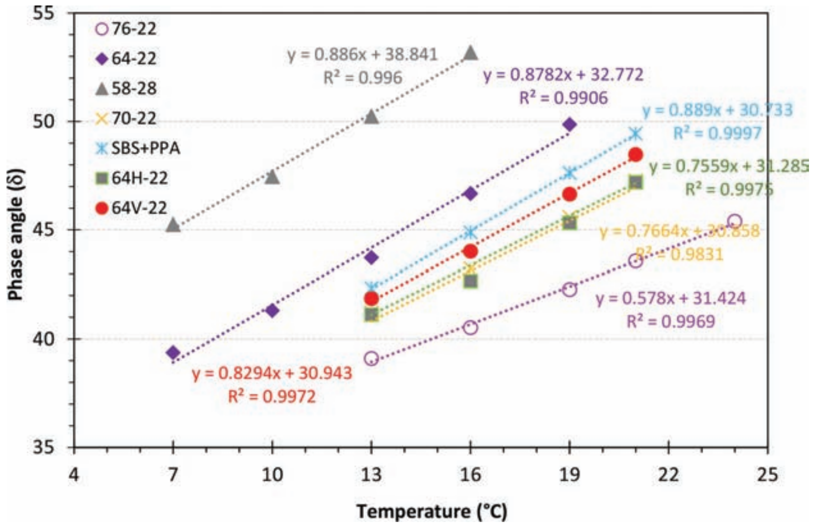

Figure 3.14 Crossover temperature from RTFO-aged binders.

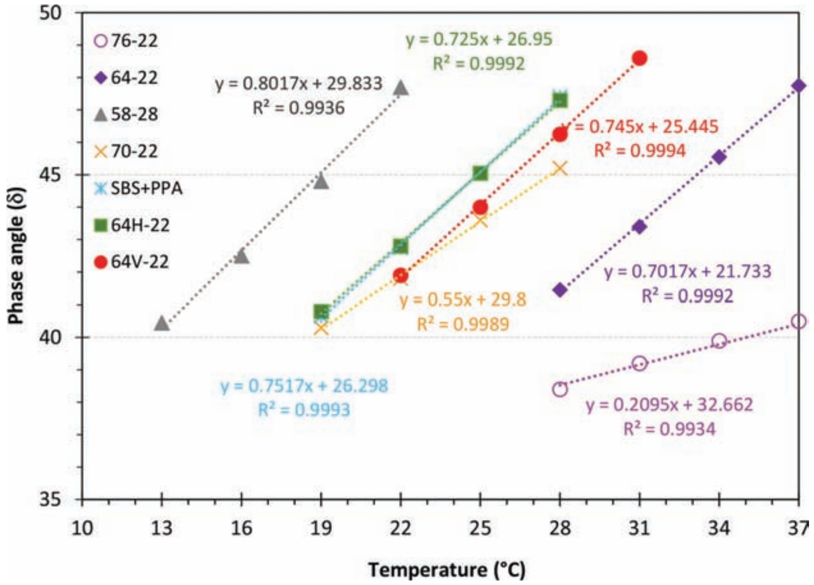

Figure 3.15 Crossover temperature from 1PAV-aged binders.

from the industry due to the extended testing time, other ways to estimate the ΔT_c from 1PAV have been proposed instead.

One method is to determine the crossover temperature ($T_{\omega C}$) of the asphalt, where the phase angle is 45° or the storage modulus, G′, is equal to the loss modulus, G″. DSR testing is performed on 8-mm diameter specimens using RTFO-aged binders and also with 1PAV-aged binders, at 10 radians/s in the intermediate temperature range to determine the temperature corresponding to $\delta = 45°$. These data are shown in Figures 3.14 and 3.15. Given the two $T_{\omega C}$ values and the 20-h aging time, the rate of change is calculated, from which the 40-h or 2PAV $T_{\omega C}$ can be estimated, as shown in the equations below and presented in Table 3.7. D'Angelo suggested setting the estimated 2PAV $T_{\omega C}$ limit at 33°C; 40-h aging recommended for binders that have values >33°C.

$$\text{Rate of change (ROC)} = \frac{(\text{1PAV } T_{\omega C} - \text{RTFO } T_{\omega C})}{20} \qquad \text{(Eq. 3.1)}$$

$$\text{2PAV } T_{\omega C} = 40 \times \text{ROC} + \text{RTFO } T_{\omega C} \qquad \text{(Eq. 3.2)}$$

D'Angelo's work with Mathy Ergon binder data showed good linear correlation ($R^2 = 80.9\%$) between 2PAV $T_{\omega c}$ and 2PAV ΔT_c. Thus Equation 3.3 can be used along with Equations 3.1 and 3.2 to estimate 2PAV ΔT_c.

TABLE 3.7

Parameters used and obtained from Equations 3.1 and 3.2

	Measured $T_{\omega c}$, °C		Calculated ROC	Calc. $T_{\omega c}$, °C
Binders	**RTFO**	**1PAV**	**1PAV**	**2PAV**
PG 64-22	13.9	33.2	0.96	52.4
PG 76-22	23.5	58.9	1.77	94.3
PG 58-28	7.0	18.9	0.60	30.9
PG 70-22	18.1	27.6	0.47	37.1
SBS+PPA	16.0	24.9	0.44	33.7
PG 64-22V	16.9	26.2	0.46	35.5
PG 64-22H	18.5	24.9	0.32	31.3

TABLE 3.8

Estimated 2PAV ΔT_c from 2PAV $T_{\omega C}$

	Measured ΔT_c, °C		Calculated ΔT_c, °C		
Binders	**1PAV**	**2PAV**	**2PAV (linear)**	**2PAV (quad.)**	**2PAV (quad.)**
PG 64-22	-1.9	-4.0	-14.2	-13.5	-13.3
PG 76-22	-3.8	-4.6	-34.9	-28.3	-37.0
PG 58-28	-0.7	-4.0	-3.6	-5.2	-4.9
PG 70-22	-2.4	-5.1	-6.7	-7.7	-7.2
SBS+PPA	-2.4	-5.5	-5.0	-6.3	-6.0
PG 64-22V	-4.4	-4.3	-5.9	-7.0	-6.6
PG 64-22H	-4.6	-6.5	-3.8	-5.4	-5.1

$$2\text{PAV}\ T_{\omega c} = -2.0282 \times 2\text{PAV}\ \Delta T_c + 23.545 \qquad (\text{Eq. } 3.3)$$

Using a larger dataset, D'Angelo arrived at two other quadratic equations shown in Equations 3.4 and 3.5, with R^2 of 79.2% and 80.2% respectively. Table 3.8 shows the measured and calculated ΔT_c values from the three equations.

$$2\text{PAV}\ T_{\omega C} = -0.0088 \times (2\text{PAV}\ \Delta T_c)^2 - 2.4463 \times 2\text{PAV}\ \Delta T_c + 17.892 \qquad (\text{Eq. } 3.4)$$

$$2\text{PAV}\ T_{\omega C} = -0.0255 \times (2\text{PAV}\ \Delta T_c)^2 - 3.0477 \times 2\text{PAV}\ \Delta T_c + 16.441 \qquad (\text{Eq. } 3.5)$$

Linear equation estimates were the closest to the observed values in most cases. For the PG 76-22 and PG 64-22 the estimates were way off the mark for unknown reasons. The PG 76-22 is likely polymer modified, which may explain the discrepancy, but the PG 64-22 is almost certainly not polymer modified.

Going by the -2.5 (watch) and -5.0 (critical) thresholds, we can expect PG 64-22 and PG 64-22V to do well, while PG 58-28 and PG 70-22 would be on the watch list based on the measured data. The SBS+PPA, PG 64-22H and PG 76-22 would be marked as poor performers, but as mentioned earlier, researchers have reported that these limits cannot be applied reliably to elastomer modified asphalts.

4. CONCLUSIONS AND RECOMMENDATIONS

Based on the literature review, testing data and analysis presented here, the following conclusions can be drawn:

- The literature shows that the ΔT_c value characterizes the relaxation properties of asphalt binders and is related to the propensity of a binder to crack. In addition, ΔT_c tends to relate to other, more complex rheological parameters. However, polymer modified binders may exhibit ΔT_c values in excess of the cracking limit despite the fact that they are typically less prone to cracking by virtue of being more elastic.
- The literature also shows fair to good correlations of ΔT_c to mixture cracking test results in most cases.
- Addition of recovered RAP binder increased the stiffness of the blended binders, thereby raising (warming) the pass/fail temperature (T_c) based on the S = 300 MPa criterion. Correspondingly, it also resulted in a decrease in the binder's ability to relax thermal stresses, as evidenced by a warming trend in T_c obtained at m-value = 0.300, in general.
- Estimation of the S-based critical temperature, ($T_{c,S}$), by extrapolating beyond the test temperature range did not always agree with the value obtained from testing at an extra temperature and interpolating, particularly for 2PAV aged binders.
- Two recovered RAP binders were used for blending purposes in this study, one of which (RAP1) had ΔT_c above -5 (less negative) and the other (RAP2) was lower than -5 (more negative).
- Addition of 20% and 40% RAP1 binder to PG 64-22 and PG 76-22 resulted in larger changes in $T_{c,S}$ compared with the changes due to the addition of RAP2.

- The effects of RAP2 on $T_{c,m}$ of PG 76-22 were not as clear cut as those seen with RAP1. There may be some chemical interaction with the polymer modified binder, perhaps.
- As in the case of recovered RAP binder, addition of recovered RAS binder also increased the stiffness of the blended binder and raised the $T_{c,S}$. But unlike the recovered RAP binder, addition of RAS appeared to improve the blended binder's thermal relaxation ability. Difficulties in blending the RAS binder into the base or some sort of interaction may explain these counterintuitive results.
- As other researchers have indicated, ΔT_c of highly oxidized binders can be very difficult, if not impossible, to obtain via BBR testing.
- Also, asphalt binders that are modified with elastomers (PMBs) tend to have very low ΔT_c values (highly negative). This does not imply that these binders have higher cracking potential, since the addition of such modifiers is used to improve the thermal cracking resistance.
- Use of the crossover temperature to estimate ΔT_c after 40-h PAV aging did not yield reliable predictions for the binders tested here.

4.1 Recommendations

Based on these conclusions, the following recommendations are made by the researchers and supported by the SAC.

- At this time, it is not recommended that INDOT implement ΔT_c in its specifications. This recommendation is based in large part on several remaining issues. One primary consideration is the caution against using ΔT_c for polymer modified binders. While INDOT can estimate which binders are likely to be modified based on the binder grade, suppliers are not obligated to divulge that information so assumptions may be inaccurate. The results of testing unmodified binders seem to be more meaningful but would require identifying or assuming which binders are unmodified and handling them differently in the lab, which could be problematic. Another consideration is that the need for 40-h PAV aging is still being debated. Some researchers strongly recommend it while others doubt the increased testing time is truly necessary.
- INDOT could consider ΔT_c a characterization or research tool for forensic studies, for certain applications like high recycled material contents, or other investigations. As research continues on a national level, future implementation in a purchase specification or quality acceptance process may become advisable.
- In the meantime, INDOT could consider additional research exploring more sources of RAP and RAS with a larger spread in ΔT_c, such as observed in the RAP stockpile testing.
- If REOB continues to be a concern, ΔT_c could be used to explore its effects. Attempts to obtain a binder known to have REOB for this project were unsuccessful.
- Difficulties in blending the RAS binder into the base asphalts make the results of that testing questionable. Other researchers have used ΔT_c on extracted binders, though the effects of the extraction may affect the results. More testing should be done on extracted binders with different recycled contents and virgin binder grades.

REFERENCES

Anderson, R. M., King, G. N., Hanson, D. I., & Blankenship, P. B. (2011). Evaluation of the relationship between asphalt binder properties and non-load related cracking. *Journal of the Association of Asphalt Paving Technologists*, *80*, 615–663.

Anderson, R. M. (2019). Delta T_c: Concept and use. In *Past, present and future of asphalt binder rheological parameters* (Transportation Research Circular Number E-C241), 21–44. Washington, DC: Transportation Research Board. http://onlinepubs.trb.org/onlinepubs/circulars/ec241.pdf

Arnold, T. S. (2017). What's in your asphalt? *Public Roads*, *81*(2). https://www.fhwa.dot.gov/publications/publicroads/17sept/03.cfm

Arshadi, A., Steger, R., Ghabchi, R., Zaman, M., Hobson, K., & Commuri, S. (2017). Performance evaluation of plant-produced warm mix asphalts containing RAP and RAS. *Journal of the Association of Asphalt Paving Technologists* (pp. 403–425). Lino Lakes, MN: Association of Asphalt Paving Technologists.

Beeson, M., Prather, M., & Huber, G. A. (2011). *Characterization of reclaimed asphalt pavement in Indiana: Changing INDOT specifications for RAP*. In Transportation Research Board 90th Annual Meeting DVD. Washington, DC: Transportation Research Board.

Bennert, T., Ericson, C., Pezeshki, D., Haas, E., Shambo rovskyy, R., & Corun, R. (2015). Laboratory performance of re-refined engine oil bottoms (REOB) modified asphalt. *Journal of the Association of Asphalt Paving Technologists*, *85*, 163–207.

Cascione, A. (2018). *The future of asphalt binder specifications* [PowerPoint presentation]. Presented at the NRRA 2018 Pavement Workshop. http://www.dot.state.mn.us/mnroad/nrra/pavementconference/2018decks/NRRA%202018%20Presentation%20-%20Future%20of%20Binder%20Testing%20cascione.pptx

Corrigan, M., & Golalipour, A. (2016). *Long term aging and rheological parameters* [PowerPoint presentation]. Presented at the Binder ETG Meeting, April 2016. https://www.asphaltpavement.org/PDFs/Engineering_ETGs/Binder_201604/14%20Golalipour%20&%20Corrigan_Long%20term%20Aging%20&%20Rheological%20Parameters%20_ETG%20Spring%202016%20Final%20version.pdf

D'Angelo, J. A. (2016). *Asphalt binders and aging 20Hr or 40Hr PAV*. Presented at the Binder ETG Meeting, April 2016. https://www.asphaltpavement.org/PDFs/Engineering_ETGs/Binder_201604/15%20DAngelo%20Asphalt%20Binders%20and%20Aging.pdf

Hesp, S., Genin, S. N., Scafe, D., Shurvell, H. F., & Subramani, S. (2009). Five year performance review of Northern Ontario pavement trial: Validation of Ontario's double-edge-notched tension (DENT) and extended bending beam rheometer (BBR) test methods. In *Proceedings of the 54th Annual Conference of the Canadian Technical Asphalt Association (CTAA)* (pp. 99–126). Victoria, Canada: Canadian Technical Asphalt Association.

Karki, P., & Zhou, F. (2018). *Evaluation of asphalt binder performance with laboratory and field test sections* (Report No. FHWA/TX-18/0-6674-01-R1). College Station, TX:

Texas A&M Transportation Institute. http://tti.tamu.edu/documents/0-6674-01-R1.pdf

Li, X., Gibson, N., Andriescu, A., & Arnold, T. S. (2017). Performance evaluation of REOB-modified asphalt binders and mixtures. *Road Materials and Pavement Design, 18*(sup1), 128–153. https://doi.org/10.1080/14680629.2016.1266754

Mensching, D. J., Rowe, G. M., Daniel, J. S., & Bennert, T. (2015). Exploring low temperature performance in Black Space. In *Journal of the Association of Asphalt Paving Technologists* (pp. 459–496). Lino Lakes, MN: Association of Asphalt Paving Technologists.

Rahbar-Rastegar, R., Daniel, J. S., & Reinke, G. (2017). Comparison of asphalt binder and mixture cracking parameters. *Journal of the Association of Asphalt Paving Technologists* (pp. 285–314). Lino Lakes, MN: Association of Asphalt Paving Technologists.

Reinke, G. (2017). *The relationship of binder delta Tc (ΔT_c) to mixture fatigue* [PowerPoint presentation]. Presented at the SEAUPG Meeting, November 2017. http://www.seaupg.org/PDF/2017/Wednesday/11-Reinke-Relationship-Binder-Delta-Tc_1ppg.pdf

REOB Task Force. (2016). *The use of REOB/VTAE in asphalt: State of the knowledge* (IS-235). Lexington, KY: Asphalt Institute. http://www.asphaltinstitute.org/download/177/

Rowe, G. M. (2016). *ΔT_c—Some thoughts on the historical development* [PowerPoint presentation]. Presented at the Binder ETG Meeting, April 28, 2016. http://www.asphaltpavement.org/PDFs/Engineering_ETGs/Binder_201604/13%20Rowe%20-%20DTc%20-%20Historical%20development.pdf

You, T., Shi, Y., Mohammad, L. N., & Cooper III, S. B. (2018). Laboratory performance of asphalt mixtures containing re-refined engine oil bottoms modified asphalt binders. *Transportation Research Record: Journal of the Transportation Research Board*, *2672*(28), 88–95. https://doi.org/10.1177/0361198118787936

Youtcheff, J. (2016). *Update on ongoing binder activities: Fall binder ETG 2016* [PowerPoint presentation]. Presented at the Binder ETG Meeting, October 2016. https://www.asphaltpavement.org/PDFs/Engineering_ETGs/Binder_201609/15%20Youtcheff%20FHWA%20Binder%20Activities%20Sept%2013-2016%20ETG.pdf

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On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

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About This Report

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Recommended Citation

McDaniel, R. S., & Shah, A. (2019). *Investigation of delta T_c for implementation in Indiana* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2019/14). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284316923