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The Effect of Asphalt Supply on Balanced Mix Design

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Preface

Standard practice assumes that if mix designers choose asphalt binder and mineral aggregate meeting their respective specifications, and if they are combined to meet established mass/volume relationships, then adequate pavement performance will be assured, providing construction best practices are followed. This approach has largely worked well for the hot-mix asphalt engineering community. Yet in the past 20 years, there has been significant growth in the development and use of laboratory aging protocols and mechanical property tests that are thought to be more reliable indicators of real pavement performance as compared to the use of volumetric relationships alone. Also, changes in refining practices (new crude oil slates and residuum blending) and the use of modern materials (recycled materials, additives, and modifiers) require a shift in focus from quantity only (volumetrics) to quality (performance). Consequently, agencies and industry in North America are migrating to an approach known as Balanced Mix Design (BMD) wherein proposed asphalt mixtures are held to physical property standards based on the results of mixture performance testing. This approach has been successfully used for high-volume roads in Europe for decades.

Performance testing as part of BMD presents two significant advantages in terms of reliability. First, as previously mentioned, the resulting asphalt mixtures will afford a greater degree of reliability than mixtures whose design basis was solely based on volumetric properties. Second, it will offer a greater degree of flexibility since it is likely that performance testing allows the incorporation of new materials into the hot-mix asphalt pool in appropriate combinations with greater assurance of success in terms of adequate field performance. Previously new materials would have to be evaluated using field trials lasting several years before they could be used with a high degree of reliability.

Yet the rise in the use of BMD has sometimes created a dilemma for mix designers. That is, if performance tests with a given combination of materials do not meet BMD requirements, then what changes can be made to facilitate meeting those requirements? If durability-related parameters (e.g., cracking) are not met, then what guidance can be provided to the designer to source a different asphalt binder, incorporate modifiers or additives, or both, assuming that binder quality is the driving cracking parameter?

Confounding this dilemma is the fact that asphalt binder continues to undergo change. Crude petroleum, the raw material upon which asphalt is based, remains variable. Practically all refineries employ a blend of crude, and various processes that generate residues susceptible to entering the asphalt pool, and those may change from time to time depending on various economic drivers. A significant asphalt supply source has risen from terminal blend facilities, which themselves may produce paving binders from an ever-changing variety of asphalts, polymers, and other modifiers. In some parts of North America, asphalt supply has been systematically removed from the marketplace due to refiners switching refining capacity to renewable fuels to comply with Environmental Protection Agency's renewable fuel standard program. Consequently, terminal blend facilities have had to reach farther and farther to secure their raw materials, sometimes internationally with asphalt not even designed to meet Superpave specifications (for example, visbreaker residues normally used for bunker fuels but rejected by IMO 2020 specs). Furthermore, the rise in additives derived from biomaterials means that mix designers are dealing with a slate of products that are wholly different than before. What would otherwise be considered waste products (e.g., scrap tires, plastic) either have been or are being considered as part of the asphalt additive pool. Although not considered a waste product, the asphalt contained in reclaimed asphalt pavement is a significant and growing, yet variable supply source. Finally, asphalt binder specifications themselves have not remained static. Since performance grade (PG) asphalt binders were adopted in 1993, there have been scores of changes to that specification, implemented locally, regionally, and nationally. Asphalt producers have responded to those changes to maintain their position in the marketplace.

Successful execution of BMD principles needs to include a body of knowledge upon which a mix designer can base decisions pertaining to material and proportion selection aimed at meeting mixture physical property test requirements. This is particularly true for the asphalt binder component. This need was identified by TRB Standing Committees on Production and Use of Asphalt, Binders for Flexible Pavements, and Asphalt Materials Selection and Mix Design and resulted in a workshop session at the 102nd Annual Meeting of the TRB, The Effect of Asphalt Supply on Balanced Mix Design. Its goal was to bring together topics and speakers to explore how BMD principles are influenced by the ever-changing characteristics of asphalt attributed to changing dynamics in the asphalt supply market and the emerging and growing presence of other substances used with and contained in asphalt binders. Adam Hand of the University of Nevada, Reno, guided the workshop. This E-Circular was developed from presentations made at the workshop.

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PUBLISHER'S NOTE

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Asphalt Supply and Balanced Mix Design

What Are the Issues?

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INTRODUCTION

Many state departments of transportation (DOTs) and asphalt mixture producers are looking forward to implementation of BMD as a method to optimize asphalt mixture composition, design, performance and sustainability (*1*). BMD is not a new concept. Francis Hveem proposed selection of design asphalt binder content based on optimizing mixture stability and durability in the 1920s and 1930s as illustrated in Figure 1. The same goals apply to BMD today though there is greater recognition of the influence of mixture components (raw materials) on performance.

A focus on asphalt mixture durability in the past decade has led to greater recognition of the influence of asphalt binder on mixture performance, especially cracking performance. A common observation is that two asphalt binders with the same PG, used in each mix design don't necessarily yield the same cracking performance. Additionally, the differences can become more predominant when cracking test specimens are long-term aged (*2*).

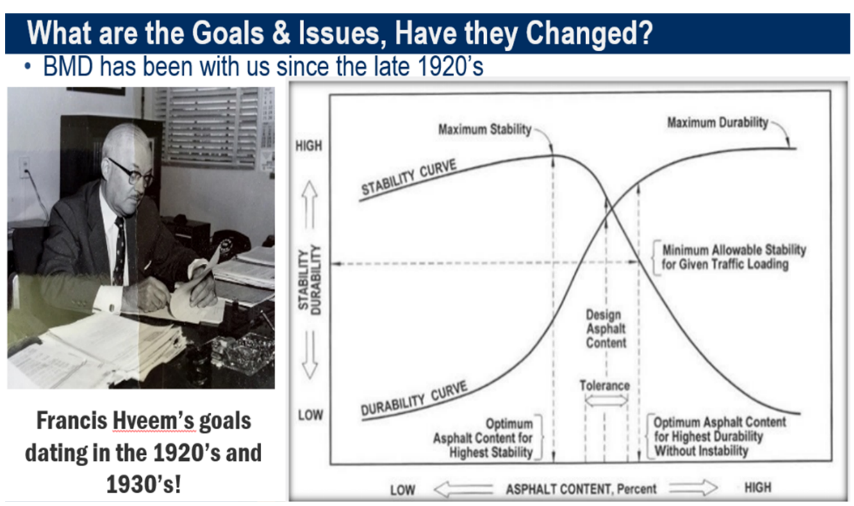


FIGURE 1 BMD philosophy is not new, but more complex.

This could be an asphalt supply and BMD issue if not recognized by DOTs, asphalt suppliers and contractors. This assumes that the contractor has a contract with the DOT or project owner, which is typical. If the contractor is also the asphalt mixture producer some risk may be reduced, and it may be further reduced if the contractor's supply chain is vertically integrated to include aggregate and asphalt binder supply.

Regardless of the supply chain, with the implementation of BMD DOT's will be specifying that laboratory mix designs and plant produced mixtures meet rutting, cracking and moisture susceptibility performance test requirements. In the traditional low bid system, the contractor will have a contract with the DOT and the contractor or asphalt mixture producer will source asphalt binder from a given supplier during the mix design process. The binder will have to meet a specific PG defined in the DOT specifications. If the supplier provides a binder during production of the same specified PG it will have fulfilled its contractual obligation. However, the binder supplied at the time of mix design and during production could have different properties (even though it is the same PG) and lead to significantly different (better or worse) BMD performance test results. Regardless of whether the BMD test results are better or worse, the contractor, not the binder supplier or mix producer, will be assuming all the risks with performance test results not meeting DOT BMD requirements. In theory, this risk could be shifted to the mixture producer by the contractor and mixture producer requiring that the mixture producer supply mixture meeting the DOT BMD performance test results.

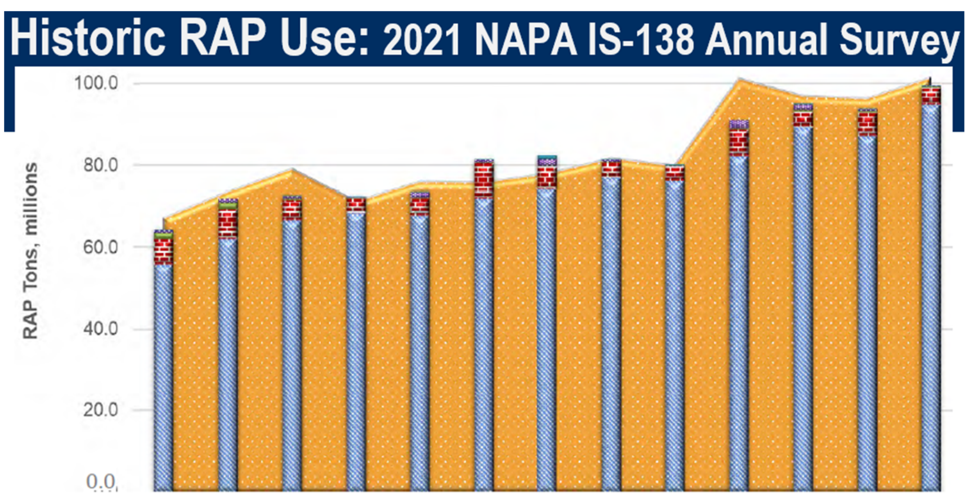
It is well established, and will subsequently be illustrated, that binders of the same PG can lead to very different BMD performance test results. This scenario could lead to challenges while implementing BMD for DOTs, asphalt binder suppliers and contractors. This leads to several technical and contractual questions that will need to be addressed by DOTs, asphalt binder suppliers, mixture producers and contractors to successfully implement BMD while fairly distributing risk among the appropriate parties.

BACKGROUND

Today asphalt mixtures contain more than asphalt binder and aggregate. They can also include recycled materials such as reclaimed asphalt pavement (RAP), reclaimed asphalt shingles, ground tire rubber, and others; and performance enhancing additives such as liquid antistrip additives, recycling agents (RA), fibers, warm-mix asphalt (WMA) additives and other materials.

Similarly, asphalt binders are different today than they were a century ago. Refining processes have changed to extract greater quantities of more valuable products than asphalt binder from crude oil that has impacted asphalt binder properties. Today, asphalt binders are commonly modified with an array of additives depending on the properties of the asphalt binders that need to be influenced. The blending of materials to meet PG grade requirements and use of polymers has become commonplace as well. It is important to recognize that asphalt binder is typically the least valuable product from crude oil refining. So many suppliers manage the refining process to minimize asphalt binder production, and its properties (quality) can be variable.

A drive to more sustainable asphalt mixtures will also lead to changes in asphalt mixtures with time. Use of RAP in asphalt mixture has been a positive sustainability story for the asphalt industry (*3*). Figure 2 shows that the annual tonnage of RAP used has been increasing with time and that about 95% of RAP generated is re-recycled in asphalt pavements. There will be efforts to increase the use of recycled materials in asphalt mixtures and asphalt binder supply (PG, blending stocks, additives) will need to change to engineer more sustainable high performing mixtures and these mixtures will need to be more consistent to meet BMD performance test requirements. Figure 3 illustrates the change in emissions from using RAP in asphalt mixtures from 2009 through 2021.



RAP	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Accepted	67.2	73.5	79.1	71.3	76.1	75.8	78.0	81.8	79.9	101.1	97.0	96.3	101.3
Landfilled	0.1	0.0	0.3	0.2	0.1	0.2	1.0	0.1	0.0	0.0	0.1	0.2	0.1
Used in Other	0.7	0.8	0.7	0.2	1.5	0.6	1.6	0.4	0.2	2.0	1.4	0.3	0.2
Used in Cold Mix	1.5	1.6	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.1
Used in Aggregate	6.2	7.3	4.9	3.6	4.0	8.5	5.5	3.7	3.4	6.4	3.8	5.8	4.2
Used in HMA/WMA	56.0	62.1	66.7	68.3	67.8	71.9	74.2	76.9	76.2	82.2	89.2	87.0	94.6

FIGURE 2 History of RAP use.

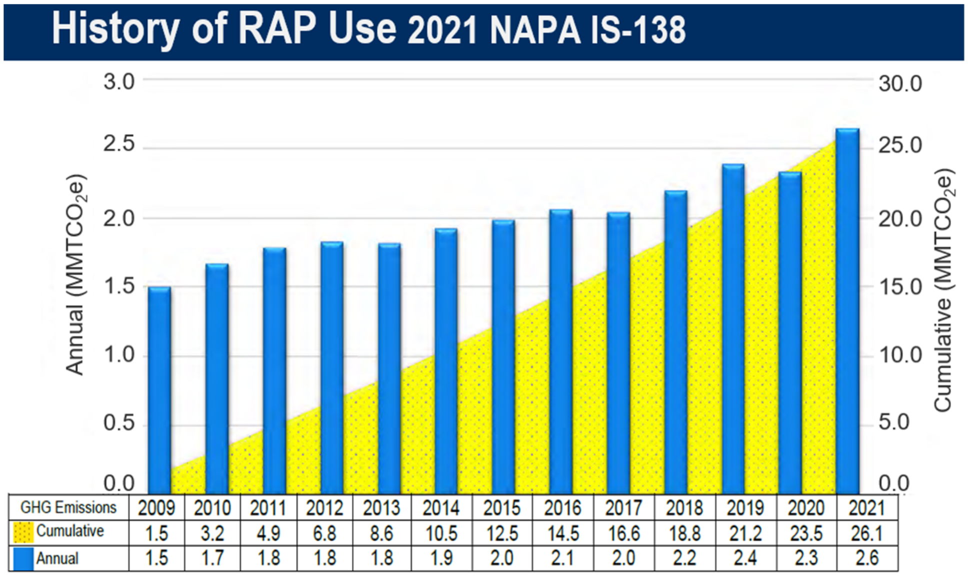


FIGURE 3 Change in emissions from using RAP in asphalt mixtures.

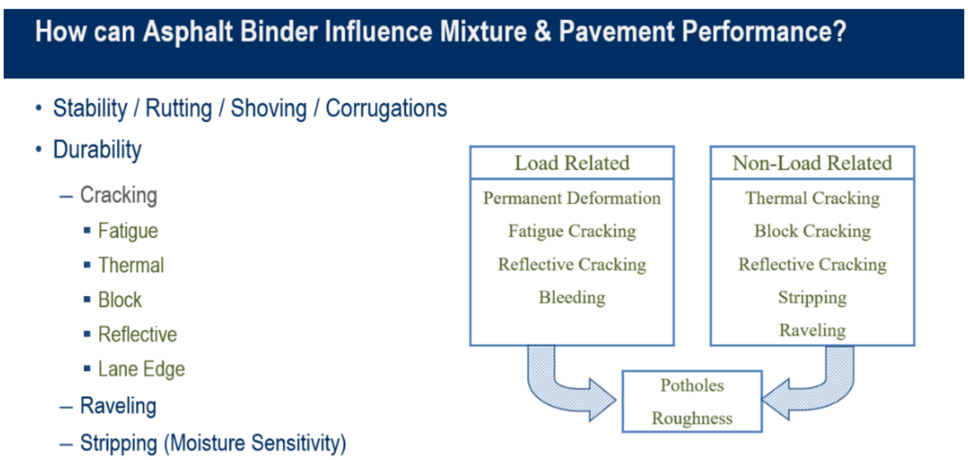


FIGURE 4 Aspects of asphalt mixture and pavement performance influenced by asphalt binder.

Figure 4 illustrates the types of asphalt pavement distresses that can occur over the life of a pavement. Asphalt binder content and properties contribute to reducing the initiation and propagation of the distresses listed in the figure influencing pavement performance. However, it is important to recognize that other mixture components also influence pavement performance. Aggregates, aggregate gradation, recycled materials and other performance enhancing additives also influence pavement performance. Like asphalt binder, changes in these mix components from mix design to production or during production can also influence pavement performance and BMD performance test results. For example, an increase in RAP dose without a change in virgin binder content or properties could lead to a stiffer mixture that is more susceptible to cracking. The point is asphalt binder is not the only mixture component that influences mixture performance, which is important to recognize in the context of the introduction section.

Figure 5 illustrates the connections between pavement geometric design, structural design, and asphalt mixture materials selection and mix design, along with how they can influence pavement construction and pavement performance. The intent of Figure 5 is to remind readers that good asphalt pavement performance requires that all these items be done correctly, for the specific conditions the asphalt pavement will be exposed to and for it to be constructible and perform well. Asphalt pavements are more complex than some realize, and diligence is required in design and construction to achieve good performance. Consistence of mix components is equally important.

OPERATIONAL IMPACTS WITH TRANSITION TO BMD

The implementation of BMD will lead to asphalt mixture and asphalt mixture component producers making changes in components and processes to fulfill BMD mix design and production requirements. It is not uncommon to hear an asphalt technologist state that asphalt binders are not the same or as good as they used to be (Figure 6). Contractors tend to have the expectation that PG binders of the same PG will be the same in the traditional low bid system. There are several reasons for this which include the following items.

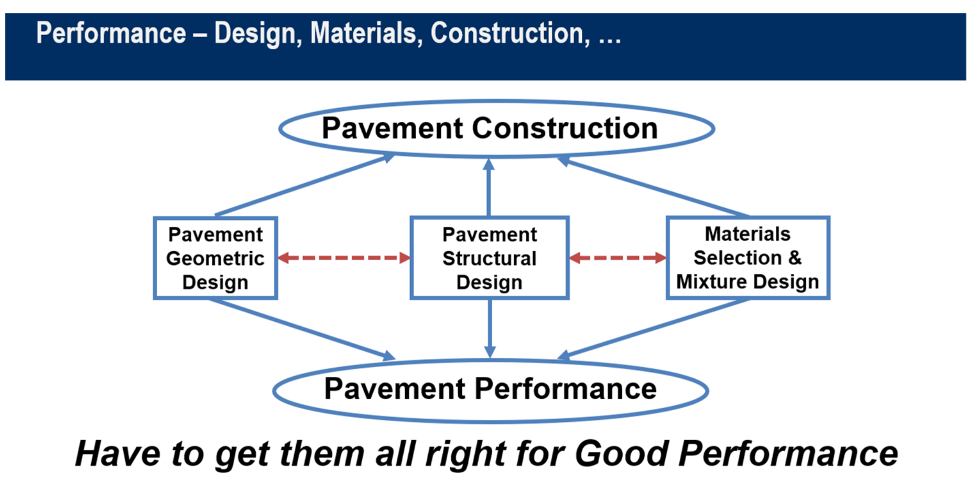


FIGURE 5 Asphalt pavement design, construction and performance relationships.

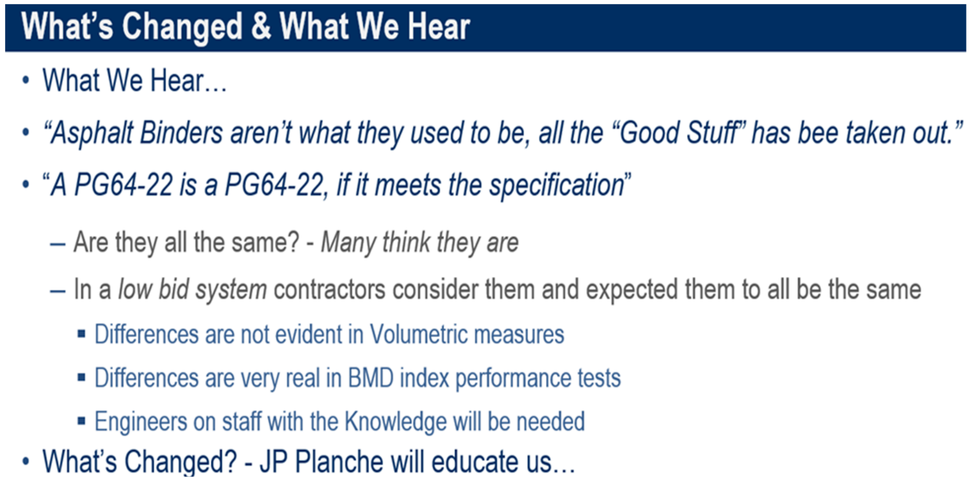


FIGURE 6 Asphalt binder supply changes.

- The binders meet the same American Association of State Highway Transportation Officials (AASHTO) PG specification requirements (*4*, *5*).
- Variability within a PG does not lead to significant differences in measurements of acceptance quality characteristics in many current agency specifications (e.g., asphalt content, gradation, laboratory compacted air voids, voids in mineral aggregate).
- Most agency specifications do not include cracking performance tests or long-term aging of performance test specimens, which can quantify differences in mixture engineering properties due to PG binders of the same and different grades.

With the implementation of BMD and mixture performance tests the third item from the list above will become particularly important as use of long-term mixture aging and cracking performance tests will become common in BMD to assure mixtures containing high RAP or reclaimed asphalt shingles (RAS) doses are properly engineered to provide good long-term performance.

Figure 7 lists several mixture component materials that can influence BMD performance test results in addition to asphalt binder. Changes of supply, dose and physical or chemical properties of each could influence BMD test results. Thus, mixture component producers and asphalt mixture producers will need to understand how changes in their respective products and process will influence BMD test results. An example of this, other than asphalt binder, is RAP. RAP doses will likely increase and as dose increases RAP consistence may need to increase to ensure consistent BMD performance test results. Some State DOTs currently allow up to 50% or more RAP in asphalt mixtures (*6*). Virtual visits of States DOTs identified that some RAP production considerations identified by State DOT or contractor personnel included:

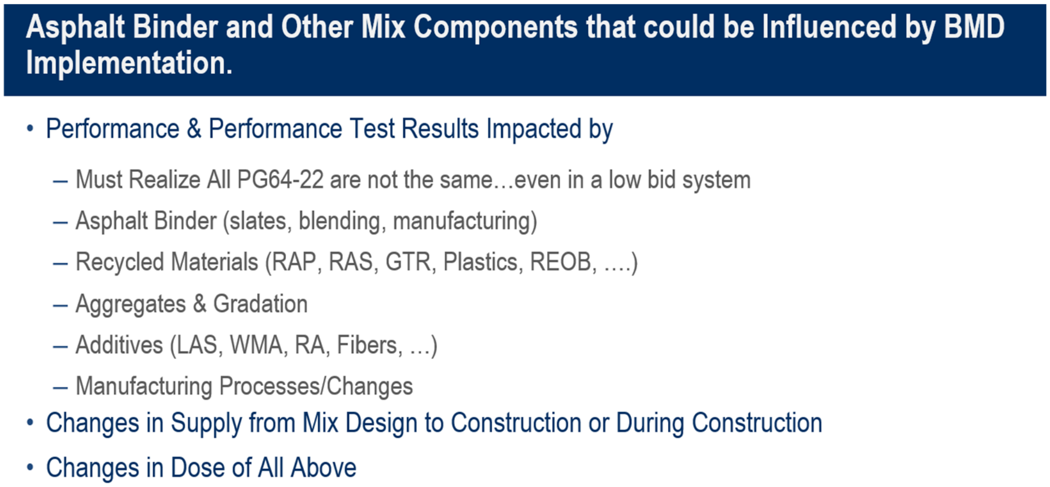


FIGURE 7 Mixture components that can influence BMD performance test results.

FIGURE 8 Importance of RAP quality and consistency for high RAP mixture production.

- Requiring dedicated RAP stockpiles.
- Processing by blending, screening, and crushing over-size materials for consistency.
- Requiring or allowing fractionation of RAP for consistency.
- Requiring RAP quality control (QC) plans or provisions for RAP be included in project QC plans.
- Requiring plant control reports indicating mix component proportioning.

Figure 8 shows a series of potential RAP stockpiles with the two on the bottom row including a stockpile of RAP prior to and after crushing and screening for consistency. The variability of the RAP gradation of the stockpile in the lower right portion of Figure 8 was lower than the variability of some of the virgin aggregate materials used at the same asphalt plant. This producer recognized the importance of RAP quality and consistency on asphalt mixture consistency and implemented more rigorous RAP production QC than was required by agency specifications.

Figure 9 shows CT_{Index} cracking test results on three mixtures, each containing two or three RAP doses, at least two PG binders of different grades and in some cases the same PG from multiple asphalt binder suppliers. The first four numbers of each mixture type are the base mixture identification, the second number set indicates RAP dose, the third number set indicates PG of the binder in the mix and last number/letter set indicates asphalt binder supplier. The crosshatched bars represent the average of three CT_{Index} test results on short-term oven aged mixtures (4 h at 275°F), while the solid filled bars represent the average of three CT_{Index} test results on long-term oven aged mixtures (5 days at 175°F).

For all three base mixtures when RAP dose went from 0% to 25% reductions in CT_{Index} values were observed as anticipated. Depending on binder supplier and RAP dose, the CT_{Index} test results on LTOA mixtures ranged from about 35 to 55% less than STOA mixtures. The first three pairs of bars from the left in Figure 9 are for the 9145 mixture. The same asphalt binder supplier provided PG 64-28 and PG 58-34 for this mixture. The second set of bars (9145-25-6428-S2) and third set of bars (9145-25-5834-S2) have the same RAP dose (25%) and with a

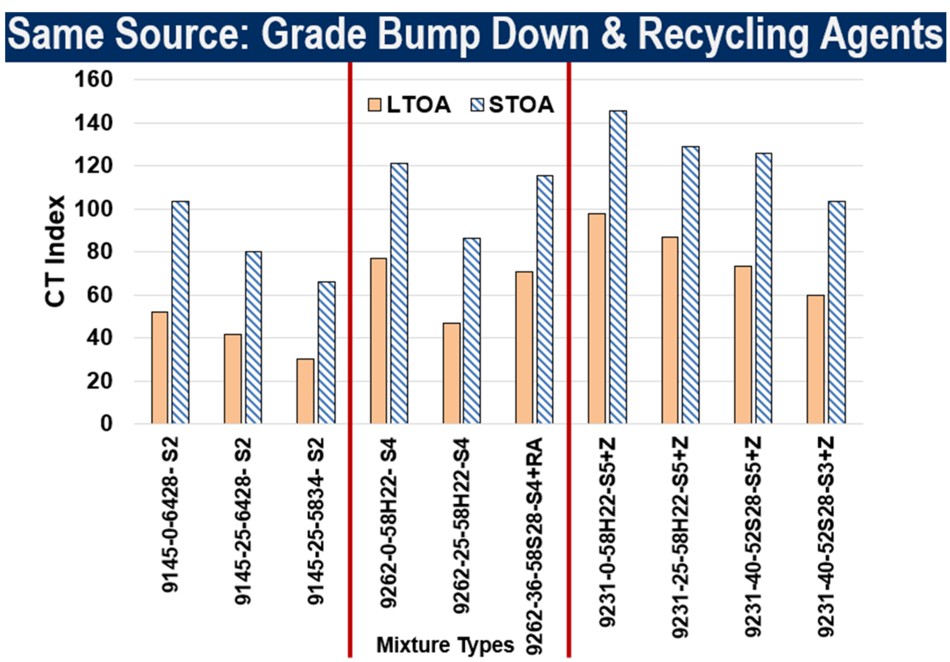


FIGURE 9 Influence of LTOA and PG bumping in asphalt mixture containing RAP.

grade bump down one full PG (9145-25-5834-S2) and the cracking performance was worse with the grade bump down as evident from reductions in both STOA and LTOA CT_{Index} for the mixture containing the PG58-34. This is an important observation as the blending charts showed a lower PG with the PG58-34 although the cracking test results showed worse mixture cracking performance. So, grade bumping down does not always mean lower mixture stiffness and better cracking performance and thus should not be assumed. The fourth, fifth and sixth sets of bars from the left in Figure 9 are for 9262. The fourth 9262-0-58H22-S4 and sixth 9262-36-58S22-S4+RA sets of bars show similar STOA and LTOA CT_{Index} cracking performance for the virgin mixture and 36% RAP mixture with a change in base binder grade combined with a low dose of recycling agent. The last four sets of bars on Figure 9 are for mixture 9231. The eighth (9231-25-58H22-S5+Z) and ninth (9231-40-52S28-S5+Z) sets of bars show that similar cracking performance can be obtained with 25% and 40% RAP with a grade bump down for STOA mixtures. However, with LTOA the 40% RAP mixture cracking performance was reduced by about 20% compared to the 25% RAP mixture. The ninth (9231-40-52S28-S5+Z) and tenth (9231-40-52S28-S3+Z) sets of bars show that with the same RAP dose of 40% and same PG from two suppliers, the cracking performance is about 20% worse between binder suppliers.

The data in Figure 9 sheds light on the importance of selecting appropriate cracking tests and performing them on both STOA and LTOA mixtures to successfully select asphalt binders. These points are stated in Figure 10 along with recognition that there is a not a single cracking test that is appropriate for use across all environments in the US due to the differences in climatic conditions across the country.

FIGURE 10 Role of BMD cracking tests and long-term aged samples for asphalt binder selection.

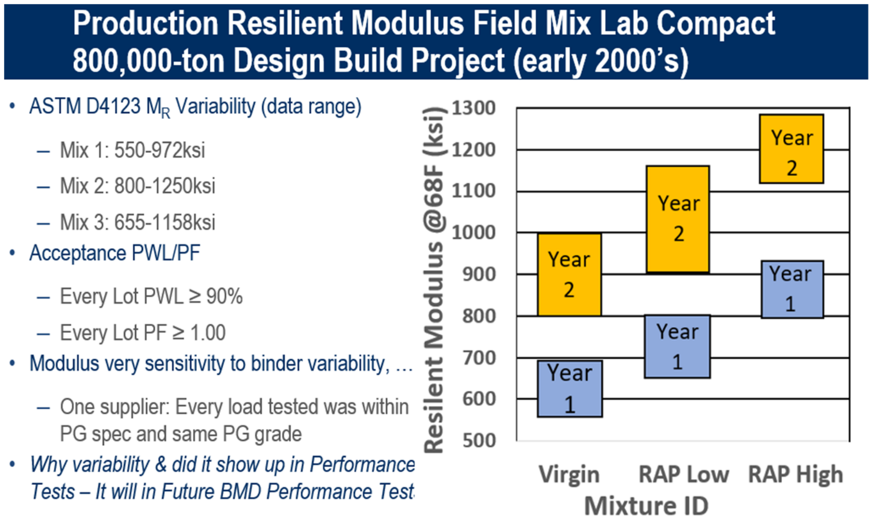


FIGURE 11 Examples of modulus variability due to asphalt binder variability.

Figure 11 shows resilient modulus test results for three asphalt mixtures used on an 800,000-ton project which was all produced from the same quarry and asphalt plant with a single asphalt binder source and single PG grade from one supplier. The project was constructed over a 2-year period with three mixtures. A virgin mix, a mix containing 15% RAP, and a mixture containing 25% RAP were used on the project. A significant shift in resilient modulus test results from the first year of construction to the second year was observed as shown in the plot of Figure 11.

However, all the mixtures placed on the project had composite percent within limits equal to or greater than 90% and resulting composite pay factors equal to or greater than 1.0. The volumetric acceptance quality characteristics in the specification were not sensitive to a change (increase) in asphalt binder stiffness with specimens compacted in a Superpave gyratory compactor. The asphalt binder met the same PG requirements in both construction years although there was a shift within the PG which was apparent in resilient modulus test results from year 1 to year 2 for all three mixtures. Had a test like several being considered by State DOTs for implementation in a BMD been used for acceptance on this project all three of the year 2 mixtures would likely have been rejected. The key point is what has been for acceptable asphalt binder variability with DOT specifications relying on percent asphalt, gradation and volumentrics will not be acceptable with the implementation of BMD.

Figure 12 shows a picture of a new road constructed at the entry to a new subdivision one year after construction. The pavement was constructed and accepted with full payment per the local government specifications. The mixture was a virgin mixture (no recycled materials) and the asphalt binder used was supplied by a supplier that provided binder for the bulk of the total asphalt mixture made at this asphalt plant during the construction season. Cores were taken from the pavement and upon recovery the binder in the mixture was several grades stiffer than what was specified. Plant production temperatures were reported to be typical for the asphalt binder grade and the pavement were constructed during the warm season. Unfortunately, neither the local agency or contractor sampled and tested the binder during construction. Nor did they retain samples. The pavement was removed and replaced at the contractor's expense as the contractor has the contract with the public agency. With the implementation of a BMD incorporating a cracking performance test on STOA and LTOA specimens this would not have been constructed.

Figure 13 shows the location of a new pavement that tied into a 10-year-old pavement at an intersection. The portion on the left side of the picture is a new pavement that was only in service over one winter. It was constructed in the fall and had to be removed and replaced in the spring.

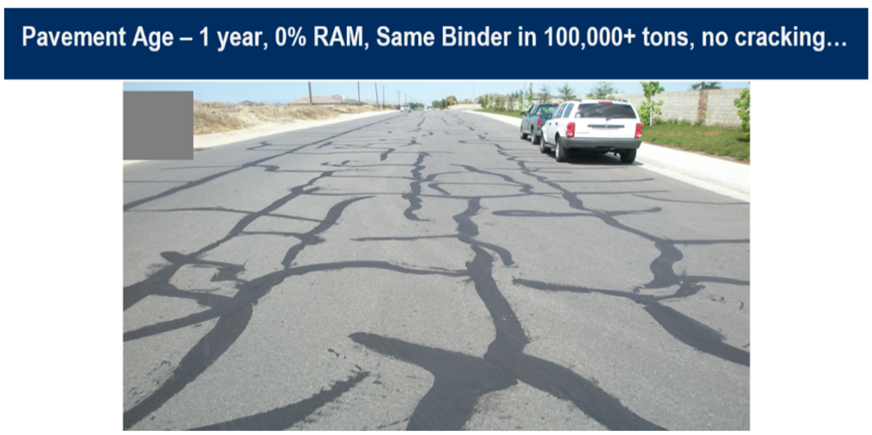


FIGURE 12 Significant block cracking in 1-year-old new asphalt pavement.

FIGURE 13 Stripping of less than 1-year-old asphalt pavement.

The existing pavement which the new pavement tied into had been in service for 10 years. This was only a portion of the project. A significant portion of the project was completed prior to a winter shutdown. All the pavement construction prior to the shutdown was performing well after the winter. Construction resumed the following spring and portion shown in Figure 13 was constructed. The asphalt binder specified for the project was a modified PG58-34 or PG58-40. The agency required the use of a liquid antistrip additive. All the binder for the project was made at the same time. Due to the early winter shutdown, the unused binder was left in the binder supplier's tank through winter.

In the spring the binder no longer met the specifications and was modified with an acid to bring it back into specification. This binder was then used to construct the pavement shown in Figure 13 which experienced a catastrophic stripping failure during the first winter of service. The agency only required moisture sensitivity testing during mix design and the mixture placed the first year did not show any signs of stripping after the first winter. So, neither the agency nor contractor did any moisture sensitivity testing when going back to work after the first winter shutdown. The pavement was removed and replaced at the contractor's expense.

SUPPLY CHAIN RISK MANAGEMENT WITH TRANSITION TO BMD

Asphalt binder is viewed as a commodity by refiners, as it should be in the context of the traditional low bid system and current specifications used by public agencies. Like any commodity its price can fluctuate with shifts in supply and demand. Many other construction materials are viewed similarly with examples listed in Figure 14. Asphalt binder, the items listed on the figure, and many other items are supplied and demonstrated to meet specifications which are used in the procurement, construction and acceptance processes for pavements. For the most part the materials supplied provide the expected performance, so the risk of poor performance is low. However, it is anticipated this will change significantly for asphalt binders with the implementation of BMD.

It has been illustrated in this document and by others that asphalt binders of the same PG grade do not provide the same asphalt mixture performance. It has also been illustrated that the aging susceptibility of asphalt binders of the same PG grade can be very different leading to significantly better or worse performance. Early experimentation with BMD performance tests has already revealed that the purchase specifications used today (AASHTO M320 and AASHTO M332) will not guarantee the desired performance and will not be able to be used in the manor they are today without significant change. In fact, they would place significant undue

FIGURE 14 Asphalt binder supply chain risk management for supplier and hot-mix asphalt (HMA) producer success.

FIGURE 15 The need to re-visit purchasing specification and contractual relationships.

risk on contractors who have contracts with the customers and lead to disputes involving all stakeholders (agencies, contractors, asphalt mix producers, binder suppliers, etc.) as suggested in Figure 15.

SUMMARY

It has become apparent that the implementation of BMD will lead to the need to revise specification and contracts in the future. Example of why have been presented in this document.

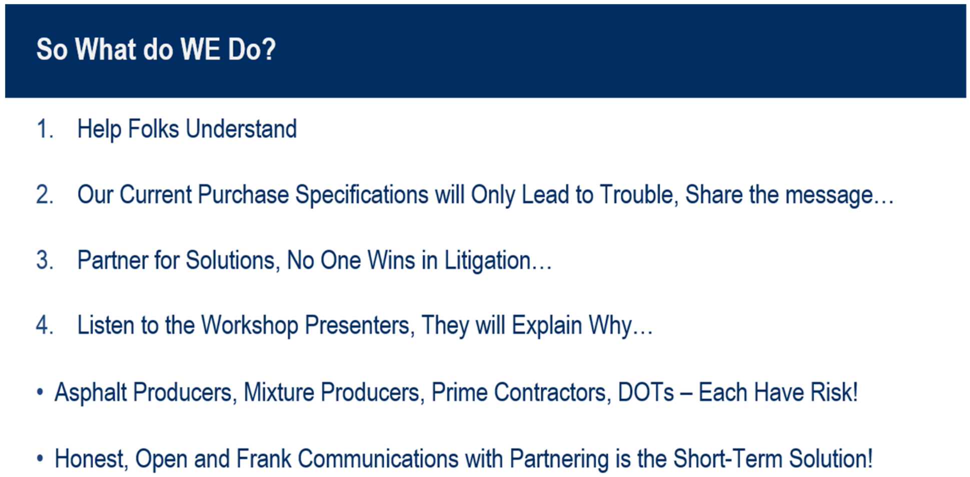


FIGURE 16 Solutions through partnering.

In addressing the reality that the asphalt binder purchase specifications used today will not be able to be used in the implementation of BMD in the future, all stakeholders will need to be open minded and work together to make changes. Changes cannot be made without people understanding the issues and working together to develop the best possible outcomes in resolving them for the future. Figure 16 lists items that could potentially be done to help in the process. Stakeholder partnering will be important to manage risk for all entities involved. It is anticipated that this will take years to work through.

During that period forward-thinking agencies, contractors and asphalt binder suppliers will make efforts to implement BMD. Hopefully the use of shadow specification and pilot projects to really understand what needs to be done to change current purchase specifications and contracts to balance risk and obtain the desired asphalt mixture performance will be used. This along with stakeholder partnering, which requires honest open and frank communications, to develop the best possible outcomes will serve the industry well. It will also make it more apparent to all stakeholders what opportunities exist for them and could lead to very successful outcomes for those that invest in the process.

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Case Studies on the Role of Asphalt Binder in Balanced Mix Design

Northeast US Experience

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The scope of this TRB workshop is the impact of the binder on BMD for asphalt concrete mixtures, with this section addressing binder properties that can help guide BMD decisions.

As agencies begin to implement BMD, asphalt mix suppliers/contractors need to have a better understanding of how asphalt binders can impact asphalt mixture performance. It is not as simple as whether the asphalt binder is modified or not, but that differences also exist between asphalt liquid suppliers providing the identical PG grade and can be significantly affected by contamination at the asphalt plant. In addition, asphalt liquid suppliers must understand that production and source changes result in the asphalt binder changes that may meet current PG grading specifications yet not provide the performance the asphalt mix suppliers/contractors are accustomed with.

The New Jersey DOT has been involved with BMD-based asphalt mixtures since 2006 (Bennert, et al., 2011). Research focused on the interrelationship between asphalt binder content, PG grade and mixture performance. Using a typical Superpave surface course mix shown in Figure 1, the asphalt content was varied from –1% optimum, optimum and +1% optimum. Specimens were compacted at the same air void level and tested for their respective rutting and fatigue cracking properties.

The resultant data shown in Figure 2 show that when the asphalt mixtures were dry of optimum, rutting performance was relatively consistent. At optimum asphalt content, the influence of the higher effective asphalt content resulted in greater magnitudes of rutting in the unmodified mix while good rutting performance was observed in the polymer-modified mixes. At

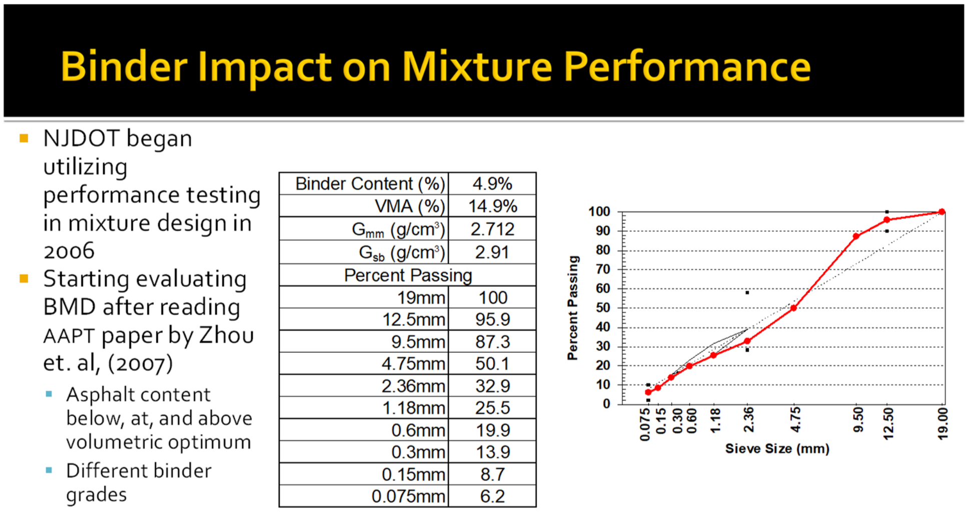


FIGURE 1 Asphalt mix composition of early BMD work in New Jersey.

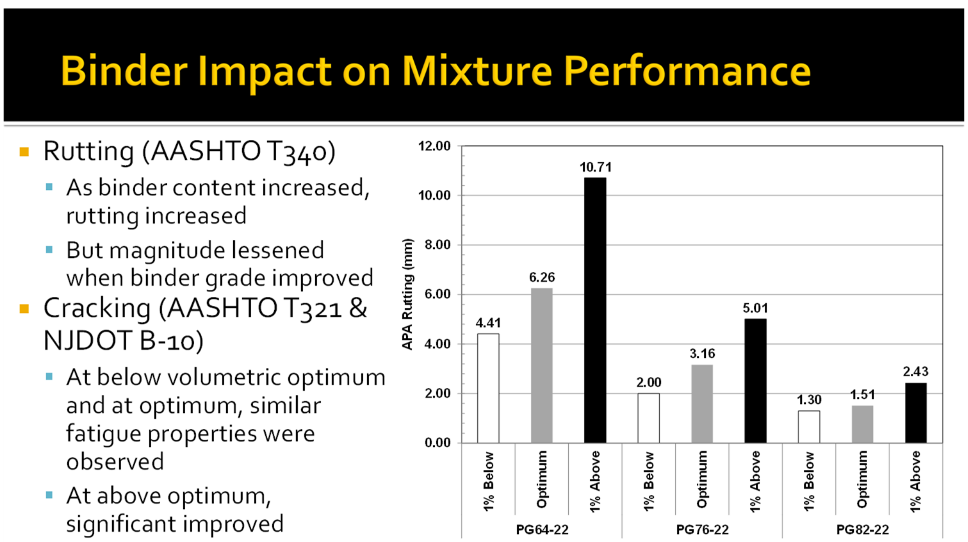


FIGURE 2 Effect of binder content and grade on lab rutting and cracking results.

above optimum, the unmodified asphalt mixture had significant rutting, while the rutting magnitudes decreased the heavier the polymer loading was in the asphalt binder.

Meanwhile as shown in Figure 3, fatigue cracking performance was not found to be as sensitive to binder modification (unmodified or polymer modified), as much as it was to effective asphalt content. For the crack initiation test (flexural beam fatigue), it was not until above optimum asphalt content was there any impact of asphalt binder modification observed. For the

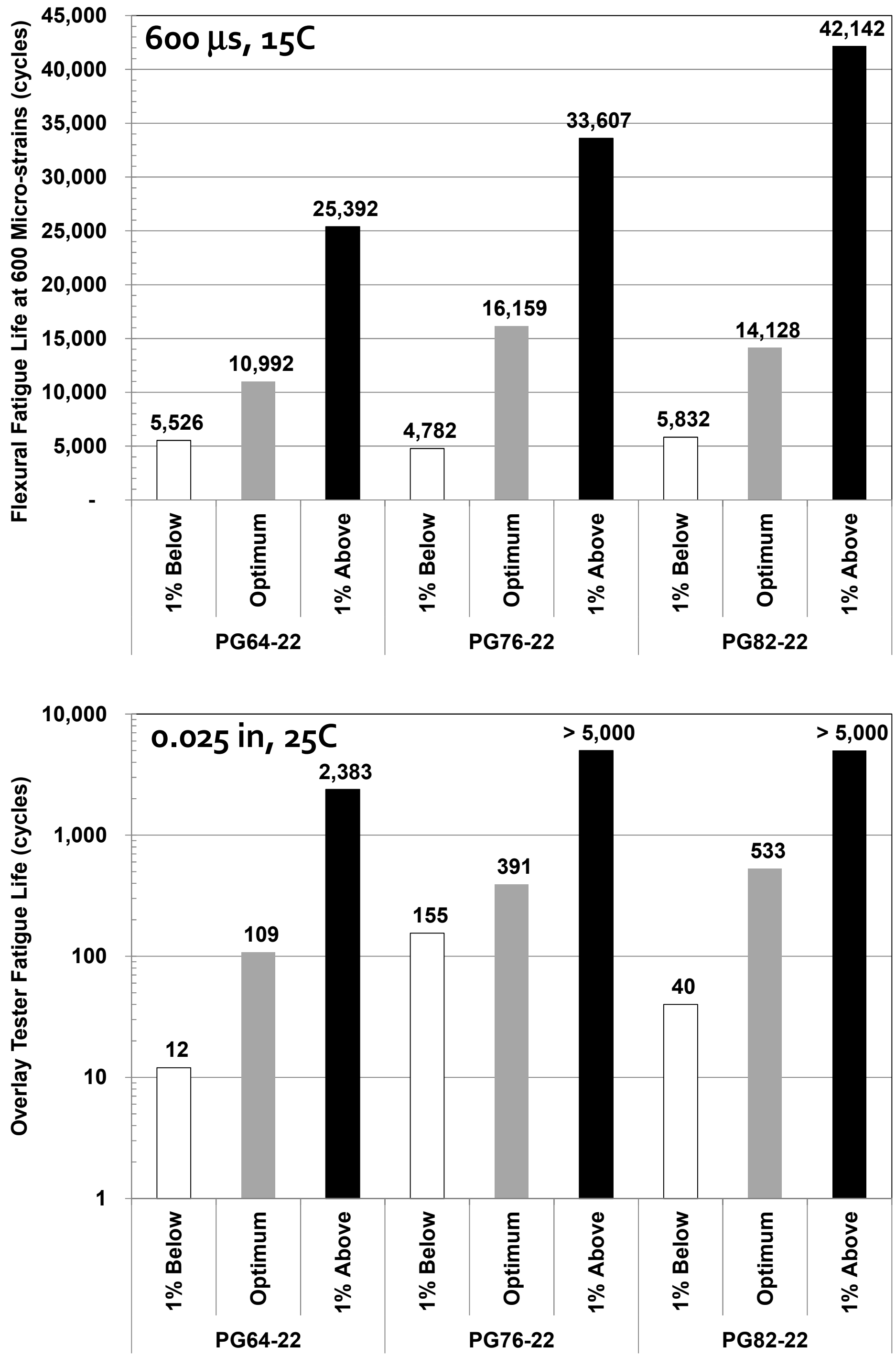


FIGURE 3 Effect of binder modification on lab fatigue performance.

crack propagation test, similar observations were made, although a slight improvement in the polymer-modified mixes was observed at the optimum asphalt content. However, the more significant factor regarding fatigue cracking performance was clearly the effective binder content.

The early research by Bennert et al. (2011) suggests that perhaps current mix design practices are sufficient for unmodified binders, but under-asphalt polymer-modified binders. Work conducted under National Cooperative Highway Research Program (NCHRP) Project 9-9A concluded this to also be true. Prowell and Brown (2007) showed that in their first 4 years of service, unmodified asphalt mixtures densified approximately six times greater magnitudes when compared to modified asphalt mixtures. Under the concept of designing mixtures for 4% air voids to mirror wheel path densities after trafficking, Prowell and Brown (2007) recommended lowering the gyration levels for polymer-modified mixtures (Table 1). Ultimately, when maintaining the identical aggregate properties and gradation, lower design gyrations equate to higher design asphalt contents. Therefore, the question posed is: Have we been designing polymer-modified asphalt mixtures incorrectly?

When laboratory testing is not feasible, one powerful tool that can be utilized to evaluate the impact of asphalt binder source and PG grade on rutting performance is the Resistivity-Rutting model (Christensen and Bonaquist, 2015). Asphalt mixture rutting performance can be modeled and evaluated under varying volumetric, gradation, design and field aging conditions. Work at Rutgers University developed an Excel-based execution of the resistivity–rutting model. Required inputs for the model include:

- Asphalt binder high temperature properties (PG grade or non-recoverable creep compliance),
- Gradation/aggregate surface area,
- Design volumetrics, and

TABLE 1 Suggested Design Gyrations for Polymer-Modified Binders (Prowell and Brown)

20-Year Design Traffic (ESALs)	2-Year Design Traffic (ESALs)	N_{design} for Binder <PG 76-XX	N_{design} for Binder <PG 76-XX or Mixes Placed >100 mm from Surface
<300,000	<300,000	50	NR
300,000–3,000,000	30,000–230,000	65	50
3,000,000–10,000,000	230,000–925,000	80	65
10,000,000–30,000,000	925,000–2,500,000	80	65
>30,000,000	>2,500,000	100	80

- Vehicle speed and long-term pavement performance high temperature at 20 mm below pavement surface.

Using the resistivity model approach, 2021 New Jersey DOT (NJDOT) samples were tested from different suppliers, as well as from the same supplier but different sampling dates (Figure 5). This analysis showed the “same” PG64E-22 can result in a wide array of rutting resistance—not just from supplier to supplier, but also throughout the year from the same supplier.

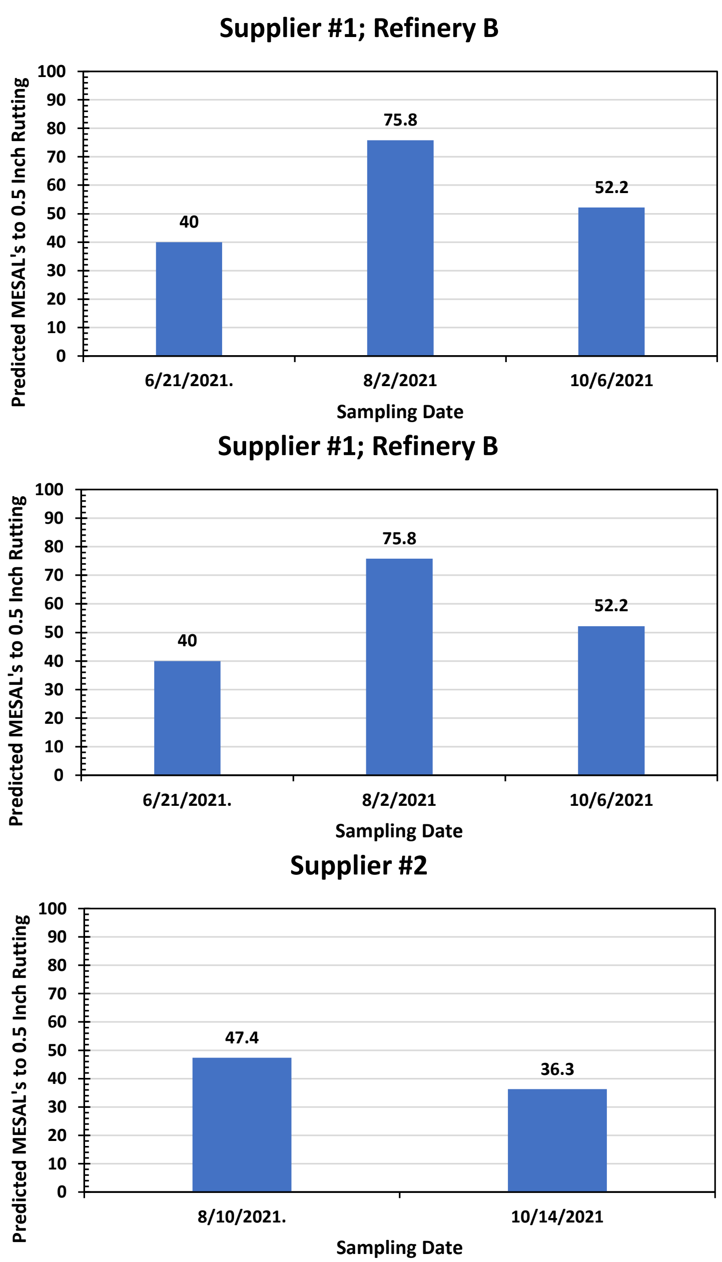


FIGURE 5 Resistivity-rutting model results on retain samples from different dates.

Similar differences were found with an unmodified PG 64S-22, but as shown in Figure 6, not as severe a change in predicted mixture rutting results. The results in Figure 6 also show the improved predicted rutting resistance between unmodified and polymer-modified asphalt binder.

The asphalt binder impact on mixture performance is more difficult as there is no consensus on which asphalt binder property to use, nor is there a current model that can be used for predicting performance. However, work under NCHRP Project 20-44(19) outlines potentially suitable asphalt binder fatigue cracking parameters. These include

- Glover-Rowe Parameter at intermediate temperature (<8,000 kPa),
- *R*-value from Bending Beam Rheometer (BBR) testing (1.5–3.2),

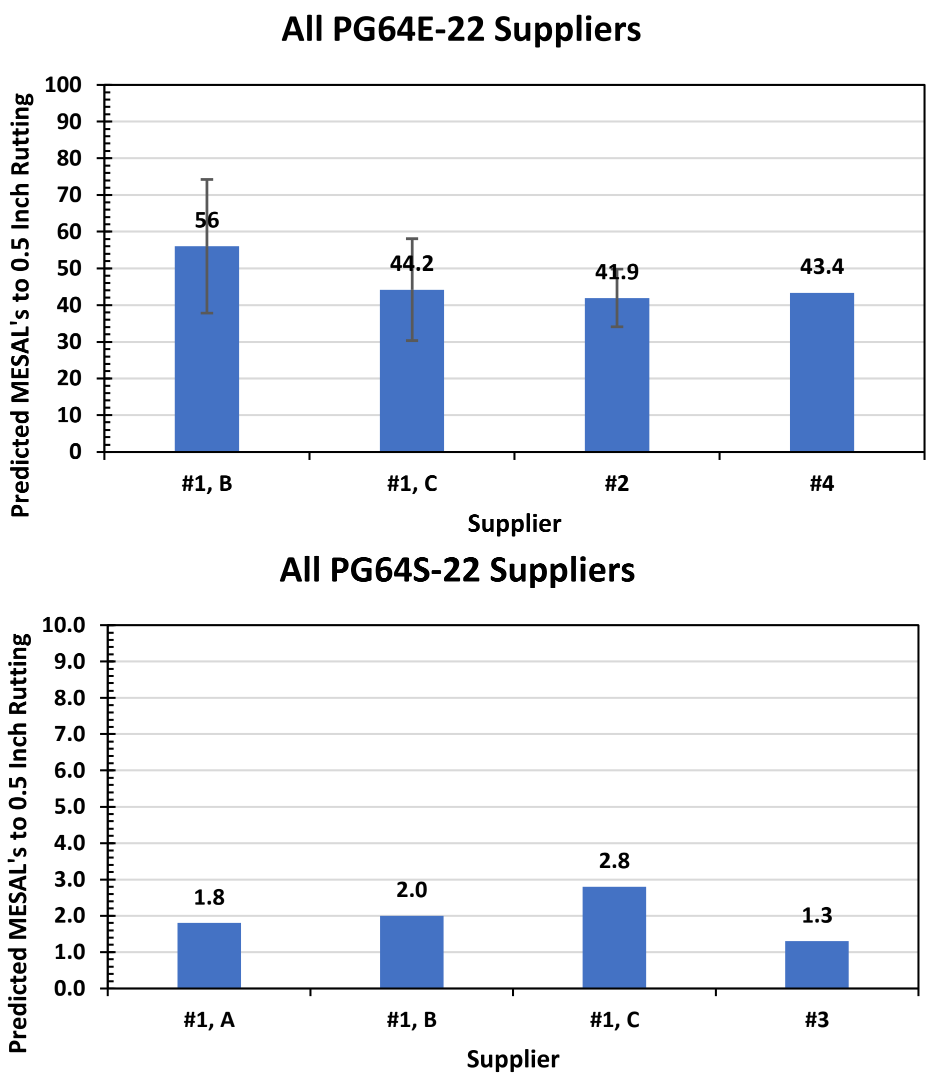


FIGURE 6 Rutting prediction of modified (PG 64 E-22) and unmodified (PG 64S-22) binders.

- DT_c from low temperature BBR testing ($\geq$3.0 degrees), and
- DT_f measured using the asphalt binder cracking device ($\geq$+4.5 degrees).

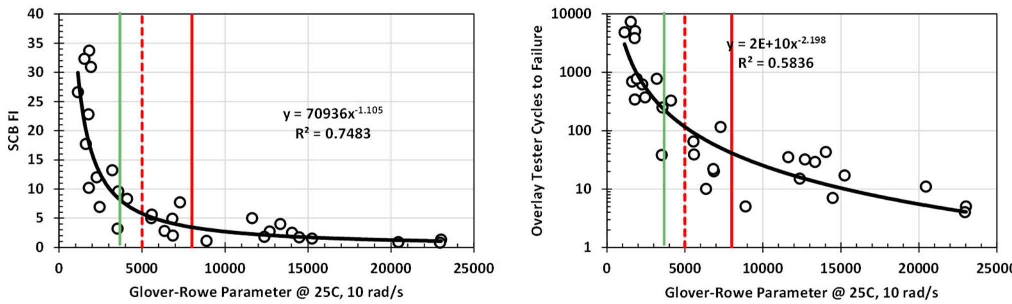
The same set of asphalt binders evaluated earlier for rutting performance were tested and compared using the NCHRP Project 20-44(19) recommended fatigue cracking parameters. The modified and unmodified asphalt binders were subjected to extended laboratory conditioning for 20 and 40 h respectively in the pressure aging vessel. These results shown in Figure 7 once again illustrate asphalt binder performance differences not only from different suppliers, but also the date of production/sampling. In Figure 7, the results in **RED** indicate a failing value for that specific criterion. It is also interesting to see that with the proposed specifications, sometimes an asphalt binder source that may have passed after only conditioning for 20 h in the pressure aging vessel fails after 40 h of conditioning. This indicates that some asphalt binder sources may show reduced levels of aging related distress early in the pavement life but once a critical aging condition occurs, the asphalt binder fatigue cracking performance rapidly declines.

Figure 8 summarizes research data showing asphalt mixture cracking performance with the Overlay Tester cycles to failure and semicircular bend flexibility index for asphalt mixtures with different asphalt binder grades and sources. The research does suggest that strong relationships between these asphalt binder fatigue cracking properties and mixture performance tests, commonly used within BMD specifications, do exist (Bennert et al., 2021).

	20 Hr PAV									40 Hr PAV								
Date	Intermediate Temperature		Low Temperature PG Grading			Asphalt Binder Cracking Device		BBR R-Value		Intermediate Temperature		Low Temperature PG Grading			Asphalt Binder Cracking Device		BBR R-Value	
	PG Grade	GRP @ 25C	BBR (Stiffness)	BBR (m-value)	ΔTc	Tcr	ΔTf	-22C	-28C	PG Grade	GRP @ 25C	BBR (Stiffness)	BBR (m-value)	ΔTc	Tcr	ΔTf	-22C	-28C
6/21/2021	19.6	1952	-27.9	-27.1	-0.8	-33.6	5.7	2.16	1.99		5602	-26.8	-23.6	**-3.2**	-32.4	5.6	2.32	2.05
8/2/2021	19.9	2592	-29.2	-27.1	**-2.1**	-34.7	**5.5**	2.26	2.12		7143	-27.6	-22.8	**-4.8**	-31.2	**3.6**	2.40	2.16
10/6/2021	20.9	4460	-28.0	-25.8	**-2.2**	-33.1	**5.1**	2.31	2.07		**9503**	-26.7	-19.9	**-6.8**	-31.7	5.0	2.46	2.22
7/14/2021	24.2	4005	-26.1	-25.2	-0.9	-32.4	6.3	2.11	1.94		7919	-25.4	-21.9	**-3.5**	-28.6	**3.2**	2.23	2.07
8/16/2021	21.9	3654	-26.6	-24.7	-1.9	-32.3	5.7	2.20	2.04		**8369**	-25.3	-21.5	**-3.8**	-30.8	5.5	2.29	2.05
9/26/2021	20.3	2330	-27.9	-26.6	-1.3	-34.8	6.9	2.26	2.01		6732	-26.6	-22.0	**-4.6**	-31.7	5.1	2.41	2.10
12/10/2021	21.2	4014	-27.4	-24.9	**-2.5**	-33.4	**6.0**	2.30	2.12		**13788**	-25.9	-16.8	**-9.1**	-29.1	**3.2**	2.53	2.23
8/10/2021	21.8	3424	-27.1	-24.3	**-2.8**	-31.7	**4.6**	2.35	2.09		**13606**	-26.1	-18.6	**-7.5**	-31.9	5.8	2.46	2.05
10/14/2021	23.5	3971	-26.7	-26.0	-0.7	-30.3	3.6	2.17	1.93		**12952**	-24.9	-19.4	**-5.5**	-26.1	**1.2**	2.28	2.06
8/24/2021	20.9	3185	-29.5	-27.9	-1.6	-35.8	6.3	2.28	2.09		**8006**	-29.1	-22.7	**-6.4**	-31.6	**2.5**	2.52	2.33

(Note: Rows 1-7 are Supplier 1, Rows 8-9 are Supplier 2, Row 10 is Supplier 3)

FIGURE 7 PG binder test results evaluated using fatigue criteria from NCHRP Project 20-44(19).



GRP @ 25C (kPa)	SCB FI @ 25C	OT Cycles @ 25C
3750	8.0	279
5000	5.8	148
8000	3.5	53

FIGURE 8 Asphalt mixture cracking performance using various binder grades and sources.

This would indicate that if an asphalt mix supplier were to receive the previous asphalt binders during the paving season, the identical asphalt mixture may meet the requirements during one project and may fail at the next.

However, state agencies and asphalt mixture suppliers need to understand that any asphalt binder performance parameter included in a specification is simply for purchasing purposes. Like conventional performance grading, the asphalt binder fatigue cracking parameters provide performance during an idealized condition. Mixture design/production makes a significant impact on overall performance. For example, the effective asphalt content by volume, VBE (i.e., VMA–Air Voids) greatly impacts fatigue cracking performance. The figures in Figure 9 show that as VBE increases, asphalt mixture fatigue performance greatly improves even when using the same asphalt binder. Essentially, an under-asphalted asphalt mixture will always have cracking and durability issues, regardless of the asphalt binder used. Therefore, there is an interrelationship between asphalt binder type and effective binder content by volume that controls fatigue cracking performance.

As the asphalt industry moves towards BMD, a better understanding of how plant production practices could potentially impact asphalt binders and their respective performance. In Figure 10, two different asphalt binder storage tanks are shown to highlight their differences. Due to the geometrical differences, horizontal tanks have greater potential to result in asphalt binder contamination as greater amounts of residual binder remain after use or after draining prior to the addition of the new asphalt binder.

Storage tank contamination is not the only place where this can occur at the asphalt plant. In Figure 11, an example of how residual asphalt binder can remain in the asphalt lines leading

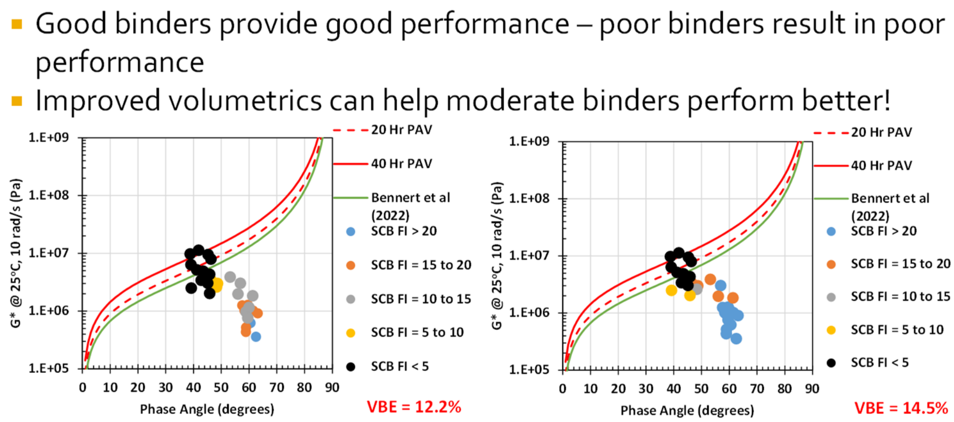


FIGURE 9 Effect of binder volume on mixture cracking performance.

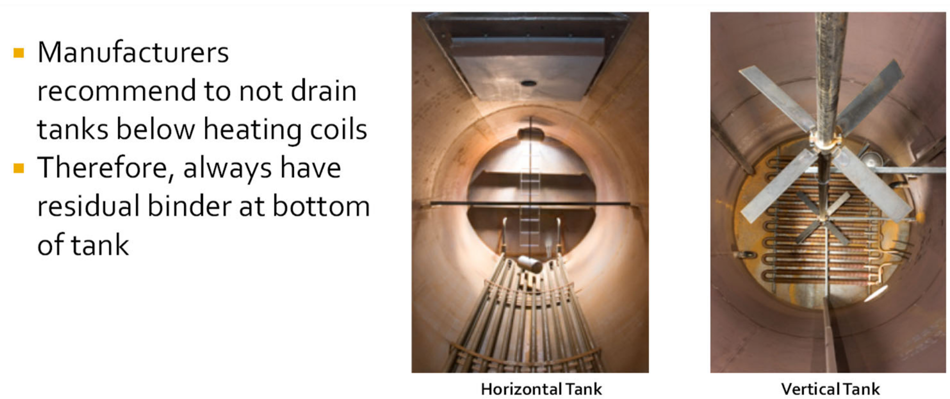


FIGURE 10 Potential effect of binder tank configuration on binder quality.

FIGURE 11 Potential effect of binder residual line fill on binder quality.

from the storage tank to the mixing vessel (i.e., drum or pug mill). In most cases, the lines would need to be completely drained or purged before full production takes place to avoid potential asphalt binder contamination issues.

Within a BMD framework, small levels of contamination can significantly impact performance. Figure 12 shows examples of NJDOT's Bridge Deck Waterproof Surface Course, BDWSC (figure on top) and NJDOT's Bituminous Rich Intermediate Course, BRIC (figure on bottom). The laboratory evaluation shows that when an unmodified PG 64-22 was blended with polymer-modified asphalt binders used specifically for those asphalt mixture types, approximately 20% contamination of the asphalt binder is all it took to cause the well performing asphalt mixtures to fail the rutting and fatigue cracking requirements.

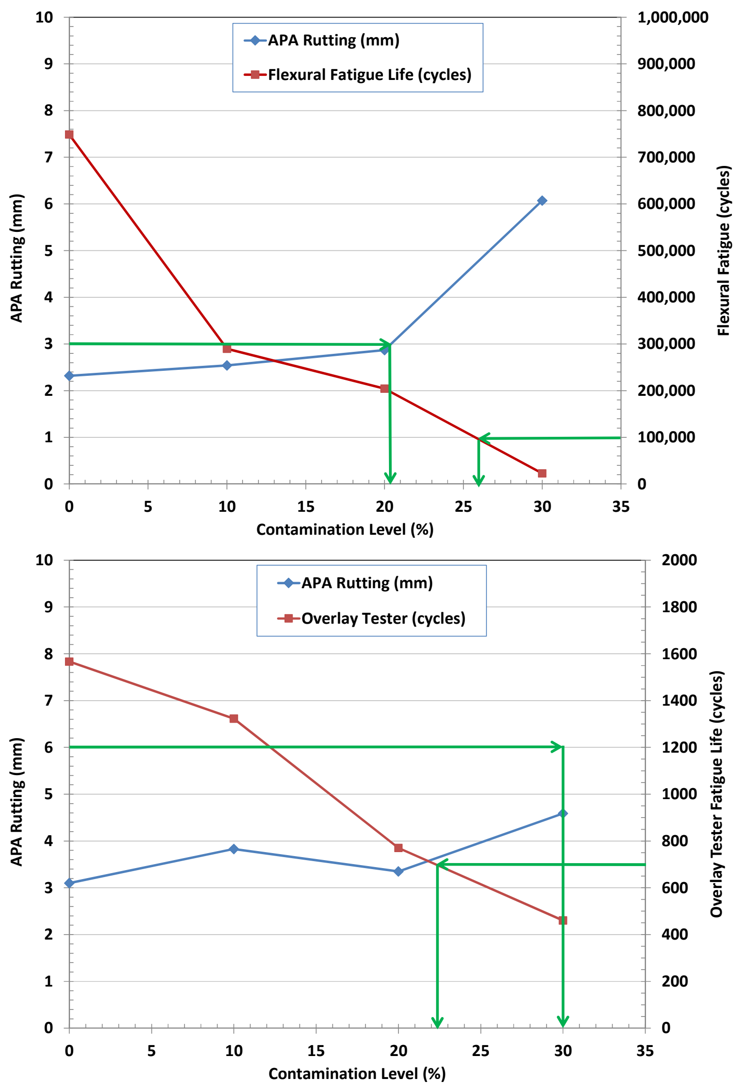
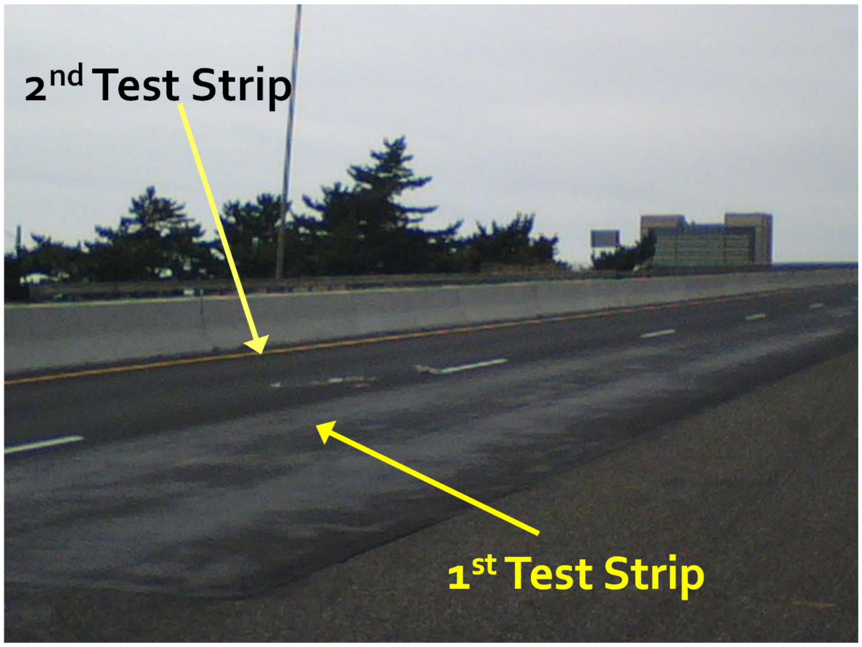


FIGURE 12 Effect of asphalt binder contamination on rutting and cracking performance.

Mechanical errors may also occur. In Figure 13, a simple lever not being switched from one binder tank to the other caused the test strip of a NJDOT BDWSC to result in significant failures. The example in Figure 13 provides strong evidence why the NJDOT requires any BMD asphalt mixtures to be tested during the test strip to ensure asphalt plants can properly produce the asphalt mixture through the plant.



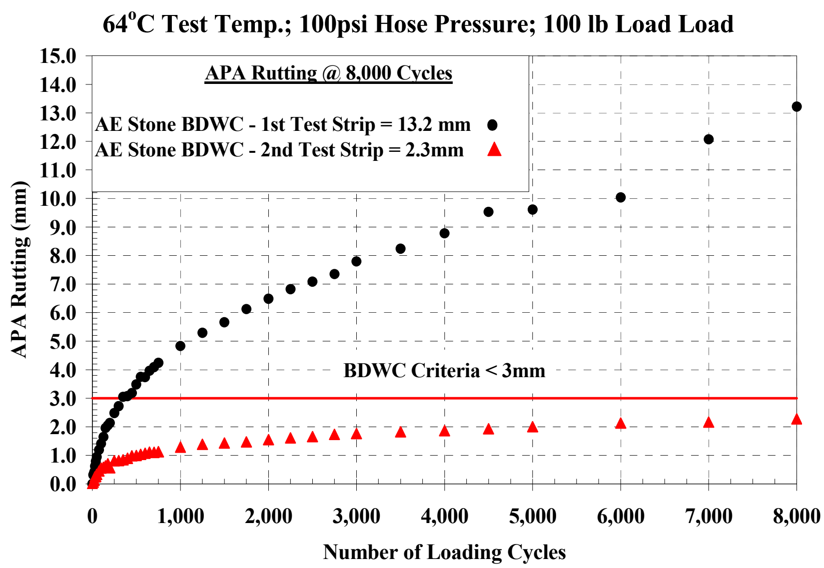


FIGURE 13 Effect on rutting performance of the wrong binder being used.

To develop a BMD protocol, the Massachusetts Department of Transportation (MassDOT) conducted a study to determine if a BMD can become unbalanced when the source of the specified asphalt binder is changed between mixture design and production, or during production (Mogawer et al., 2019). In the study, MassDOT's commonly specified PG 64–28 was obtained from two different sources. The two sources were designated Source A and Source B. Although the two binders had the same PG, the sources had significantly different relaxation properties as measured by ΔT_c. ΔT_c is a parameter that is used to measure a binder's loss of relaxation due to aging. Loss of relaxation can increase the risk of non-load associated cracking. A minimum ΔT_c of –5.0°C has been suggested as a preliminary criterion. Therefore, binders with a ΔT_c of –5.0°C or more negative are unacceptable because they may be susceptible to non-load associated cracking. Figure 14 shows that binder Source A passed this preliminary criterion while the binder Source B failed. These binder sources were utilized in the study to assess whether the poor relaxation properties of binder Source B would affect cracking performance of the mixture such that the BMD would become unbalanced. Mixtures were fabricated using both binder sources, and cracking performance tests were conducted using the Indirect Tensile Asphalt Cracking Test (IDEAL-CT). Cracking test results indicated that the mixture fabricated with binder Source A, which passed the minimum ΔT_c, provided higher or better, CT_{Index} values. Mixture fabricated with the binder Source B, which failed the minimum ΔT_c, provided lower or worse CT_{Index} values. Thus, it was concluded that binder source might lead to a BMD becoming unbalanced during production in terms of cracking.

In the MassDOT study (Mogawer et al., 2019), a statistical analysis was conducted on mixture cracking test results obtained from the Illinois Flexibility Index Test (I-FIT) to determine the effect of aggregate gradation, binder content, binder source, and the interaction of these three parameters on the measured flexibility index (FI) and fracture energy (FE). As shown in Figure 15, the statistical analysis illustrated that FI and FE did not agree with each other as

Binder Source	Continuous Grade	PG Grade	Delta T_c (ΔT_c)
A	66.2-28.4	PG64-28	+2.3°C
B	65.6-27.7	PG64-28 (Borderline)	-6.0°C

A minimum ΔT_c of -5.0°C has been suggested as a preliminary criterion, therefore binders with a ΔT_c of -5.0°C or more negative are considered unacceptable.

FIGURE 14 Binder relaxation properties derived from MassDOT study.

Dependent Variable: FI	
Source	P-Value
Gradation	0.030
Binder Content	0.000
Binder Source	0.897
Gradation*Binder Content	0.820
Gradation*Binder Source	0.000
Binder Content*Binder Source	0.163
Gradation*Binder Content* Binder Source	0.678

Dependent Variable: FE	
Source	P-Value
Gradation	0.000
Binder Content	0.270
Binder Source	0.000
Gradation*Binder Content	0.168
Gradation*Binder Source	0.774
Binder Content*Binder Source	0.836
Gradation*Binder Content* Binder Source	0.935

FIGURE 15 Effect of gradation, binder source, binder content and interactions on I-FIT on FE and FI.

aggregate gradation had a significant effect on FI and FE, but binder content had no effect on FE and binder source had no effect on FI. The interaction between gradation and binder source revealed that the effect of gradation on FI had some dependence on binder source. Binder source had a significant effect on FE with binder Source A providing the higher, or better, FE. This agreed with binder testing results which indicated binder Source A had the higher, or better, ΔT_c binder relaxation property.

In the MassDOT study (Mogawer et al., 2019), further statistical analysis was conducted to determine which variable and interaction among variables had a significant effect on the mixture cracking performance test results. The performance tests performed were the I-FIT, Indirect Tensile Asphalt Cracking Test (IDEAL-CT), and mixture BBR tests. As demonstrated in Figure 16, the specific variable, or interaction among variables, which had a significant effect (SIG) on the cracking test results depended on the mixture performance test. The statistical analysis showed that the measures of cracking performance utilized did not provide the same conclusions.

In conclusion, the research presented shows that the performance of the asphalt binder can play a significant role in the rutting and cracking properties of the asphalt mixture. The data also illustrates that asphalt binder and mixture performance can vary significantly from liquid supplier to liquid supplier, as well as within different production dates of the same liquid supplier, even when the same PG is selected and used. It is important for the different stakeholders (i.e., asphalt liquid supplier, asphalt mixture supplier, and agency) to understand that differences exist and how impactful they can be on the final asphalt mixture performance, especially if BMD requirements must be met for design, construction and acceptance.

Variable	IFIT FI	IFIT FE	IDEAL-CT	Mixture BBR m-value	Mixture BBR Stiffness
Gradation	SIG	SIG	-	-	SIG
Binder Content	SIG	-	SIG	-	-
Binder Source	-	SIG	SIG	-	SIG
Gradation*Binder Content	-	-	SIG	-	SIG
Gradation*Binder Source	SIG	-	-	-	-
Binder Content*Binder Source	-	-	-	-	-
Gradation*Binder Content*Binder Source	-	-	-	-	-

FIGURE 16 Effect of gradation, binder source, binder contant and interactions on FE, FI, IDEAL-CT, and BBR S and m.

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Relationships Between Binder Properties and Mix Properties

Results Based on French Experience

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INTRODUCTION

Most characteristics of asphalt materials (mechanical performance, deterioration mechanisms) depend largely on binder characteristics. Despite this, the French mix design approach is based mainly on mix performance tests, and binder specifications are limited to very simple characteristics like penetrability, softening point and viscosity. When mix performance is satisfactory, this approach can be sufficient, but if mix characteristics are not attained, it can be difficult to determine the origin of the problem, and if it is caused by binder properties. The quality of bitumen is increasingly addressed by users through its flow properties at different temperatures, its chemical composition, its resistance to traffic and the effects of aging and climatic variations on life duration. Therefore, increasing efforts are made in France (at least at the research level) to try to improve binder characterization and understand better the links between binder and mix properties.

FRENCH MIX DESIGN METHODOLOGY

In France, a performance-based methodology for the design of asphalt mixes has been used since the years 1980 (Moutier F., 1993, Delorme et. al, 2007,). This methodology is summarized in Figure 1 and includes the following steps:

1. Selection of aggregates and binder—definition of grading and binder content: The French specifications include different types of mixes, used for surface layers and structural layers. For each type of mix, the first step consists in defining the components (aggregates; binder). Depending on the type of mix, and level of traffic, the specifications define: aggregate characteristics, grading, binder grade and minimum binder content.

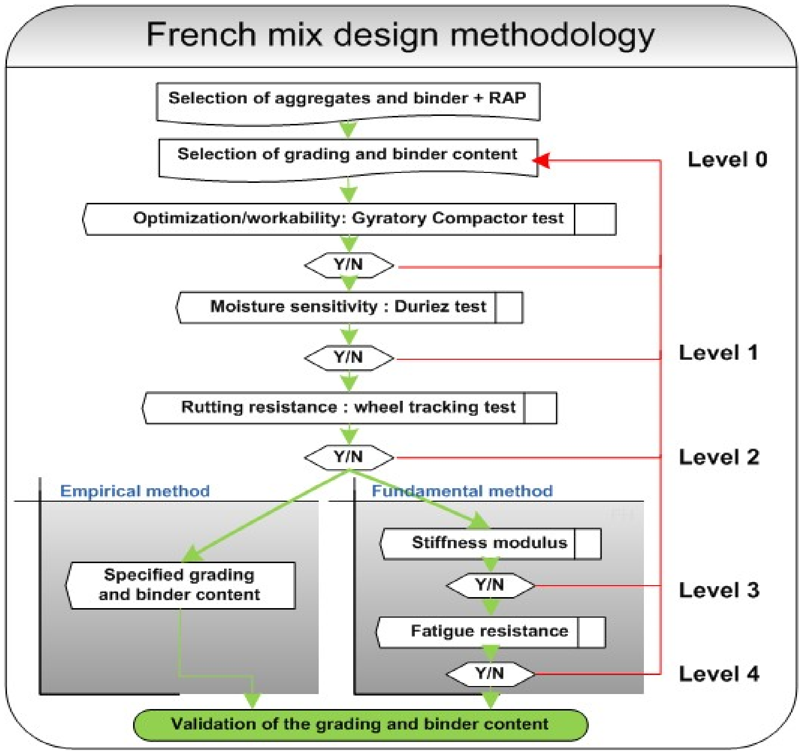


FIGURE 1 Summary of the French mix design methodology.

2. Determination of compaction ability (EN 12697-31) and moisture sensitivity (EN 12697-12): Compaction ability is determined by the gyratory compaction test. The mix must reach a specified void content after a specified number of gyrations, depending on material type and layer thickness. Moisture sensitivity is determined by the Duriez test, based on the comparison of resistance in direct compression before and after immersion in water.
3. Determination of resistance to permanent deformation (EN 12697-22): The resistance to permanent deformation is determined by the large device wheel tracking test, which consists in submitting a slab of material to wheel loading, at a temperature of 60°C.
4. Determination of stiffness (EN 12697-26): Stiffness can be determined either by a complex modulus test (sinusoidal loading, at different frequencies and temperatures), or a uniaxial tensile test (at different loading speeds and temperatures).
5. Determination of fatigue resistance (EN 12697-24): Fatigue resistance is determined by two-point bending fatigue tests on trapezoidal specimens, performed at 10°C and 25 Hz, in strain-controlled mode.

Steps 1, 2, and 3 apply to all materials. Steps 4 (stiffness) and 5 (fatigue) apply only for mixes used for structural layers.

The objective is to obtain a low void content or maximum compaction with less than 6 % of bitumen content and crushed aggregates. This task requires optimizing mix grading and binder content. For a defined layer thickness, the Gyratory Shear Compactor is used to evaluate the energy needed of compaction to reduce the voids content to a defined minimum. This optimization is generally made using four grading fractions. This minimum void content must be low but not fall below a minimum threshold to obtain good mechanical characteristics (rutting resistance, stiffness modulus, fatigue life), for a binder content greater than 4% (Moutier, 1993).

FRENCH SPECIFICATIONS FOR BINDERS AND MIXES

Binder Specifications

Binder specifications used in France, summarized in Table 1, are based on European specifications (standard EN 12591). They are limited, and based mainly on penetration, softening point and minimum viscosity. An equivalent of US PG grades does not exist. Mix design is based essentially on mix properties. It should be noted, though, that France has a mild climate, with much lower climatic variations than the US, as shown on Figure 2, which presents the PG high and low temperatures for France. Therefore, assessing extreme temperature performance of binders is not as critical.

In France, typical bitumen grades used for bituminous mixes are 35/50 and 50/70. Harder bitumens (20/30) are also used, for high modulus mixes. The aged bitumen from RAP has a lower penetration and is more viscous than when first mixed. This reclaimed bitumen is generally balanced by the addition of fresh binder that is softer than those typically used to produce hot mixes.

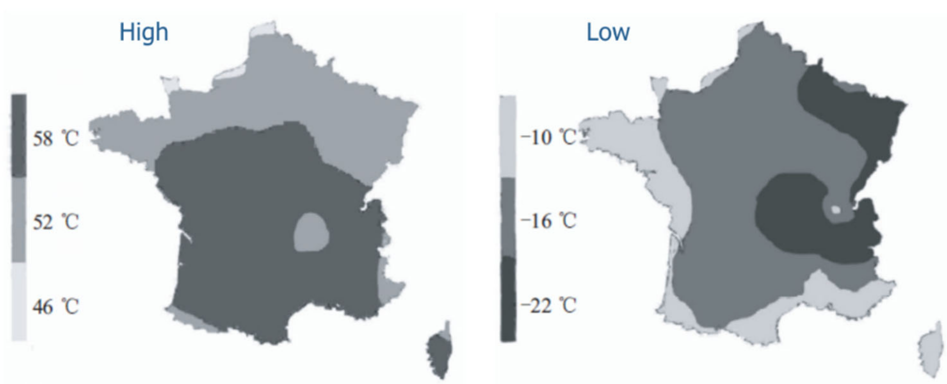


FIGURE 2 PG pavement temperatures for France.

TABLE 1 European Specifications for Paving Grade Bitumen

Type of Binder			**Paving Grade Bitumen According EN12591**					
			20/30	30/45	35/50	50/70	70/100	160/220
Requirement/Characteristic	**Test Method**	**Unit**	**Range of Values**					
Penetration at 25°C	EN 1426	X 0.1 mm	20–30	30–45	35–50	50–70	70–100	160–220
Softening point	EN 1427	°C	55–63	52–60	50–58	46–54	43–51	35–43
Mass change at 163°C	EN 12607-1	%	≤0.5	≤0.5	≤0.5	≤0.5	≤0.8	≤1.0
Retained penetration	EN 1426	%	≥55	≥53	≥53	≥50	≥46	≥37
Increasing softening point	EN 1427	°C	≤8	≤8	≤8	≤9	≤9	≤11
Flash point	EN ISO 2592	°C	≥240	≥240	≥240	≥230	≥230	≥220
Fraass breaking point	EN 12592	°C	≤–5	≤–5	≤–5	≤–8	≤–10	≤–15
Solubility	EN 12592	% (m/m)	≥99	≥99	≥99	≥99	≥99	≥99
Dynamic viscosity at 60°C	EN 12596	Pa-s	≥440	≥260	≥225	≥145	≥90	≥30
Kinematic viscosity at 163°C	EN 12595	Mm²/s	≥530	≥400	≥370	≥295	≥230	≥135

Mix Specifications

Table 2 presents an example of performance specifications used in France for a very common mix, semi-coarse bituminous concrete (BBSG), used both for surface and binder courses. Specifications concern composition (aggregate characteristics, aggregate grading, binder content void content), and mix performance (gyratory compaction, wheel tracking, moisture sensitivity, modulus, fatigue).

INFLUENCE OF BINDER PROPERTIES ON MIX PERFORMANCE

Binder characteristics influence mix properties at all stages of use, from mixing and compaction to short-term performance (modulus), and long-term performance (aging, fatigue resistance). This note focuses on several main mechanical properties: modulus, fatigue, rutting and low temperature cracking. Clearly, the aging phenomenon affects mix properties and is also important for understanding the relationship between binder properties and mix performance.

INFLUENCE ON COMPLEX MODULUS

Bituminous mixes consist of a relatively dense assembly of aggregates and binder which gives the mix cohesion and impermeability. Their mechanical characteristics depend on the components used, and on the manufacturing conditions. Despite its small quantity in the mixture (around 5% in mass), the binder confers its viscoelastic behavior to the mixture [Franken L., Vanelstraete A. (1995)]. Adhesion between aggregates and binder strongly influences the mechanical properties. Other parameters such as aggregate size and grading, filler size distribution, bitumen properties, and void content have a significant influence.

TABLE 2 Example of Mix Specifications for a Bituminous Concrete

French designation	BBSG 1 0/10
Binder characteristics	Type (*for modified binder*) and PG Minimum content 3%
Void content	5% to 10% (after 60 gyrations)
Moisture sensitivity (ITSR)	>70%
Resistance to rutting	< 10% after 30,000 cycles at 60°C
Stiffness modulus	>5,500 MPa at 15°C, 10Hz
Fatigue failure strain	>100 µ strain at 10°C, 25Hz

Figure 3 illustrates the influence of binder properties on complex modulus of the same type of asphalt concrete (same aggregates and binder content). The choice of the binder (low pen grade, polymer-modified) modifies the variation of the complex modulus with frequency / temperature. Complex modulus can thus be optimized for different applications: low PG for high modulus mixes, modified binders for surface courses to improve performance over a large temperature range, etc.

Multi-scale modeling represents an efficient tool to understand and predict the influence of binder properties on mix complex modulus. Three scales need to be considered (Figure 4): the mastic (bitumen matrix embedding filler); the mortar (mastic matrix embedding sand grains); the mix, made of three phases (coarse aggregates coated with thin bituminous mastic, mortar phase and air voids). Aggregates are represented as spheres coated with a bituminous mastic layer, which thickness is given by a power law. Grain to grain contact also needs to be considered in the model especially to describe the behavior at high temperature or low frequency.

Figure 5 illustrates the use of a multi-scale model for the prediction of mix linear visco-elastic modulus. (Some et al., 2022). The proposed model combines a Mori–Tanaka scheme at mastic and mortar scale and generalized self-consistent scheme at the mixture scale. The necessary input data are:

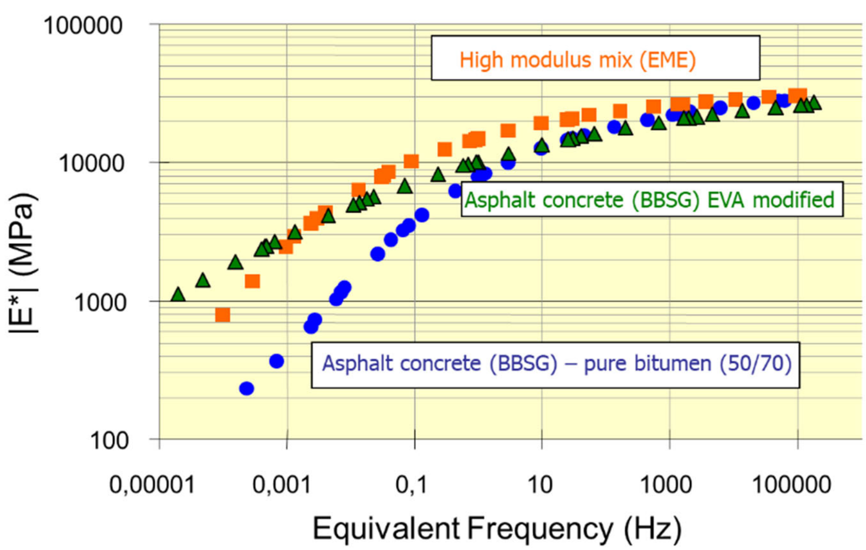


FIGURE 3 Examples of mix master curves for the same grading and different binders.

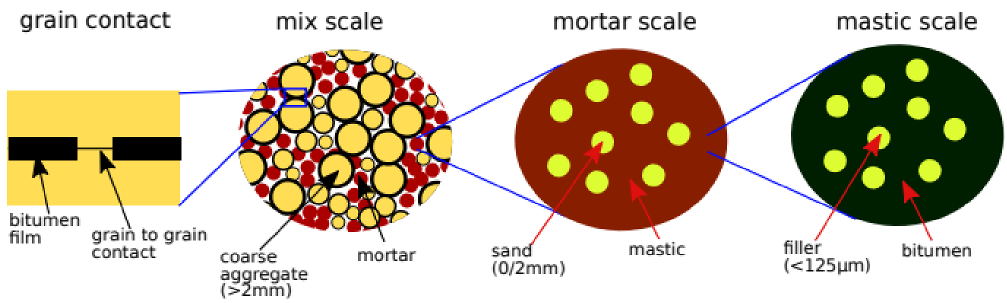


FIGURE 4 Determination of the complex modulus of a bituminous mix by multi-scale modeling (C. Some, 2022).

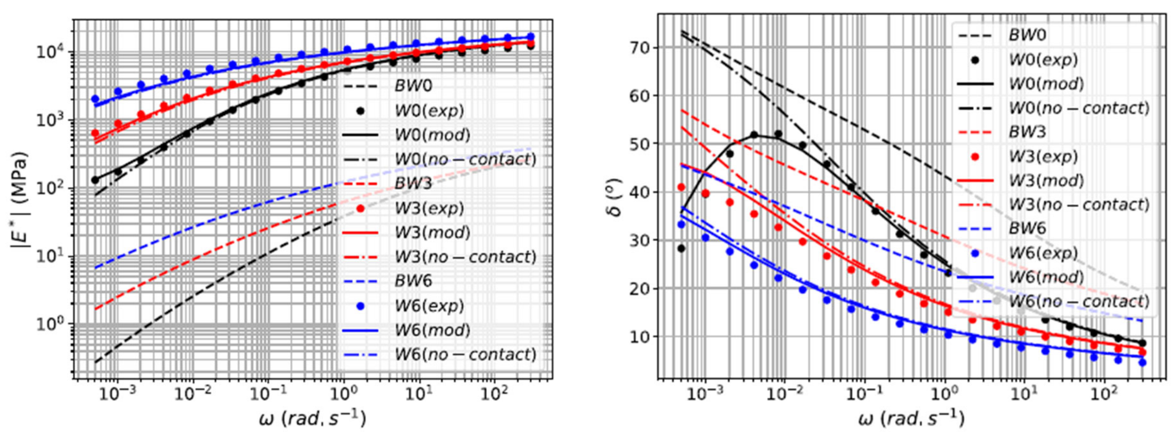


FIGURE 5 Comparison between multi-scale model without grain–grain contact (no-contact), with grain–grain contact (mod) and the experiments (exp) modeled with 2S2P1D model for WMA with different oxidative aging duration 0, 3, 6 days (W0, W3, W6) and corresponding aged bitumen (BW0, BW3, BW6) (Some et al. 2022).

- The linear viscoelastic properties of the bitumen (and then mastic and mortar) and the volume fraction of each constituent relative to the mixture total volume.
- The elastic modulus, Poisson's ratio and density of the aggregates, sands and fines, and the bitumen bulk modulus and density.

The multi-scale model predicts the $l.v.e.$ properties of mixes and mortars even at temperatures higher than 30°C.

INFLUENCE ON RESISTANCE TO RUTTING

In France, resistance to rutting is determined using the large-scale wheel tracking test (Standard NF EN 12697-22). The test consists in submitting a slab of asphalt material to wheel loading, with a contact pressure like that of real truck tires, at a loading frequency of 1 Hz and a temperature of 60°C, and the evolution of the rut depth with the number of loads is recorded.

Figure 6 illustrates the influence of different binders (standard 50/70 grade, 10/20 grade, multigrade and polymer-modified bitumen) on resistance to rutting, with the same aggregates. Low-grade bitumen (10/20) and multiphalte 60/80 lead to the best performance (Corté et al., 1997). Figure 7 presents, in comparison, rutting obtained with the same mixes in a full scale accelerated pavement test (APT). A good agreement between laboratory performance and APT results is obtained, thus confirming the good representativeness of the laboratory wheel tracking test.

The deformation (or rutting) of bituminous mixes depends on the interaction of a large number of parameters such as volumetric composition and constituent's properties, e.g., aggregate size/shape, nature and flow behavior of the bitumen. In particular, the rheology of the binder at high temperature has a large influence. Relevant binder properties to characterize resistance to rutting are low shear viscosity, zero shear viscosity (ZSV) and/or non-recoverable creep compliance (J_{nr}), determined from multiple stress creep recovery tests (MSCRT) following the standard EN 16659 or AASHTO procedure (TP 70).

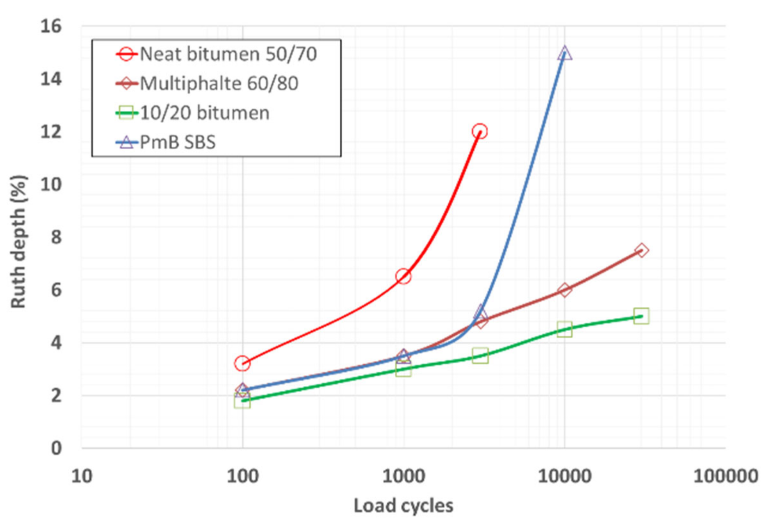


FIGURE 6 Influence of different binders on resistance to rutting, with the same aggregates.

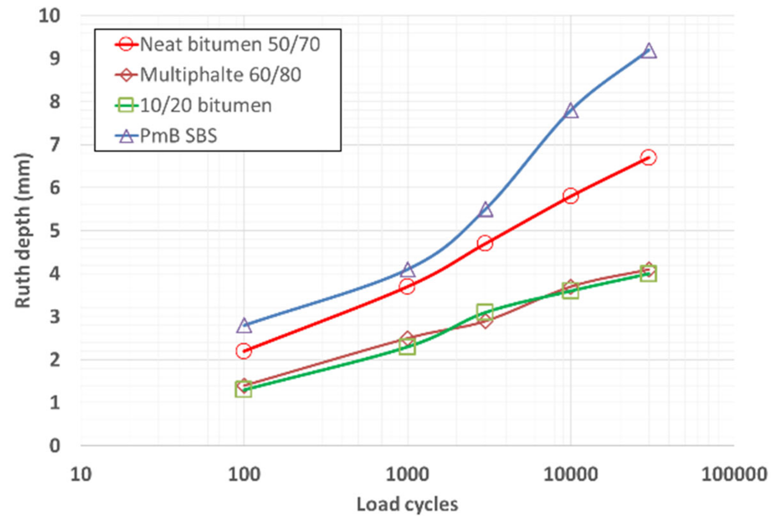


FIGURE 7 Influence of binder characteristics: (*a*) on lab rutting resistance and (*b*) on field rutting resistance (APT experiment) (Corté et al. 1997).

Robertus and al. (2012) performed an extensive study to compare the rutting rate obtained in wheel tracking tests with stiffness modulus G*, ZSV and J_{nr} values, determined at 45°C and 60°C, for a range of neat and modified binders. The study indicated:

- Poor correlation, when considering all binders, between wheel tracking rate and ZSV.
- A good correlation between G* and rutting rate (R^2 = 0.94) for unmodified (rheological simple) binders. However, this correlation is not valid for most polymer-modified binders.
- A good correlation, for all binders, between rutting rate (at 45°C and 60°C) and J_{nr} at 60° (see Figure 8).

Further studies confirmed a good correlation between rutting resistance and J_{nr} parameter for fresh and short-term aged binders. In conclusion, J_{nr} appears as a suitable rheological parameter to assess the contribution of the binder to rutting of bituminous mixes.

INFLUENCE ON FATIGUE PROPERTIES

Fatigue properties are determined using two-point bending fatigue tests (Standard NF EN 12697-24). The tests are performed at 10°C and 25 Hz, in strain-controlled mode. Three different strain levels are applied, and a fatigue law of the following form is determined:

$$\varepsilon = \varepsilon_6(10°C, 25Hz)(\frac{NE}{10^6})^b$$

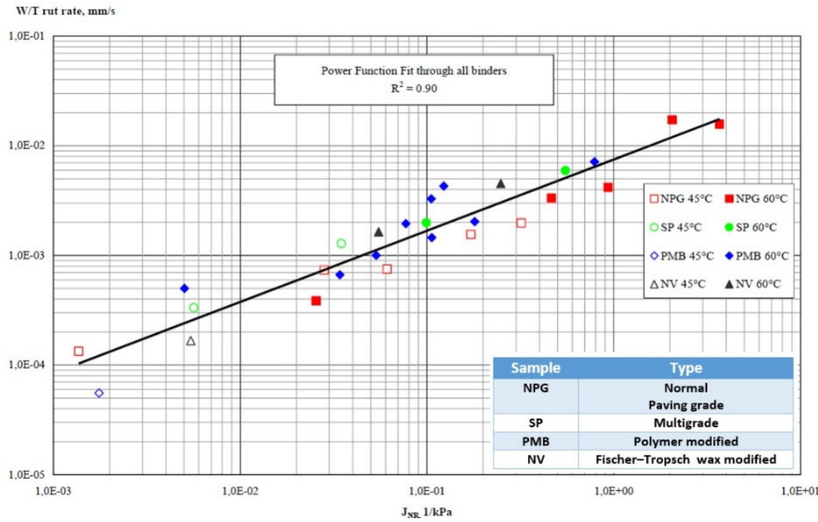


FIGURE 8 Wheel tracking rut rate against J_{nr} of fresh bitumen at 60°C (Robertus et al. 2012).

Where ε is the strain leading to failure, *NE* the number of applied loads, and ε_6 and *b* the parameters of the fatigue law.

Fatigue resistance is a complex property largely influenced by mix design (grading, binder content and voids content), binder properties, and loading conditions (controlled stress or controlled strain). Additionally, correspondence between lab and field fatigue performance is not straightforward, due to the influence of other factors (rest periods between loads, climatic variations, aging).

Mix design studies indicate that there is no direct relationship between binder complex modulus and mix fatigue. Links between fatigue behavior of binders and mixes were largely investigated.

Shen et al. (2006) performed fatigue tests on binders and mastic with Dynamic Shear Rheometer (DSR) and fatigue tests on mix with 4 points bending beam. They concluded that the slope of the fatigue damage curve of the mix depends mainly on the properties of the binder and its energy dissipation characteristics.

Chailleux et al. (2009) performed fatigue tests on binders using two different loading modes (tension compression and torsion), with a Metravib rheometer. For the same mix, and different binders, a good correlation was obtained between the fatigue parameters ε_6 (strain leading to failure for 1 million load cycles) of the binders and of the corresponding mixes (Figure 9). Chailleux et al. (2009) also investigated the relationship between binder fatigue performance and chemical composition. They proposed a correlation between fatigue failure strain ε_6 and

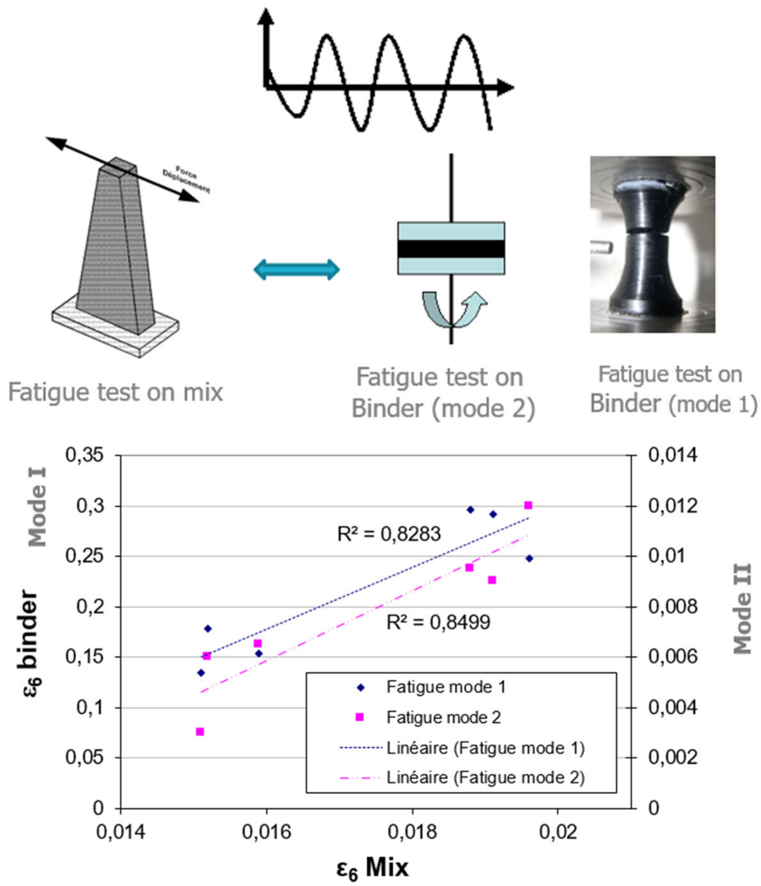


FIGURE 9 Relationship between fatigue resistance of binders and of corresponding mixes, for two different loading modes.

composition in percentage of bitumen [crystallisable fractions (**CF**), asphaltenes (**A**) and asphaltene aggregates (**AA**)] (Figure 10).

INFLUENCE ON LOW TEMPERATURE CRACKING

The Thermal Stress Restrained Specimen test (TSRST, Standard NF EN 12697-46) is largely used in France to characterize low temperature cracking of asphalt mixes (Figure 11). This test consists in submitting a cylindrical asphalt mix specimen, restrained in displacement, to a decreasing temperature, and measuring the generated tensile stress until failure. The test allows to determine a vertical stress szz versus temperature curve, and a failure stress ε_f associated with a failure temperature T_f.

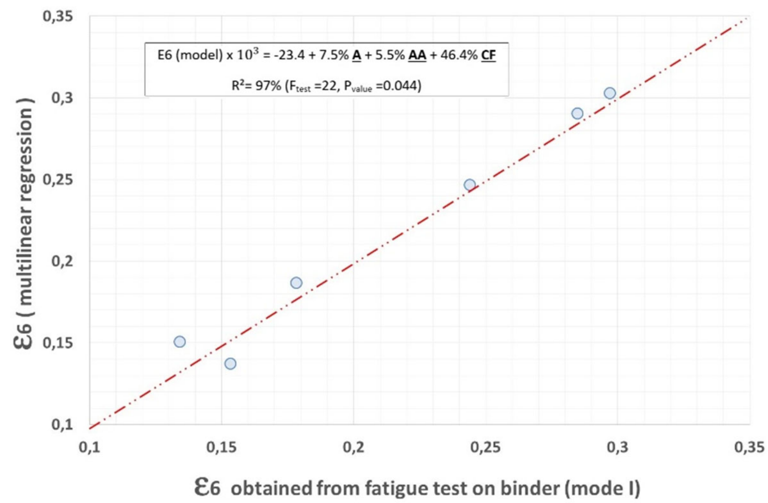


FIGURE10 Relationship between binder fatigue resistance and chemical composition.

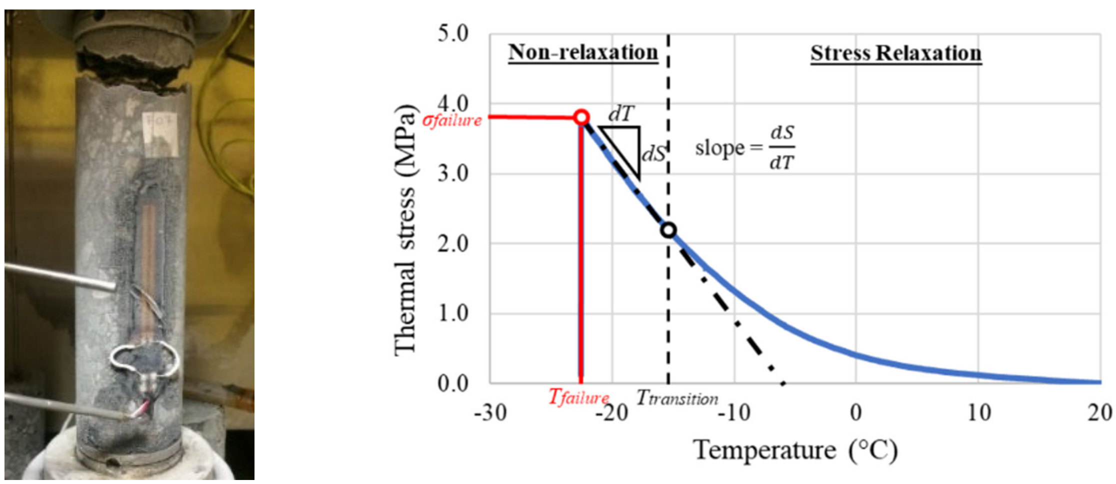
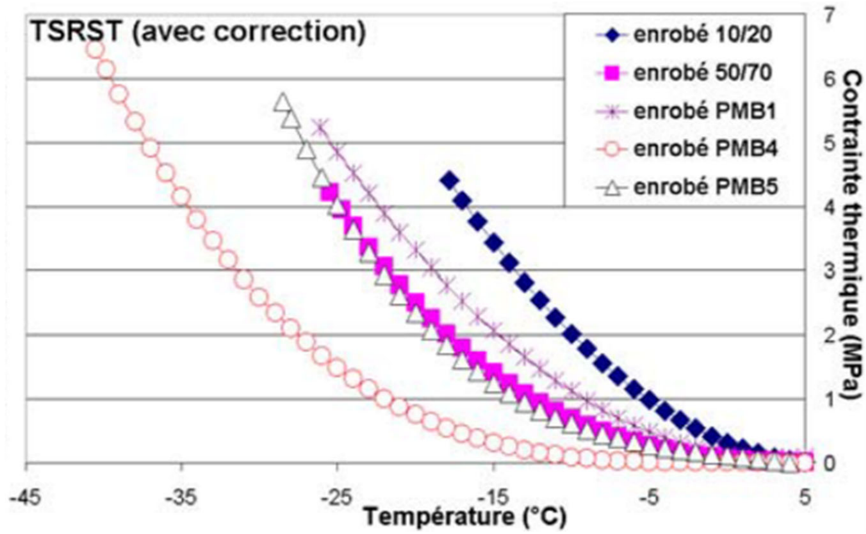


FIGURE 11 TSRST test specimen and evolution of thermal vertical stress (szz) when temperature decreases.

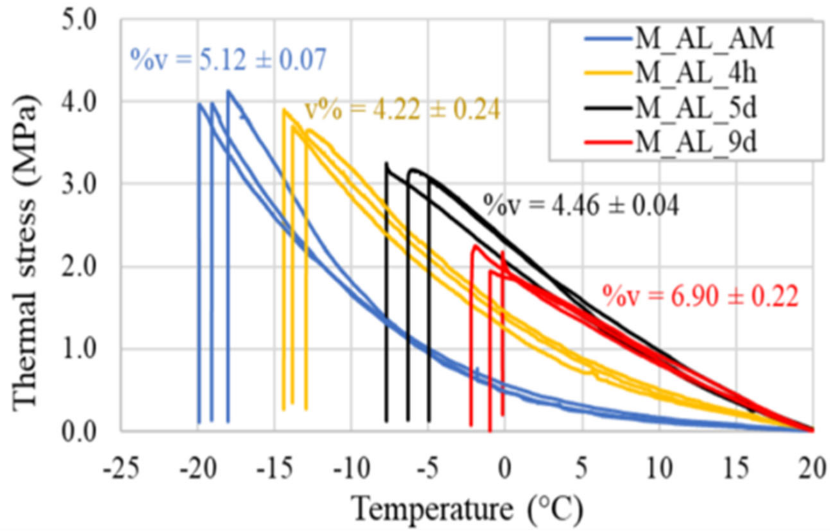
Binder characteristics influence largely TSRST results, as illustrated in the examples of Figure 12, which show the influence on low temperature cracking of (1) different binders modified by polymers (Olard et al. 2005) and (2) binders with different levels of aging (Siroma, 2022).

Low temperature binder performance can also be characterized by the DT_c criterion based on the BBR test (standard EN 14771). DT_c is applicable to pure binders but less relevant for modified binders. In France, feedback from site observations led to define a critical value for DT_c = –5°C.

However, the BBR does not measure failure characteristics. To evaluate more directly low temperature cracking resistance, a fracture toughness test (FTT) for binders (CEN/TS 15963) has been developed in Europe. It is a 3-point bending test on notched specimen, under monotonic



(a)

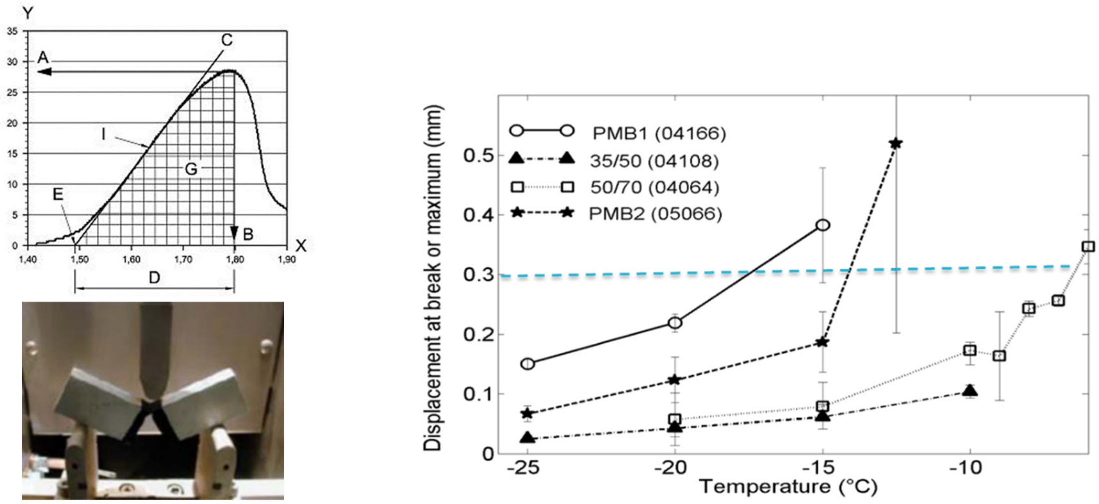


(b)

FIGURE 12 Comparison between different mixes with TSRST Tests: (*a*) contribution of modified binders and (*b*) effect of binder aging time (0 h, 4 h, 5 days, 9 days of aging following International Union of Laboratories and Experts in Construction Materials, Systems and Structures procedure).

loading at a speed of 0.01 mm/s (Figure 13). The test is used to determine a critical cracking temperature, defined as the temperature at which the displacement at failure is 0.3 mm.

Some results from an international round robin test carried out between eight different laboratories have shown that this FTT is a promising tool for characterizing the low temperature behavior of bituminous binders (Chailleux, 2012)



(a) (b)

FIGURE 13 (*a*) Load-displacement curve from binder FTT and calculated displacement D at failure, and view of failed specimen at the end of the test and (*b*) comparison of critical temperatures of different binders.

CONCLUSIONS

The present French mix design methodology is based solely on mix performance tests. This approach does not always allow us to reach the desired performance, due to problems of binder quality. Clearly, a better selection of the binder, based on relevant binder tests, could facilitate mix design and help improve mix performance.

Binder tests to perform depend on the targeted mix properties. According to French experience, the following recommendations can be made:

- Mix stiffness can be predicted based on binder complex modulus and mix composition. Multi-scale modeling represents an efficient theoretical prediction method.
- Non-recoverable creep compliance J_{nr}, determined from MSCRT can be recommended for binder characterization relative to resistance to rutting, for both neat and modified binders.
- Fatigue properties of binders appear well correlated with fatigue resistance of mixes; in particular, the slope of the fatigue curve of the mix seems to be governed by binder properties.
- Low temperature cracking of asphalt mixes is one of the most directly linked with binder properties. Rheological characteristics, determined by the BBR test may not be sufficient

to predict cracking resistance, in particular for modified binders. A better insight can be obtained using the FTT for binders.

Finally, the most important binder properties to evaluate also depend on the type of application:

- For surface courses, the most important properties are resistance to rutting, thermal cracking and aging.
- For structural layers, key properties are stiffness and fatigue resistance.

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Impact of Asphalt Binder and Aggregate Supply on Balanced Mix Design

A Contractor's Perspective

CHENG LING
Pike Industries, Inc.

INTRODUCTION

This document summarizes several examples demonstrating the impact of asphalt binder and aggregate supply on BMD according to the recent experience from an asphalt contractor in Vermont since BMD was implemented by Vermont Agency of Transportation (VTrans) in 2019. Challenges for BMD implementation lying ahead from a contractor's perspective are presented and research needs to address the gaps are also discussed.

IMPACT OF ASPHALT BINDER SUPPLY SOURCE

Switching the binder source is very common among asphalt contractors during the production depending on the availability and cost of the materials. However, unlike Superpave volumetric design, the BMD test results may be significantly different when various binder sources are used, as studies have shown that the asphalt binder plays a critical role on asphalt mix performance in the lab. Here is an example of how the different binder sources affect the performance test results (*1*). In this example, a Type IVS (NMAS of 9.5 mm) design mix out of a local contractor's facility in Vermont was selected and the mix performance test specimens were fabricated using PG 70-28 polymer-modified binders from three different suppliers in the region, namely Source A, B, and C. HWTT, I-FIT and IDEAL-CT were conducted to check the binder source impact. The test results are presented in Figure 1 and further explained as follows.

The HWTT results presented in Figure 1*a* show that the final rut depths of mixtures made with three binders are all similar. This validates the findings from other researchers that HWTT result is well correlated to binder stiffness, which could be captured by binder PG and MSCR tests (*2*, *3*). The FI comparison in Figure 1*b* shows some difference among mixtures with three binder sources. Source C gives the highest value while Source B gives the lowest. CT index results in Figure 1*c* also show that Source B gives the lowest value. However, Source A seems to

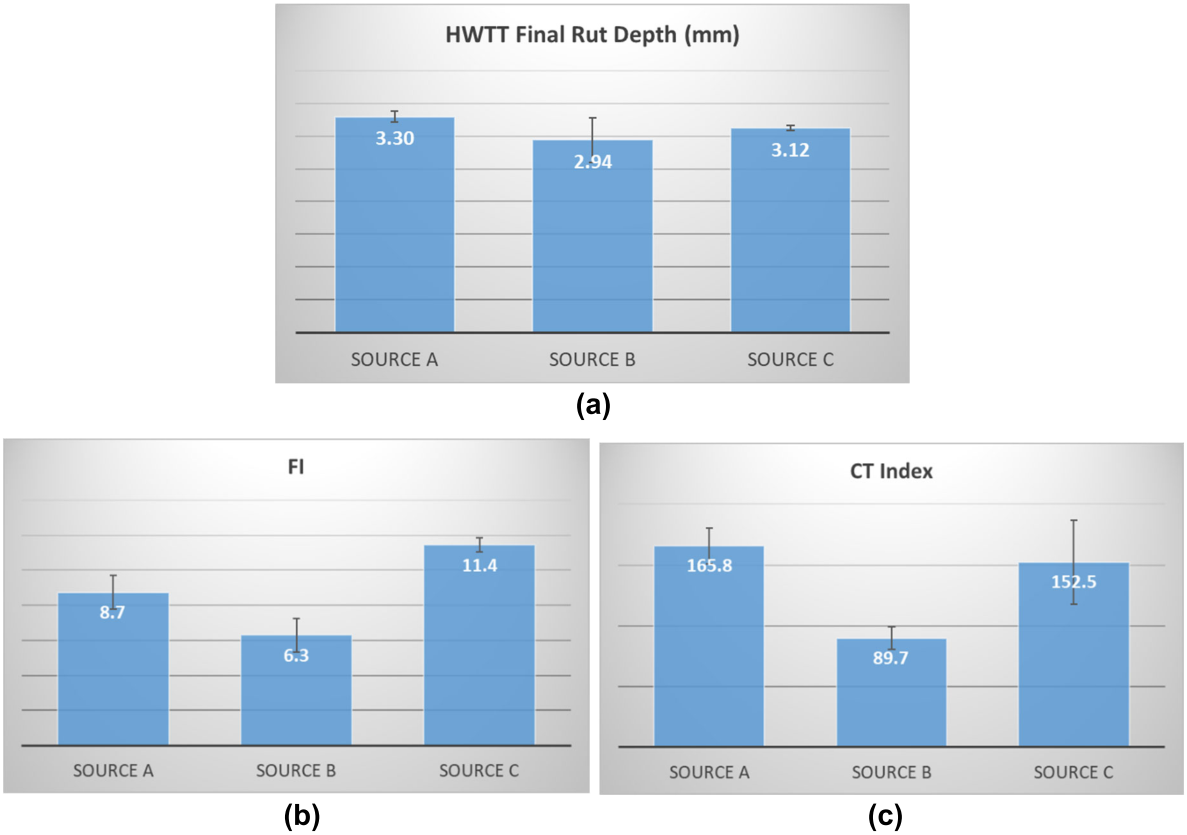

FIGURE 1 Mix performance test results with binders from three supply sources: (*a*) HWTT rut depth, (*b*) FI, and (*c*) CT index.

yield slightly higher CT index than Source C, which is different from the FI ranking. Overall, the binder source has demonstrated a significant impact on the cracking test results based on the limited data presented here. Depending on the test selected, the ranking may be different as well.

Asphalt binder supply has been and will remain volatile in the coming years. There's a need to better understand the impact of binder supply source on the mix performance, as BMD test results could be influenced by changing asphalt binder supplies. For mix producers and contractors, a binder screening tool would be much desired during the material selection stage to identify the favorable binder source on the market.

IMPACT OF AGGREGATE SUPPLY SOURCE

Besides the binder source, the aggregate source and quality may also affect the mix performance. Below is an example from a Wisconsin Highway Research Program study (*2*) showing how the aggregate quality matters. At low test temperature, the Disc-Shaped Compact Tension (DCT) FE of the mix with granite aggregates (550 J/m^2) is much higher than the mix with limestone aggregates (360 J/m^2). When looking at the fracture surfaces of the mix specimens as presented in Figure 2, it was found that for weaker aggregates such as limestone, the crack path travels through the aggregate; for stronger aggregates like granite, the crack path goes around. Therefore, the low temperature cracking resistance could be controlled by either aggregate quality or mastic stiffness, depending on the type and quality of aggregate used. We need a better understanding of what aggregate fundamental properties are critical in BMD, and how we could measure those properties and select aggregate source according to them.

COMPATIBILITY BETWEEN ASPHALT BINDER AND AGGREGATE

Figure 3 shows another example of FI for mixes fabricated with two binder sources and two aggregate types out of different locations. At Location #1 where limestone aggregates are primarily used, mix with binder source A shows a higher FI than source B. However, at Location #2 where gneiss aggregates are used, the ranking is reversed and the mix with binder source B gives a much higher FI value. This observation indicates that there may not be a consistent trend when evaluating the impact of binder source across different locations using different aggregate types, as the aggregate surface chemistry, absorption, and other physical or chemical properties on binder-aggregate interface may affect the mix performance test results. Such compatibility between asphalt binder and aggregate source also needs to be better understood and considered during the BMD evaluation and implementation. More research is needed to help the practitioners quickly check the binder-aggregate compatibility in selecting materials to meet the BMD specifications.

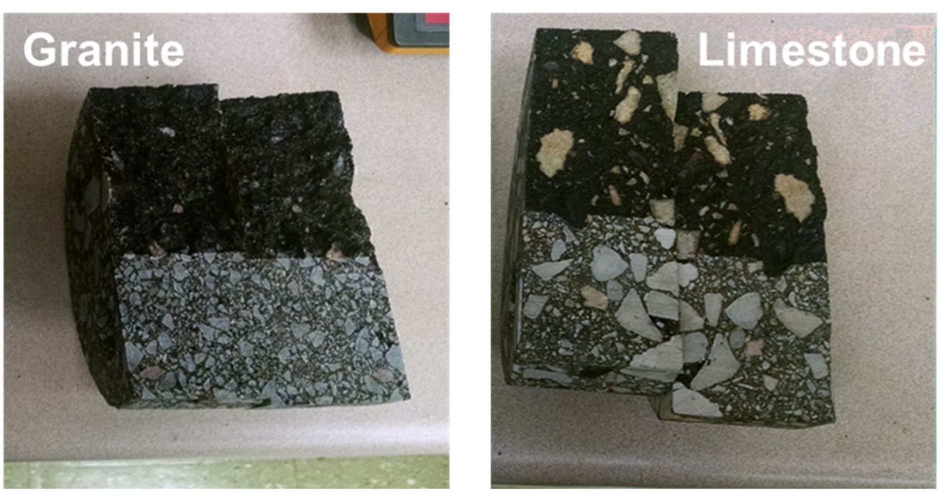

FIGURE 2 Fracture surfaces of a granite mix (left) and a limestone mix (right) after DCT test.

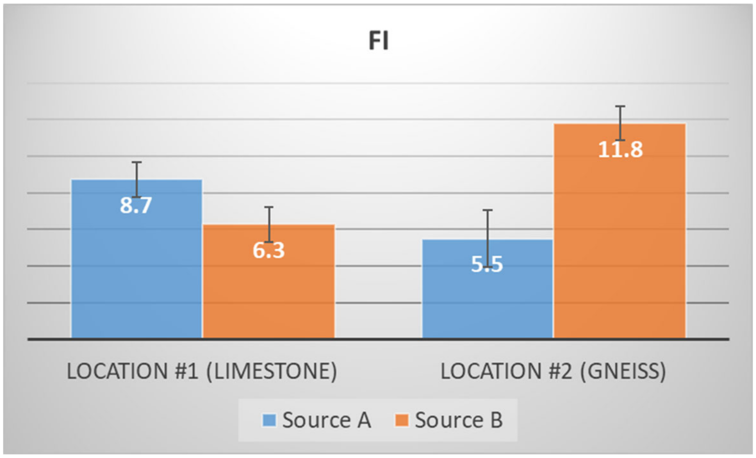

FIGURE 3 An example showing how the compatibility between asphalt binder and aggregate affects FI.

SUMMARY

This short document presents several examples illustrating the impact of asphalt binder supply, aggregate supply, and binder-aggregate compatibility on BMD according to the observations and experience from an asphalt contractor. Better understanding of these impacts is needed, and critical fundamental properties are to be investigated on the mix component materials. Quick screening tools are also desired to help contractors identify the favorable binder and aggregate supply sources as well as check the compatibility between the binder and aggregate selected to meet the BMD specifications.

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Balanced Mix Design

Does Chemistry Matter?

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JERAMIE ADAMS
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The scope of this TRB workshop is to discuss the impact of the binder on BMD for asphalt concrete mixtures. This section focuses on binder chemical formulations, their relationships with binder physical properties, and how they can guide BMD decisions.

This presentation attempts to address an important question: BMD: does chemistry matter? To do this, the presentation was based on the contents outlined in Figure 1, starting with discussing changes that are currently happening or likely to happen soon in the asphalt industry at various levels, then discussing and showing how these changes affect binder grading and its significance. In the second half of the presentation, the focus is on how to cope with these changes, what knowledge is needed in terms of chemical composition, structure, and physical properties, and how to obtain it. The presentation ends with a summary and some perspectives on what to expect or could happen next in the field of binder formulation, production, and assessment.

FIGURE 1 Presentation outline.

CONTEXT OF CHANGES

When it comes to binder supply nothing is set in stone. The context is constantly changing, driven by economics, geopolitics, societal, regulatory, and newer environmental factors which often are interconnected as shown in Figure 2. The refinery schematic modified from an industry publication (AI 2015), encompasses most units that can be used to make asphalt materials. Some asphalt bases have different Chemical Abstracts Service numbers with possibly slightly different chemical makeups.

Beside changes in crude oils, asphalt variability also depends on the complexity of a refinery, which opens options beside classical atmospheric / vacuum distillations. IMO 2020 regulation on marine fuel sulfur content [IMO 2020] opened them even wider as heavy sulfur fuel oil feeds can now be advantageously diverted to the asphalt pool with no sulfur restriction. High temperature conversion such as visbreaking is often used to produce these residues, imparting incompatibility, and instability.

PG or Not PG?

Figure 3 points out that these changes in asphalt production and supply are not captured by Superpave specifications which were developed in the early nineties for binders produced back then. When not well-controlled these changes are suspected of leading to early damage in the

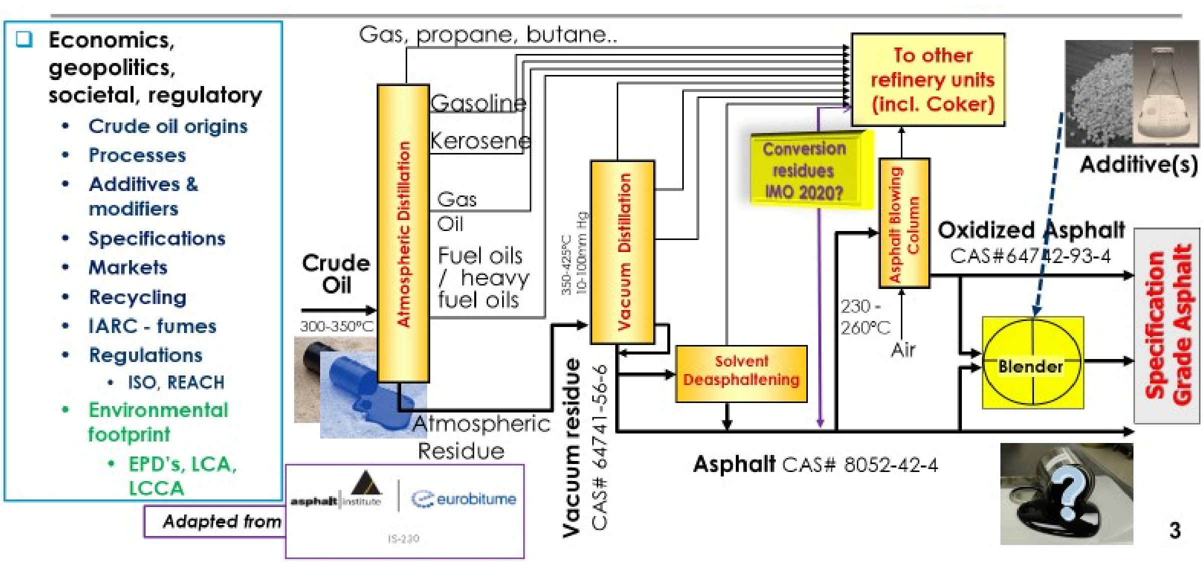


FIGURE 2 Drivers in asphalt binder supply.

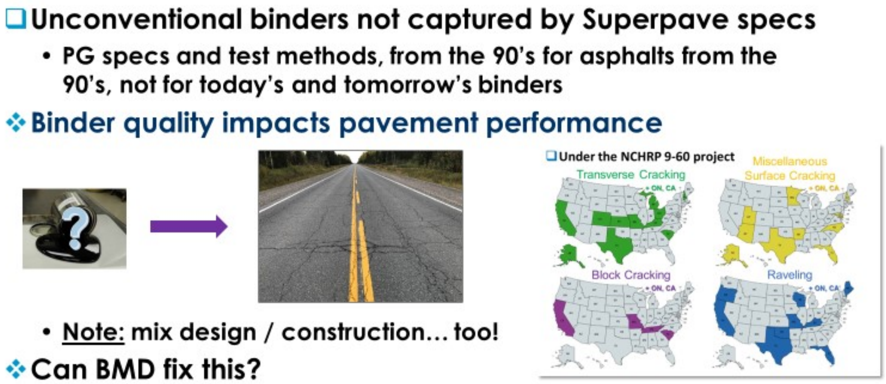


FIGURE 3 Consequences of changes in asphalt supply and quality.

field, particularly in the form of cracking or raveling and were the basis for launching NCHRP 9-60. These suspicions of binder-related field damage were confirmed by the agency survey conducted under this project. A question arises: can BMD prevent the issues from happening? Figure 3 summarizes these points. More details can be found elsewhere (Elwardany et al. 2020, 2021).

Figures 4, 5, 6, and 7 show examples of PG grades obtained through various processes, asphalt sources, and additives or polymers. They show them defined within their PG lower and upper temperature limits, and as a function of their composition and other properties. This variability increases for wider PG UTI's (useful temperature interval, difference of the higher and lower PG temperatures) particularly in terms of the newer parameters such as MSCR J_{nr} or strain recovery, or BBR DTc. Such parameters did not exist, nor were they considered under the Strategic Highway Research Program (SHRP).

A little less than 100 binders are part of this study carried out as part of the Asphalt Industry Research Consortium (AIRC) initiated, run, and managed by WRI. AIRC is one of its kind consortium projects in the field of bitumen/asphalt that brings the major players and institutions together to develop/test/benchmark new asphalt products amongst the rapidly changing feedstocks on one hand and the market forces on the other hand, to benefit the whole asphalt industry and consumers (road users). They originate from North America, Asia, Europe, and Oceania. They include pretty much all possible processes, blends, even biomass components, additives, and polymers.

Styrene-butadiene-styrene (SBS) polymer-modified asphalts are center stage to this study with respect to their market share. Figures 5 and 6 show that their DTc can vary a lot as a function of the bases that were used to produce them, and of the production process whether it involves crosslinking. As SBS modification generally makes DTc more negative, asphalt bases

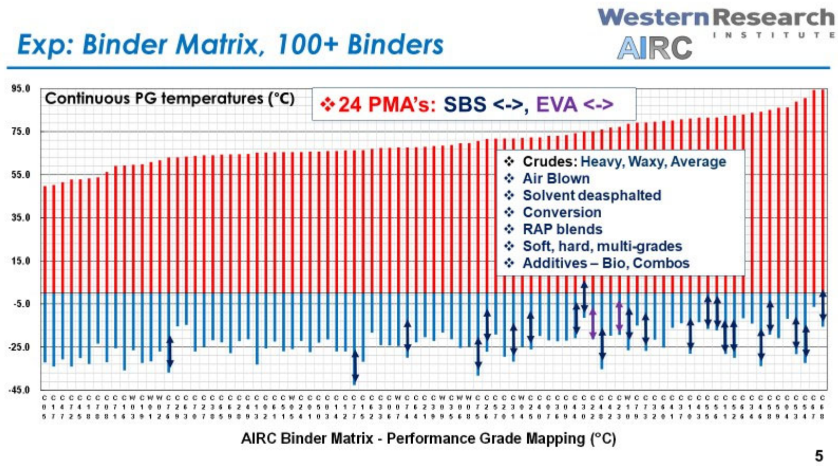


FIGURE 4 Continuous temperature intervals of various PG binders in experimental matrix.

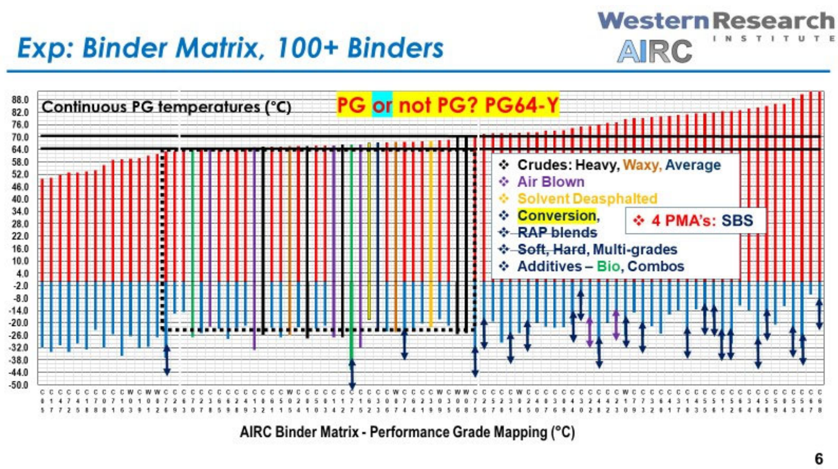


FIGURE 5 PG 64-YY binders in experimental matrix.

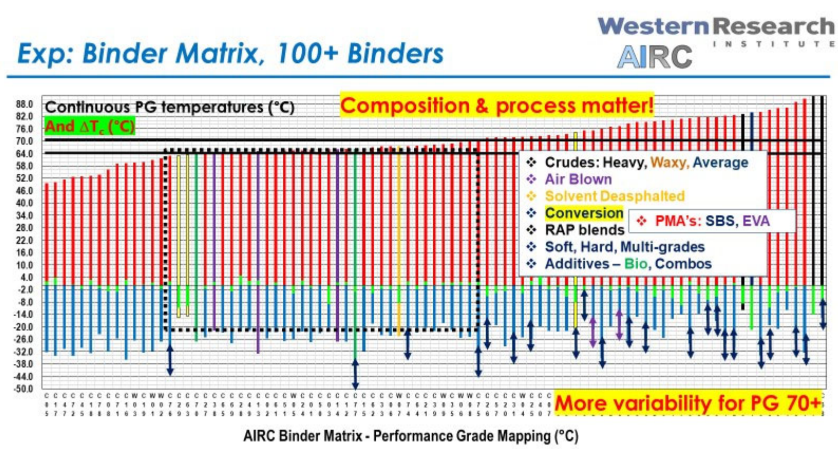


FIGURE 6 PG 70-YY binders in experimental matrix.

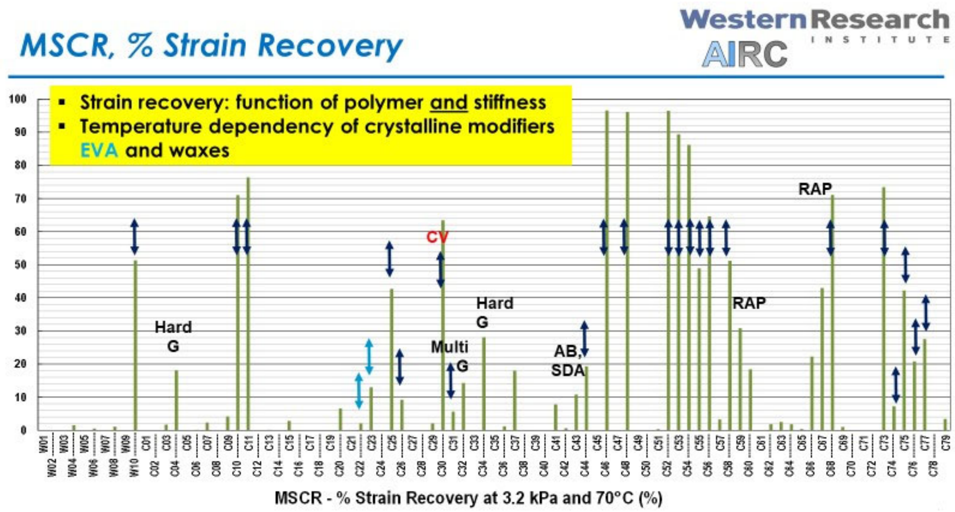


FIGURE 7 MSCR strain recovery of experimental binders.

with higher DTc are preferable. Crosslinking helps limiting the negative impact of the SBS modification. It has been shown that it can be attributed to a more homogeneous structure of crosslinked polymer-modified asphalt (PMA), where both the polymer structure and the asphaltene structure are intermingled at the micron level (Elwardany et al. 2021; Kumbargeri et al. 2022).

Figure 7 shows that although strain recovery is a general attribute to SBS modification, the stiffness of the binder can also impart some degrees of recovery, but to a lesser extent. Softer grade and unmodified asphalts do not show any recovery.

Note: in the graphs presented in Figures 4 to 7, the blue arrows represent SBS-modified asphalts.

The NCHRP Project 9-60 is about “Addressing Impacts of Changes in Asphalt Binder Formulation and Manufacture on Pavement Performance through Changes in Asphalt Binder Specifications.” The research carried out under this project focuses on the effect of variability on cracking resistance. Phases I and II of this project involved 50 different binders mostly used in North America (a couple from Europe), half of them with field data, and started by looking at the standardized rheological parameters obtained by BBR as presented in Figure 8. Although most PMAs (red bars) feature the best low temperature PG (lowest LTPG), their ranking completely changes when considering DTc, getting spread across the board. Note the visbroken residue from Europe shows a record low DTc.

The main outcomes of the NCHRP Project 9-60 are presented in Elwardany et al. (2020) and (2021), Kumbargeri et al (2023). The project Phase III is ongoing, involving a ruggedness study focusing on binder sensitivity and an interlaboratory study, and further refining of the proposed limits if need be (based on the results of the comprehensive test program proposed for Phase III).

Looking at the whole matrix in Figure 9, most of the binders are m-controlled, which means they have weak to poor relaxation properties. This is in general agreement with their field performance which showed extensive cracking for the poorer ones. Binders with crude sources from Canada or Venezuela were generally S-controlled (Kumbargeri et al. 2023).

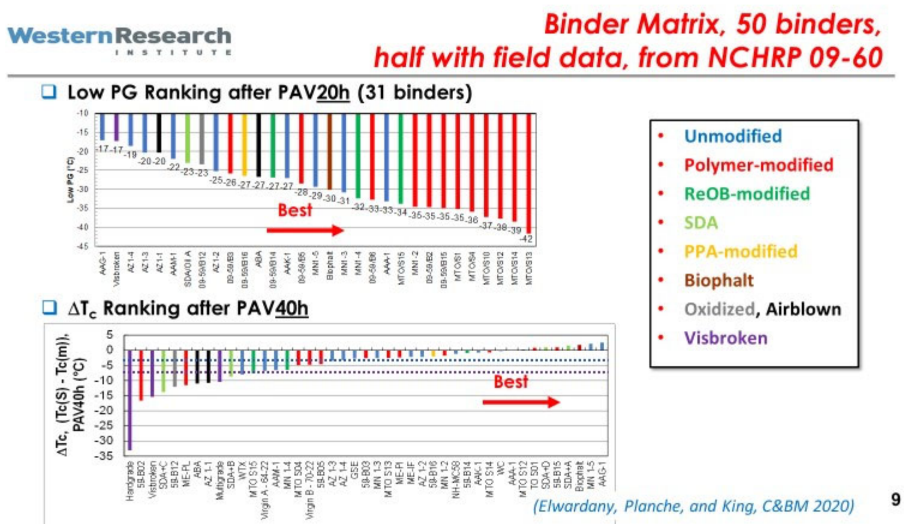


FIGURE 8 Effect of pressure aging vessel (PAV) aging on DTc.

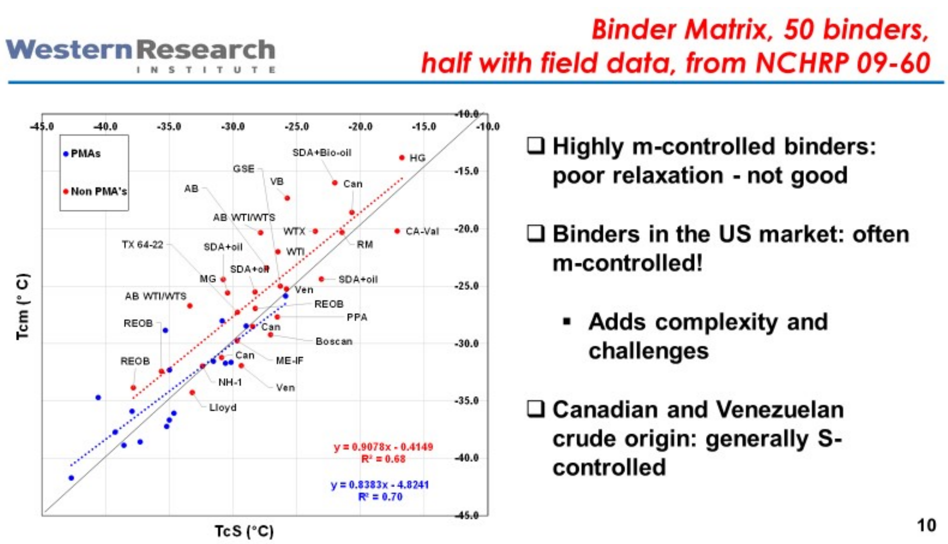


FIGURE 9 S- versus m-controlled binders.

But cracking is not only related to relaxation properties as measured by rheology, BBR or DSR, it is a failure property that requires a failure test to be more fully assessed. In the original SHRP specifications, the direct tension test (DTT) was recommended in case of PMAs which were stiffer at low temperatures than normal paving grades. For various reasons this test was abandoned and therefore not an option for Project 9-60. Since a major objective of Project 9-60 was to try to predict non-load-related block cracking, the research focused on using the asphalt binder cracking device (ABCD) test in which the sample cracks upon cooling in the absence of external loading. The project developed a new parameter DTf, subtracting TcS from BBR and Tcr from ABCD, the critical temperature at which the binder fails under cooling. Like DTc, DTf is normalized by TcS with respect to binder stiffness and thus its glass transition temperature. DTf was found to give more credit to most PMAs, not only SBS, and improved the ranking for most of them. Those not behaving well under this new parameter were indeed problematic from a formulation and/or field performance standpoint—they included a PMA made from a visbroken residue. Figure 10 shows the ranking difference for DTc and DTf after PAV40 (40 h aging). Ultimately, the specification framework was developed for both PAV20 and PAV40 aging options, with an emphasis on PAV20 for the sake of simplicity and testing efficiency.

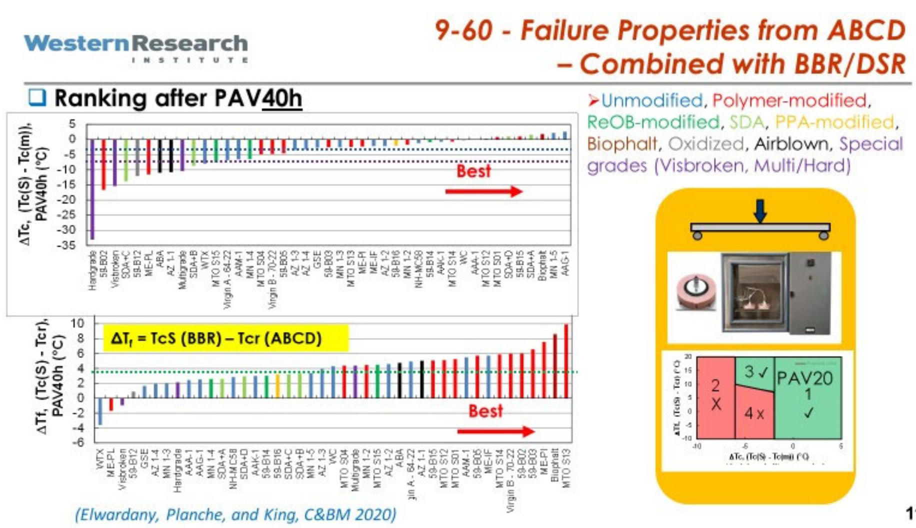


FIGURE 10 Ranking difference for DTc and DTf after PAV40.

HOW TO COPE WITH CHANGES

Now that it is established that a PG grade is not just PG grade, but with properties that are very dependent on its composition, how to cope with these changes in binder supply? Figure 11 presents a couple of approaches. The holistic approach to understand and predict rather than the traditional trial and error, is used for NCHRP Project 9-60 and AIRC projects carried out at WRI.

The core of the chemical analysis is the SAR-AD method (Saturates, Aromatics, Resins and Asphaltene Determinator) developed by WRI which allows to separate asphalt binders into eight subfractions of saturates (1), aromatics (3), resins (1) and asphaltenes (3), based on their solubility, aromaticity, and polarity. This method is presented in Figure 12, which also shows what type of model molecular structure relates to what subfraction (Adams et al. 2019, 2021).

Figure 13 shows that this analysis can be used for a wide variety of hydrocrabons including coal tar, shale oil, asphaltite or petroleum products. It can differentiate vacuum residues and asphalts easily as a function of their crude origin or process. It is important to note that some of these products are incompatible at higher concentrations with asphalts because of their imbalance composition. This is generally the case of refined motor oil residues (REOB or VTAE) for example.

Figure 14 shows colloidal instability indices (CII) for the wide range of binders from the AIRC study. Air blowing and polymer modification tend to increase CII, leading to less compatible systems.

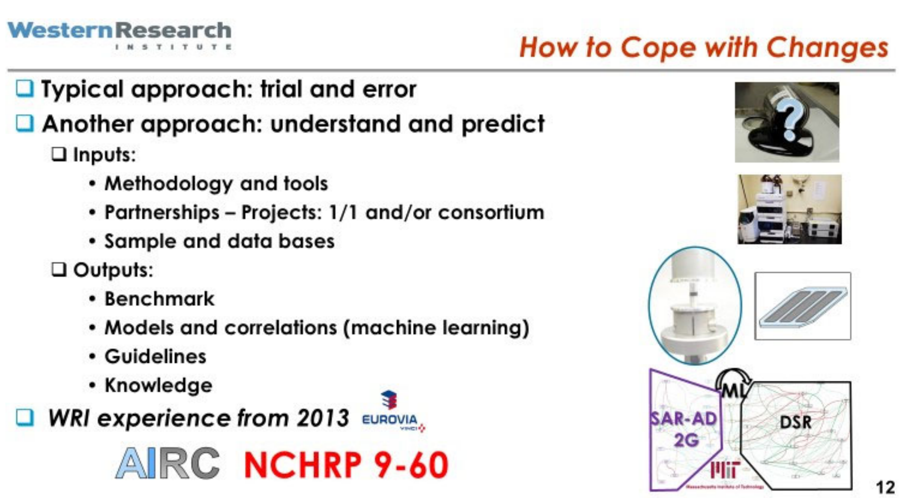


FIGURE 11 Methodology to cope with changes in asphalt supply.

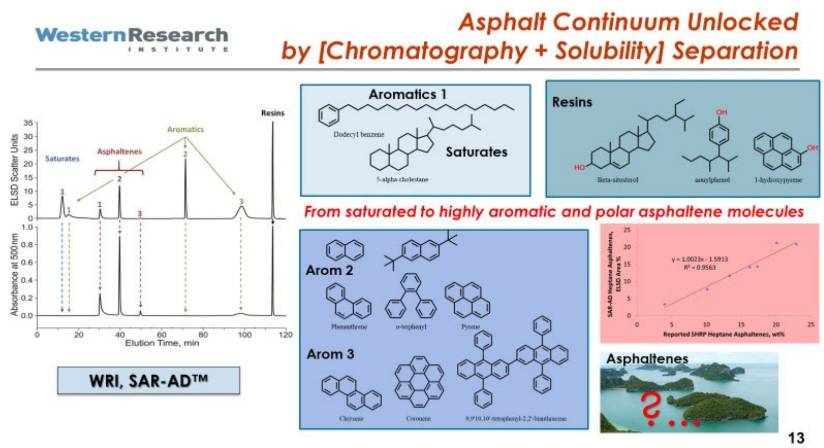


FIGURE 12 Subfractions in SAR-AD.

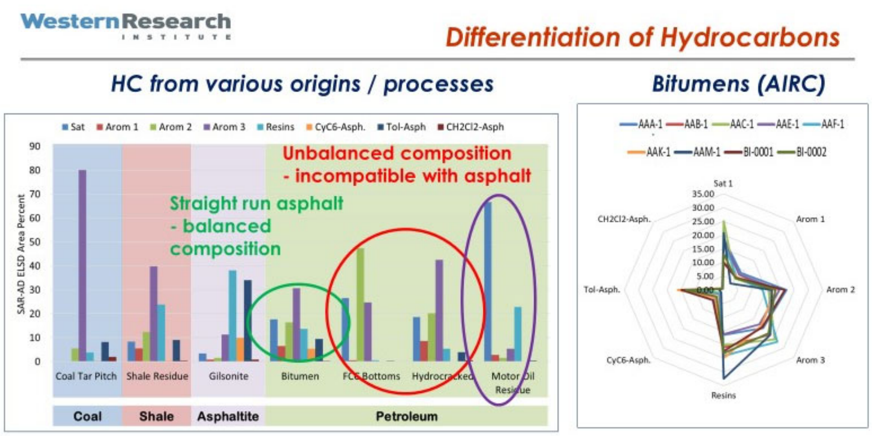


FIGURE 13 Various hydrocarbons evaluated using SAR-AD.

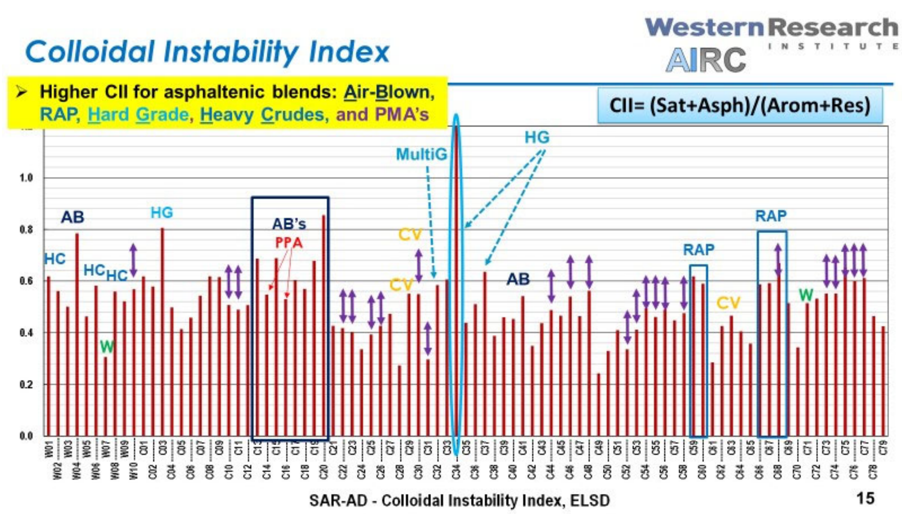


FIGURE 14 Colloidal index for various binder sources.

Under NCHRP 9-60 the relationships between DTc and the composition were studied, and a clear trend was observed, as in Figure 15. However, the correlation coefficient remains low as relaxation is also based on molecular associations which are not directly captured by SAR-AD. Figures 16, 17, and 18 focus on such structural analysis made by size exclusion chromatography (SEC) which sorts molecules as function of their size, with larger molecules showing at lower retention time. The wide variety of AIRC binders features most structures, and relates to a large range of rheological behaviors under black space (BS)—not captured by regular PG assessment:

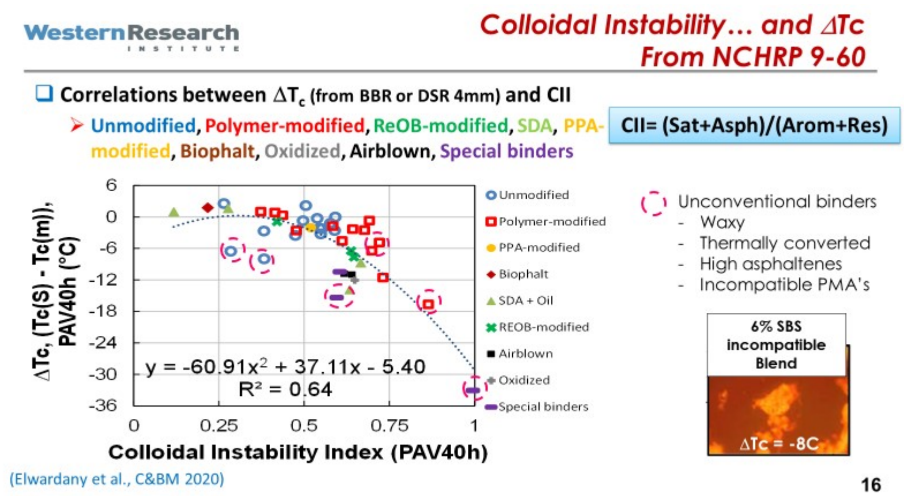


FIGURE 15 Relationship between DTc and colloidal index.

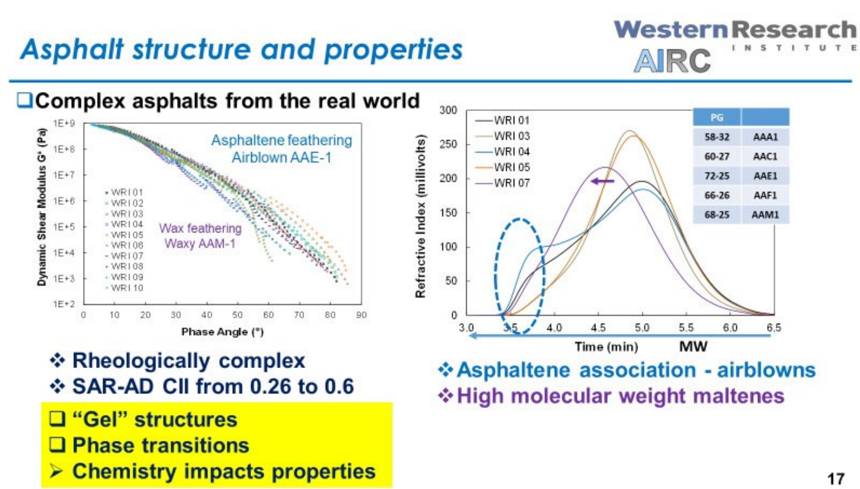


FIGURE 16 Rheologically complex asphalt binders presented in black space.

- "Sol" like structures of straight run asphalts (unimodal chromatogram): smooth BS curve,
- High molecular weight of waxy asphalts from crudes like West Texas Intermediate: feathered BS curve,
- "Gel" like structures of airblown / highly associated asphaltenes asphalts (shoulder peak): complex BS curves with feathering starting at low phase angle (around 30 degrees), and
- Complex structures of PMAs, bimodal with a polymer peak at low retention time and an asphalt matrix peak at higher retention time: complex BS curves with a polymer plateau.

See Adams et al. (2019) for more details.

The shape of the polymer peak in case of SBS can usually inform about the production process, either a physical blend (narrower polymer distribution peak) when only time, temperature and stirring are used or a crosslinking process (wider polymer distribution peak) which involves adding a reactant, classically a sulfur derivative. This is very simplified because crosslinking can be much more complex and usually proprietary. Figure 17 also shows the effect of the base asphalt effect for three PMAs made using the same formulation and crosslinking process, just changing the base asphalt. The shift in the polymer plateau starting point in the DSR BS to lower phase angle was attributed to changes in the maltene stability and composition, and indirectly to the asphaltene content – the higher the phase angle the more stable the PMA. The ultraviolet (UV) fluorescence microscopy observations and SEC curves

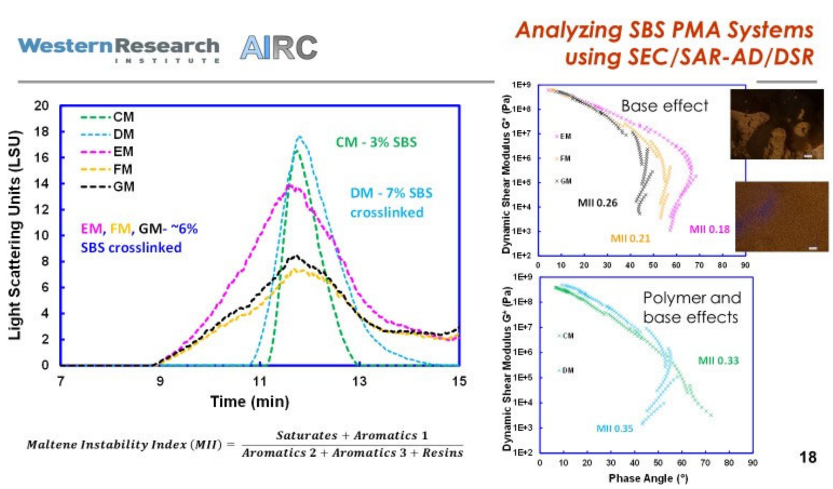


FIGURE 17 Effect of base asphalt on PMA systems.

also differentiated the PMAs accordingly: the more homogeneous PMA (EM) was made from a more compatible base asphalt, and through a better controlled crosslinking. Figure 17 also shows that base binders with "same PG grade" can actually very different and have huge impact on the quality and performance of the respective PMAs made from them.

Figure 18 focuses on visbroken residues. During a visbreaking process at very high temperature, aliphatic substituents are chopped from aromatic molecules to form lighter high value products such as fuels. Leftover residues after proper distillation are more instable, less compatible and usually more rigid and brittle at low temperatures particularly after aging. This is shown through their very negative DTc, their extremely elastic behavior in BS and special SEC chromatogram with a lower molecular weight distribution (blue curves).

Detailed information on these findings can be found in Adams et al (2019) and Kumbargeri et al (2022).

Why using such complicated analytical methods when FTIR (Fourier Transformed Infrared) spectroscopy is widely spread, used and cheap? Figure 19 shows the absence of trend between the change in carbonyl and sulfoxides upon aging (PAV20) and DTc. Functional groups are good aging indicators but are not the main drivers of the rheological properties which are largely affected by the asphalt matrix which is a very complex chemical continuum not captured by FTIR.

So what? What can be done with all this information (Figure 20)? The purpose of these studies is not to develop chemical composition-based specifications—they would not be readily acceptable by the industry, the suppliers because they would be too stringent particularly in a

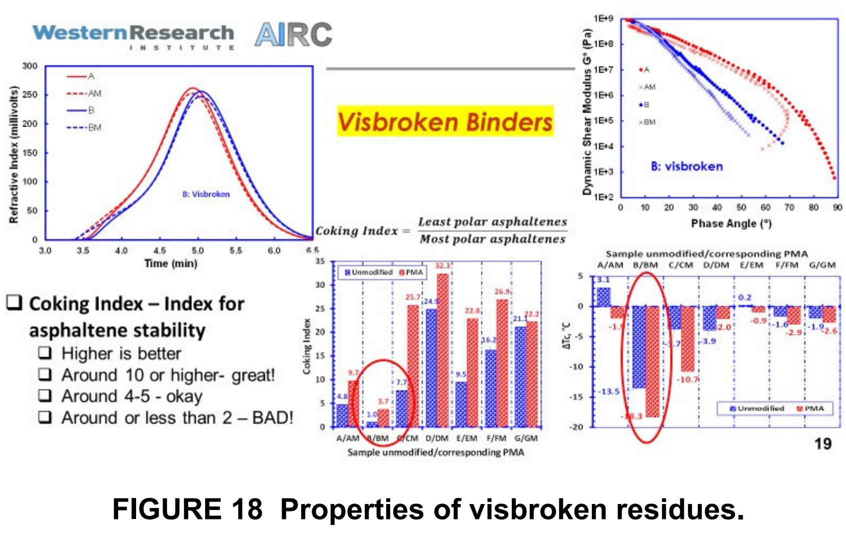


FIGURE 18 Properties of visbroken residues.

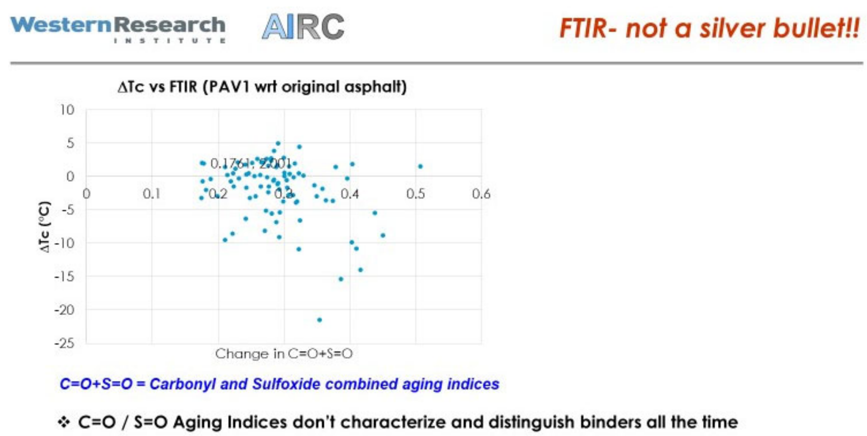
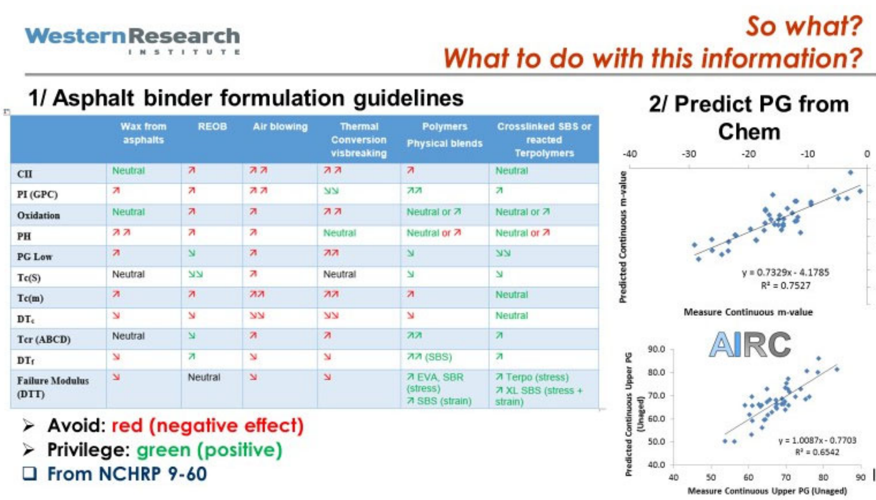


FIGURE 19 Limitation of using aging indices using FTIR.



	Wax from asphalts	REOB	Air blowing	Thermal Conversion visbreaking	Polymers Physical blends	Crosslinked SBS or reacted Terpolymers
CII	Neutral	↗	↗↗	↗↗	↗	Neutral
PI (GPC)	↗	↗	↗↗	↘↘	↗↗	↗
Oxidation	Neutral	↗	↗	↗↗	Neutral or ↗	Neutral or ↗
PH	↗↗	↗	↗	Neutral	Neutral or ↗	Neutral or ↗
PG Low	↗	↘	↗	↗↗	↘	↘↘
Tc(S)	Neutral	↘↘	↗	Neutral	↘	↘
Tc(m)	↗	↗	↗↗	↗↗	↗	Neutral
DT_c	↘	↘	↘↘	↘↘	↘	Neutral
Tcr (ABCD)	Neutral	↘	↗	↗	↗↗	↗
DT_f	↘	↗	↘	↘	↗↗ (SBS)	↗
Failure Modulus (DTT)	↘	Neutral	↘	↘	↗ EVA, SBR (stress) ↗ SBS (strain)	↗ Terpo (stress) ↗ XL SBS (stress + strain)

FIGURE 20 Effects of composition parameters.

low bid environment and very difficult to technically establish. The purpose is to make formulation guidelines based on huge databases, to ultimately help the industry make the right formulation / supply decisions. Altogether AIRC and Project 9-60 represent over 150 binders. More work is needed to exploit and validate the trends already obtained. Ultimately, such a tool should be useful for the industry at large, particularly binder suppliers or producers (Kumbargeri et al. 2023; Planche 2018).

The guideline table (Figure 20) shows various effects of composition parameter—what works for permanent deformation resistance may not work for cracking resistance.

SUMMARY

Figure 21 summarizes the main findings and trends presented in this section. The authors of this presentation are convinced that chemistry does matter to produce and supply the right binders for the right application even more so in the context of BMD. One may think in terms of BBD for BMD: Balanced Binder Design for Balanced Mix Design.

FIGURE 21 Summary of key points in presentation.

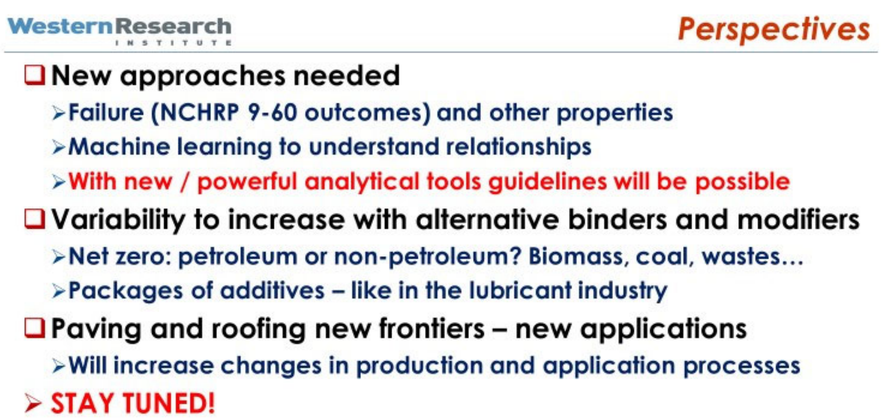


FIGURE 22 New approaches needed to relate binder chemical and physical properties.

SOME PERSPECTIVES

As binder production continues to evolve, new approaches are needed to assess new binders and relate their chemical and physical properties to performance. Establishing these relationships is complicated and requires machine learning. This will only get worse with increasing variability and introducing alternative binders or new additives with biomass components.

However, there is a good chance that this novelty will open the realm of possibilities for new applications both in paving and roofing. This is summarized in Figure 22.

For example, Figure 23 shows new possibilities of in depth chemical and structural analysis based on coupling SAR-AD with various detectors to get a better insight into the fraction chemistry such as aromaticity by fluorescence microscopy, functional groups by FTIR, or even molecular weight and molecular associations by SEC. This latter option involves diverting the solution flow through specially designed columns (Adams et al. 2021; Siroma et al. 2022).

As presented earlier, molecular interactions and associations play a very important role regarding asphalt viscoelasticity and relaxation. This second generation of fraction separation allows to observe and measure it. It is key to the AIRC iteration 3 to fingerprint asphalt binders, whether conventional or alternative with biomass fractions, polymer-modified or aged, for example, see Figure 24.

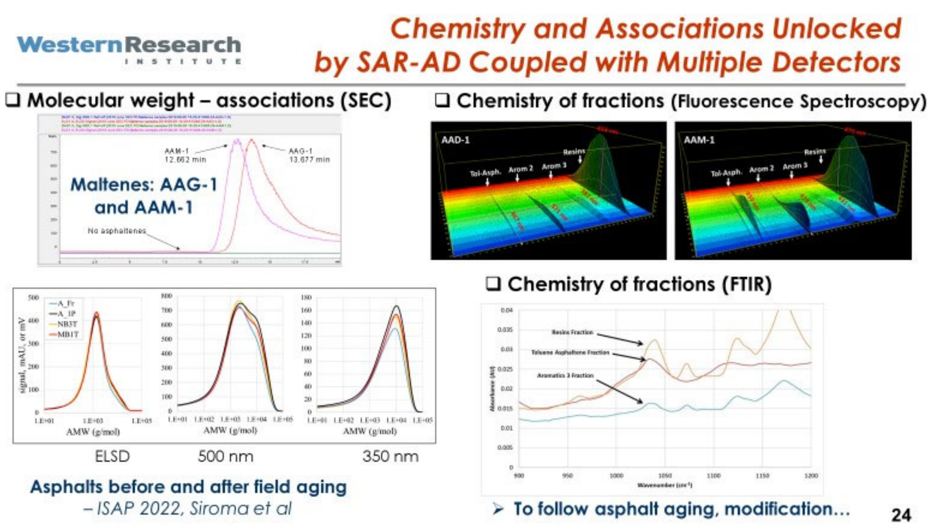


FIGURE 23 Example of a new approach using SAR-AD with various detectors.

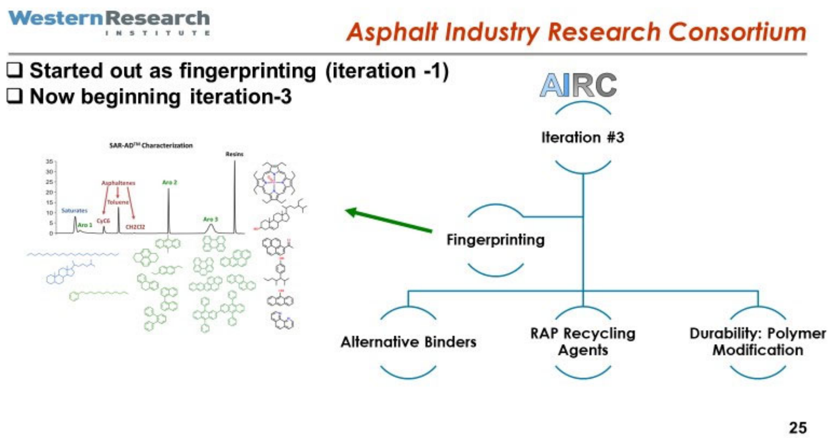


FIGURE 24 Fingerprinting conventional or alternative asphalt binders.

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Siroma et al. Asphaltene Agglomeration Through Physical–Chemical and Rheological Testing. ISAP 2022 Symposium, San Jose, Costa Rica, October 25–27, 2022.

Engineering Recycled Binder Blends to Meet Balanced Mix Design Requirements

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Texas A&M University

The scope of this TRB workshop is the impact of the binder on BMD for asphalt concrete mixtures, with this section addressing binder properties that can help guide BMD decisions. The title of this presentation is Engineering Recycled Binder Blends to Meet BMD Requirements.

This presentation summarizes the activities of the different multi-year national and state research and implementation efforts shown in Figure 1 in chronological order. NCHRP Project 9-58, The Effects of Recycling Agents on Asphalt Mixtures with High RAS and RAP Binder Ratios and NCHRP Project 20-44(24), Pilot Test of Proposed Standard Practice for Recycling Agents in Asphalt Mixtures Incorporating RAP and RAS are now complete, and NCHRP Project 9-65, Capturing Durability of High Recycled Binder Ratio (RBR) Asphalt Mixtures and TxDOT BMD efforts are ongoing. These projects are all searching for design (and acceptance) methods to encourage the use of recycled asphalt materials (RAM), defined as 0.3–0.5 RBR, to realize economic and environmental benefits while maintaining balanced engineering performance. These efforts are working toward the development of an AASHTO Standard Practice that includes guidelines and tools to engineer each unique materials combination of component materials at specific proportions to produce durable asphalt concrete mixtures. This presentation focuses on the role of modern binders in BMD that addresses the importance of characterizing quality instead of only quantity as in volumetric mix design. These modern binders often include modifiers and may incorporate additives including RA, WMA products, or other recycled materials including plastics and tire rubber.

A study by Kaseer et al. (2021) included a comparison of unmodified binder and mixture properties for most field sections from four of the five field projects associated with NCHRP Project 9-58 as shown in Figure 2. The Nevada field project was not utilized in this comparison. Including some additional laboratory combinations, in total 23 binder blends and corresponding mixtures were characterized by five binder parameters and three mixture parameters.

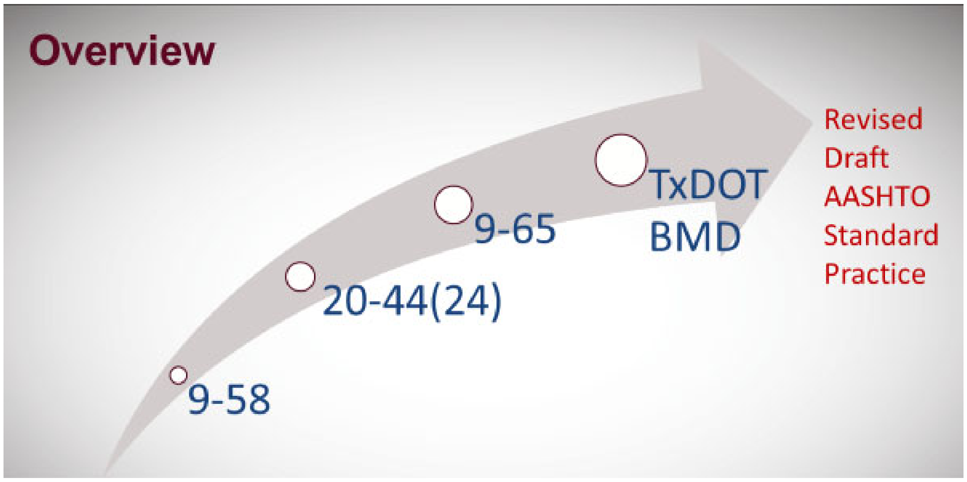


FIGURE 1 Overview of research efforts summarized in this presentation.

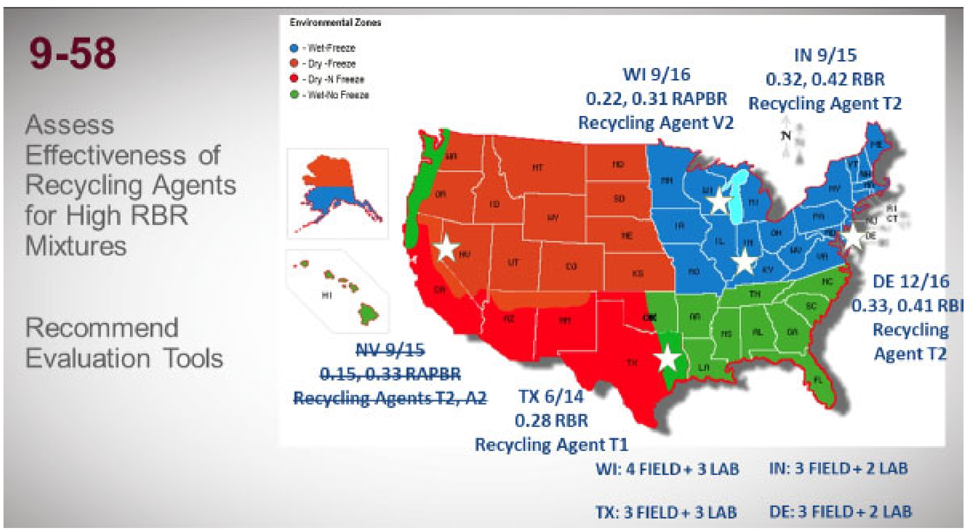


FIGURE 2 Field projects associated with NCHRP Project 9-58.

Data from all five NCHRP 9-58 field projects was utilized to develop the first draft AASHTO Standard Practice for engineering high RBR recycled mixtures that include four parts as shown in Figure 3. The goal of the standard practice is to provide guidance toward production of a materials combination that sustains balanced performance with aging.

The guidelines for component materials selection and proportioning shown in Figure 4 recognize the limitations of some base or virgin binders with lower capacity for recycling (low DT_c) and some heavily aged RAM that should be utilized with caution at high RBR. In addition, a restriction on RAS content and total RBR based on the scope and results of these research efforts are provided.

FIGURE 3 Components of AASHTO Standard Practice for engineering high RBR mixtures.

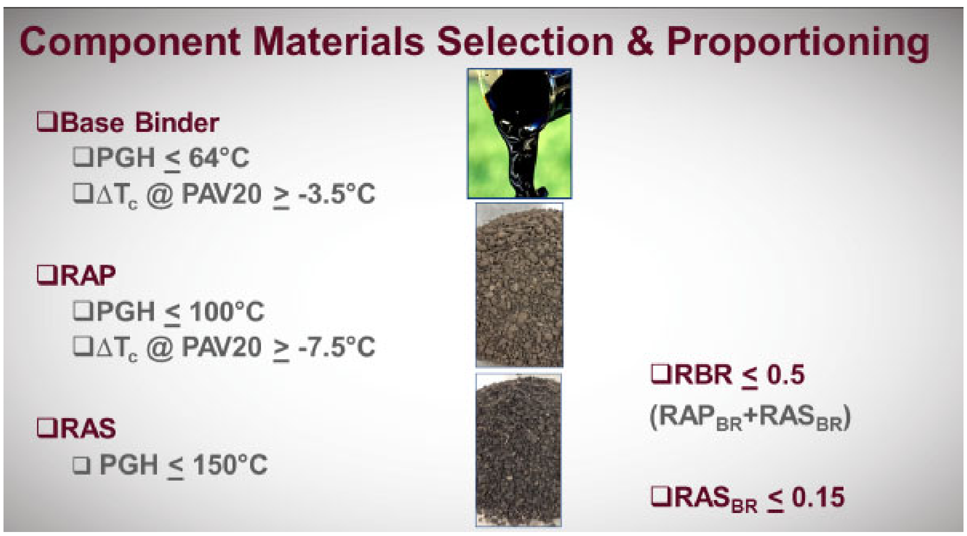


FIGURE 4 Component material selection and proportioning.

Proportioning guidance is also provided with respect to recycling agent dose selection. Three different methods were explored as shown in Figure 5, with the initial recommendation to match continuous high temperature performance grade (PGH) of the target climate and obtain the slope rate of each recycling agent from the material supplier or use the values provided for bio-based or petroleum-based RA. Note that these slope rates were developed with earlier generation products from almost a decade ago. This method provides the maximum dose to enhance cracking resistance and durability without sacrificing rutting resistance. In NCHRP Project 9-58, the low temperature PG (PGL) was also always restored to that required by the target climate.

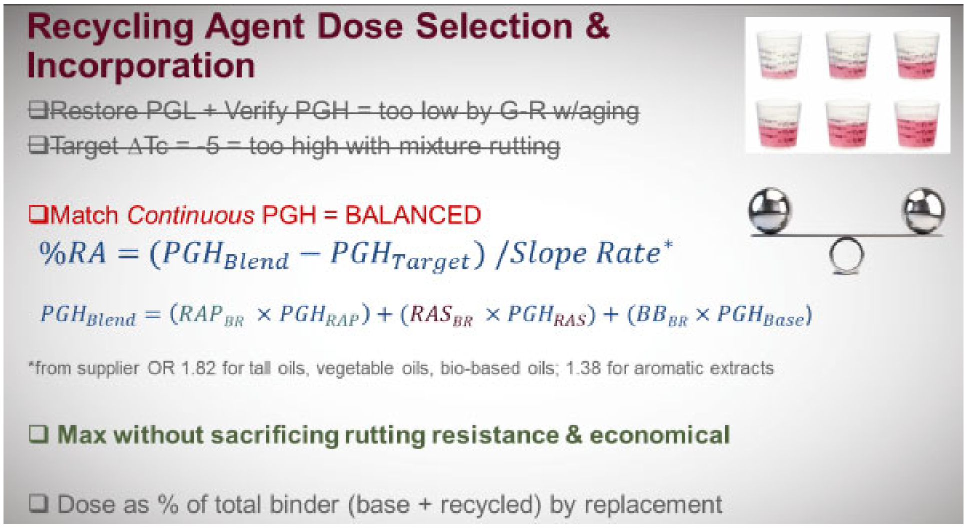
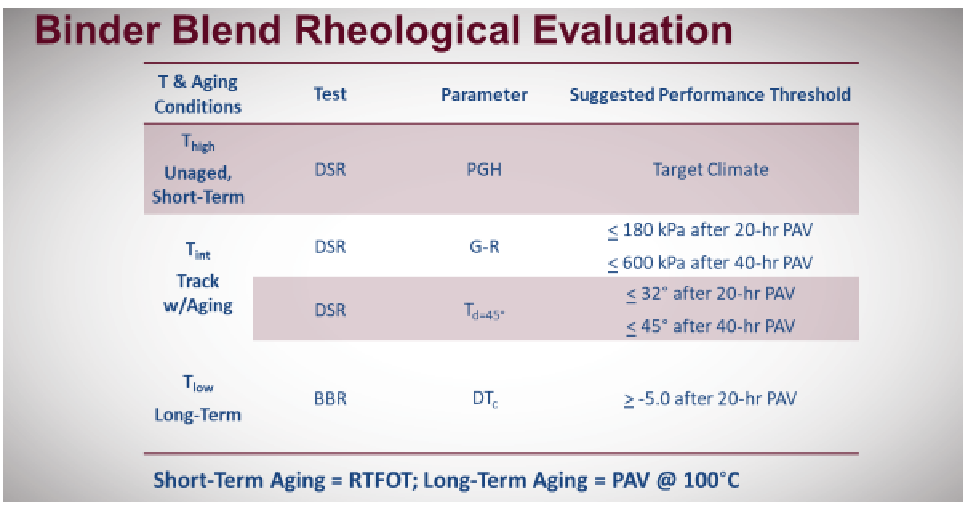


FIGURE 5 Recycling agent dose selection.



T & Aging Conditions	Test	Parameter	Suggested Performance Threshold
T_{high} Unaged, Short-Term	DSR	PGH	Target Climate
T_{int} Track w/Aging	DSR	G-R	≤ 180 kPa after 20-hr PAV ≤ 600 kPa after 40-hr PAV
	DSR	$T_{d=45°}$	≤ 32° after 20-hr PAV ≤ 45° after 40-hr PAV
T_{low} Long-Term	BBR	DT_c	≥ -5.0 after 20-hr PAV

FIGURE 6 Evaluation tools for recycled and rejuvenated binder blends.

Figure 6 shows the initial evaluation tools for recycled and rejuvenated binder blends across the temperature spectrum. The Glover-Rowe (G-R) parameter and DT_c thresholds were adopted from existing work based on age-related cracking but with specific PAV conditioning. The crossover temperature ($T_{d=45°}$) thresholds are correlated to those for the G-R parameter and either parameter can be used to control intermediate temperature cracking resistance.

Figures 7 and 8 show the binder and mixture tests, conditions, and parameters used in the comparative study by Kaseer et al. (2021). The DSR was utilized to conduct frequency sweeps to obtain the G-R parameter, the crossover temperature ($T_{d=45°}$), and the *R*-value from the

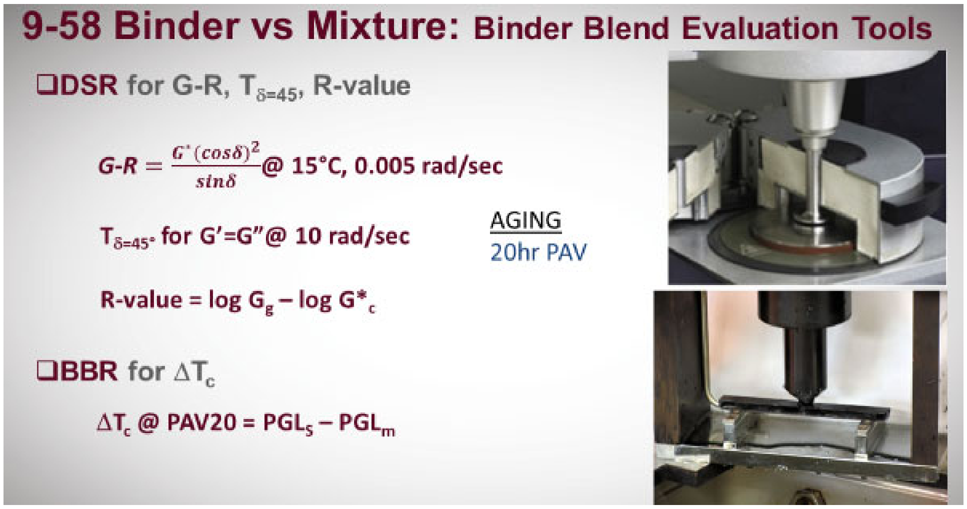


FIGURE 7 Binder tests conditions and parameters used by Kaseer et al. (2021).

FIGURE 8 Mixture tests conditions and parameters used by Kaseer et al. (2021).

Christensen-Anderson-Marasteanu model. The intermediate- temperature PG (PGI) was also determined from DSR data. The BBR was used to determine DT_c. The Illinois Flexibility Index Test (I-FIT) was used to determine the energy-based FI as the primary mixture parameter measured after long-term oven aging of compacted specimens to characterize cracking temperature at an intermediate temperature of 25°C. For low temperature cracking resistance, FE (G_f) was determined in the DCT test at –18°C and the Cracking Resistance Index due to environmental conditions (CRI_{Env}) was found in the Uniaxial Thermal Stress and Strain Test with temperature decreasing at 10°C per hour from 20°C.

Kaseer et al. (2021) compared these binder and mixture properties by determining the strength of their correlation using the coefficient of determination (R^2) of a power model or Pearson's correlation coefficient (r) of a linear model for DT_c that includes zero and negative values. Figure 9 presents these comparisons with green and blue indicating strong (>0.8) and moderate (0.6–0.8) correlation, respectively, and yellow and red indicating fair (0.4–0.6) and poor (<0.4) correlation, respectively. These results rank the rheological binder properties as follows from strongest to weakest correlation with mixture cracking resistance: DT_c, G-R or T, R-value, and PGI. The correlation with DT_c was by far the strongest.

NCHRP Implementation Project 20-44(24) applied the initial draft AASHTO Standard Practice to two additional field projects, including four field sections in Delaware as shown in Figure 10. An additional mixture cracking test, IDEAL-CT, was also conducted. A similar comparison was conducted with similar results indicating a moderate correlation between DT_c and cracking tolerance index (CT_{Index}) and a strong correlation between the G-R parameter and FI. This strong correlation was also robust with respect to specimen type and field aging.

Ongoing NCHRP Project 9-65 will revise the initial draft AASHTO Standard Practice developed and applied in NCHRP Projects 9-58 and 20-44(24), respectively, to address durability with respect to aging, moisture, and traffic. The preliminary framework to

9-58 Binder vs Mixture

Kaseer et al. (2021). Relationship Between Rheological Indices and Cracking Performance of Virgin, Recycled, and Rejuvenated Asphalt Binders and Mixtures. Transportation Research Record 2675 (9), 1-17. https://doi.org/10.1177/03611981211007479

	Coefficient of Determination (R^2)					Pearson's Correlation Coefficient
Binder Index / Mixture Parameter	PGI	ΔT_c linear	G-R	$T_{\delta=45^\circ}$	R-Value	ΔT_c
LMLC Mixtures						
FI (TX)	0.19	0.63	0.75	0.80	0.57	0.84
FI (DE)	0.89	1.00	0.91	0.93	0.65	1.00
FI (IN)	0.11	0.55	0.64	0.56	0.14	0.74
FI (WI)	0.55	0.95	0.61	0.54	0.78	0.97
G_f (WI)	na	0.79	na	na	na	0.89
CRI_{ENV} (WI)	na	0.69	na	na	na	0.83
Field Cores						
FI (DE)	0.08	0.95	0.53	1.00	1.00	-0.97
FI (IN)	0.40	0.78	0.54	0.54	0.56	0.88
FI (WI)	0.40	0.91	0.65	0.74	0.81	0.95

FIGURE 9 Strength of relationships among binder and mixture properties.

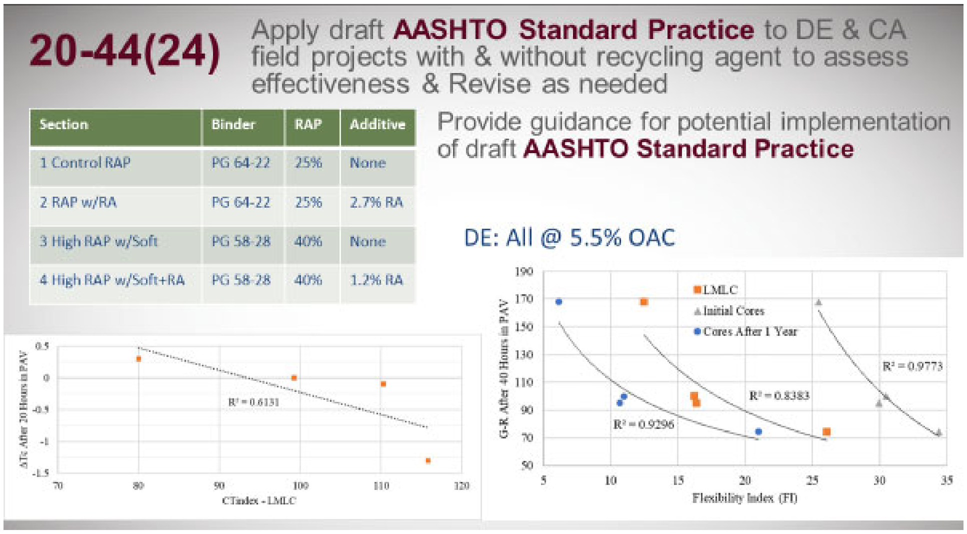


FIGURE 10 Application of draft AASHTO Standard Practice to additional projects in Delaware and California.

FIGURE 11 NCHRP 9-65 extends AASHTO Standard Practice Developed in NCHRP Projects 9-58 and 20-44(24) to address durability.

capture durability defines required mixture performance and aging and moisture conditioning with respect to the four environmental zones shown in Figure 11: Wet Freeze (blue), Dry Freeze (orange), Wet No Freeze (green), and Dry No Freeze (red). The selected mixture tests to assure durability are also shown in Figure 11 from left to right: DCT and IDEAL-CT for cracking, Cantabro for raveling, and Hamburg Wheel Tracking Test (HWT) for moisture susceptibility along with indirect tensile (IDT) strength with the same set-up as for IDEAL-CT.

Figure 12 lists the materials included in NCHRP Project 9-65 which is only a laboratory study that utilizes mix designs gathered from contractors. The four environmental zones were combined into North/Freeze and South/No Freeze regions with respect to the typical base binder, with PG 58-28 for the North and PG 64-22 for the South. Materials were procured from four aggregate sources, two defined as moisture susceptible due to the requirement of an anti-stripping agent (ASA) and two classified as moisture resistant, in four different states. RAP was also procured from these same four states, and RAS were gathered from the northern states. Moisture damage strategies include with and without ASA, and high RAM strategies include the following:

- Substituting the base or virgin binder by:
  - Increasing DT_c.
  - Decreasing PG (to PG 52-34 for North/Freeze and to PG 58-28 or South/No Freeze).
  - Using a PMA.
- Adding a recycling agent.
- Reducing the RAM binder availability.
- Hybrid.

Figure 13 presents the preliminary framework with required mixture performance and aging and moisture conditioning with respect to the four environmental zones shown in Figure 13. Longer aging is utilized for the South/No Freeze region as compared to the North/Freeze region. Freeze/Thaw (F/T) conditioning is required for the North/Freeze region, and moisture resistance is not required for the Dry No Freeze Zone.

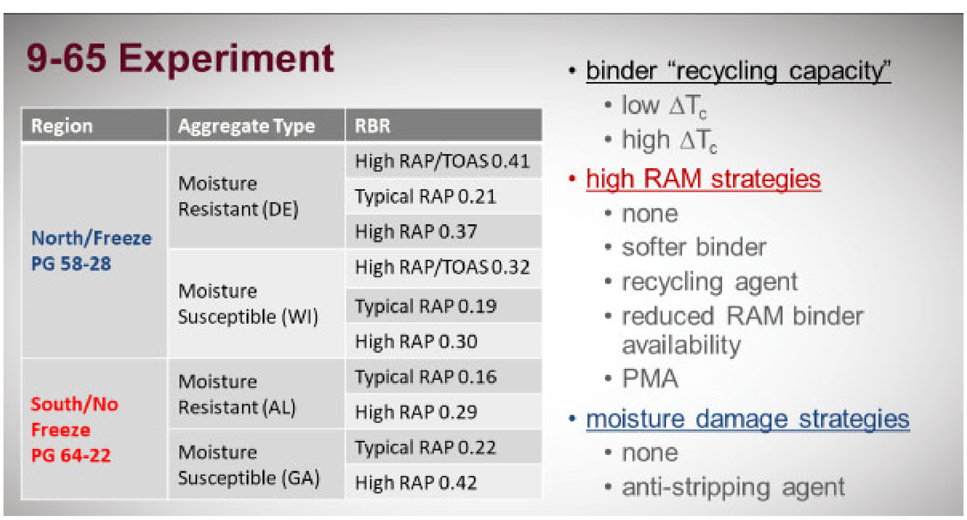


FIGURE 12 Materials and environmental zones considered in NCHRP Project 9-65.

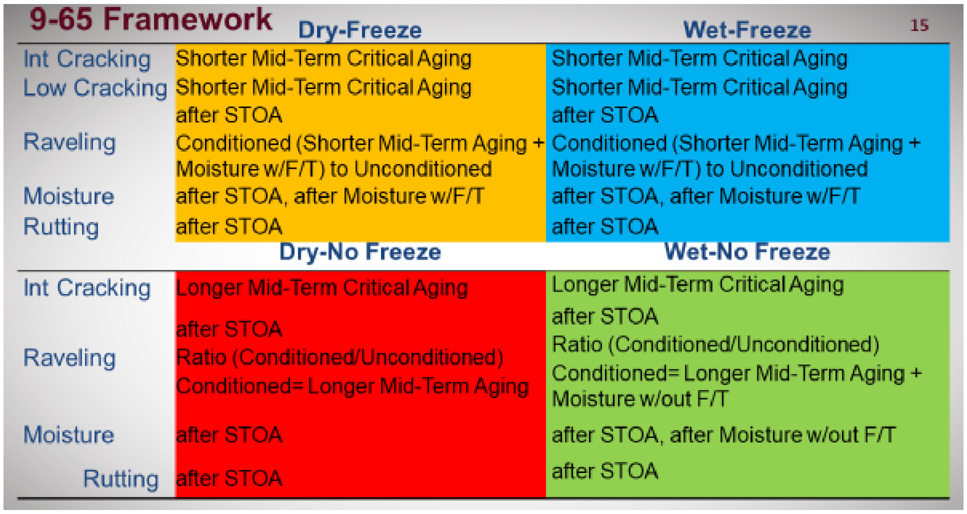


FIGURE 13 Aging and moisture conditioning used in NCHRP Project 9-65.

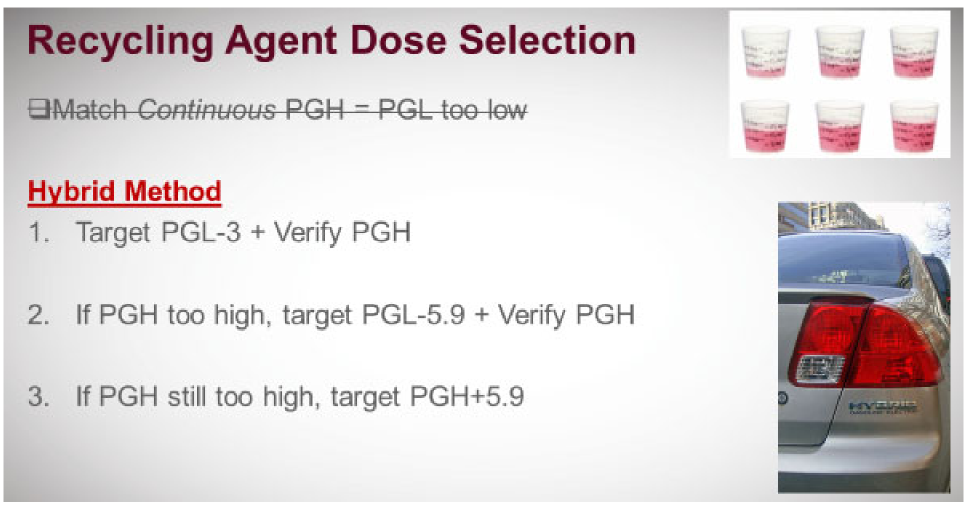


FIGURE 14 Hybrid recycling agent dose selection used in NCHRP Project 9-65.

During NCHRP Project 9-65, a hybrid recycling agent dose selection method was developed based on binder blends where the PGL was not restored to that required by the target climate by the initial recommendation to match continuous high temperature performance grade (PGH) of the target climate. The revised recommendation is a three-step process shown in Figure 14 that will likely provide an adequate dose for the North/Freeze region with the first step but steps 2 and 3 will be needed for the South/No Freeze region. Step 2 may provide an adequate dose for mixtures with lower RBR, softer RAP (lower RAP PGH), and/or a base binder with a higher recycling capacity (DT_c). Step 3 is equivalent to the initial recommendation from NCHRP Project 9-58 and will likely be needed for mixtures with higher RBR, stiffer RAP (higher RAP PGH), and/or a base binder with a lower recycling capacity (DT_c). Economics should also be considered to determine if this strategy is viable.

The Texas Department of Transportation (TxDOT) BMD effort is an ongoing collaboration to review, revise, and further develop a BMD specification for Superpave asphalt concrete mixtures. From 2019–2022, nine field projects each with multiple field sections for a total of 33 field sections were constructed across Texas as shown in Figure 15 (with county names illegible but not relevant). These mixtures were evaluated in the laboratory with aging and in the field with time. The focus is on increasing RAM content with mitigation strategies as needed and maintenance of balanced performance. Other factors evaluated include aggregate type, mixture type primarily related to aggregate gradation, and binder source.

Figure 16 shows the mixture testing and associated performance thresholds used in the TxDOT BMD effort. The current special specification relies on repeated loading tests to balance rutting and cracking performance, including the HWT and the Overlay Test, respectively. More practical monotonic loading tests including the IDEAL-CT and the ideal rutting test (IDEAL-RT) are under evaluation as alternates to simplify mix design and make performance assessment practical during production and acceptance. A loose mix mid-term oven aging protocol of 20 h at 95°C was also established for the cracking tests.

A comparison of binder and mixture tests was also completed during the TxDOT BMD effort (Mohanraj et al. (2022)) using the binder tests listed on Figure 17. The best correlation (strong based on criteria specified previously) was found between mixture CT_{Index} and a new binder

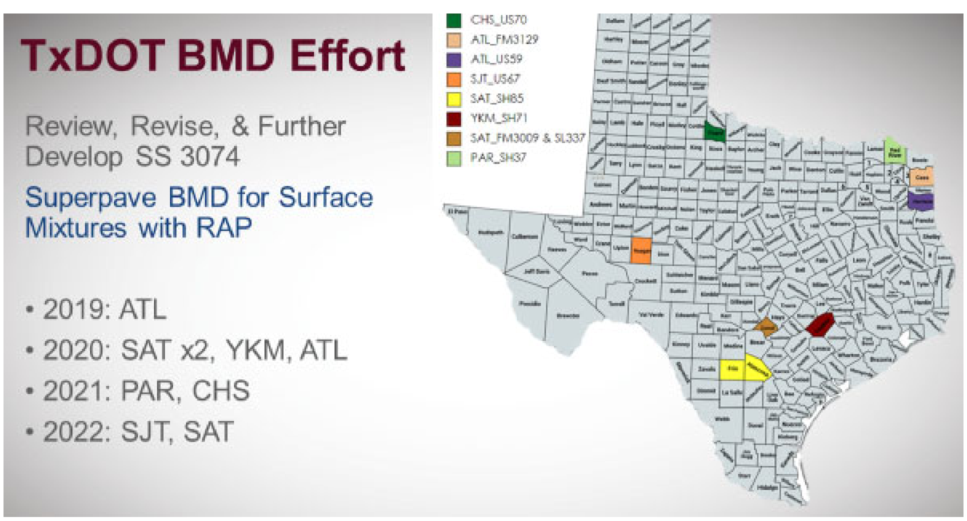


FIGURE 15 Timeline and location of TxDOT BMD projects.

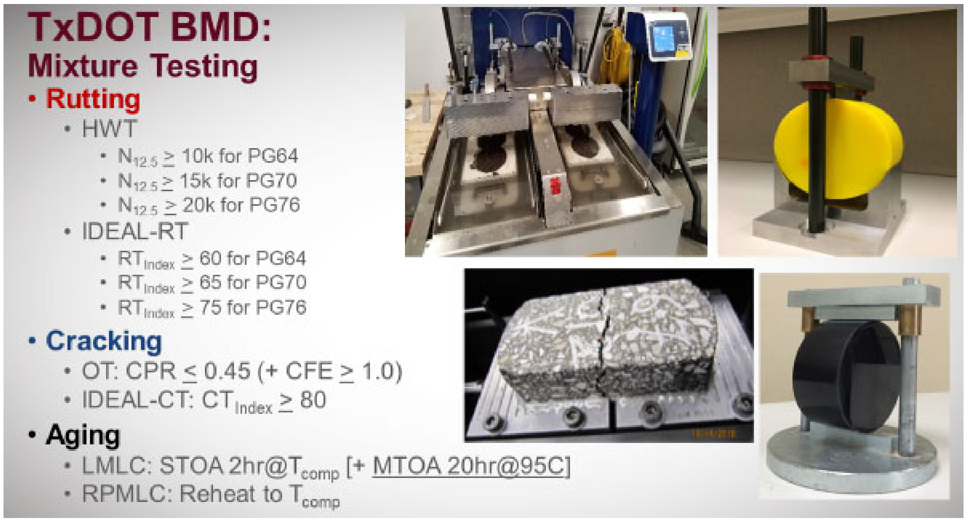


FIGURE 16 TxDOT mixture tests and performance criteria.

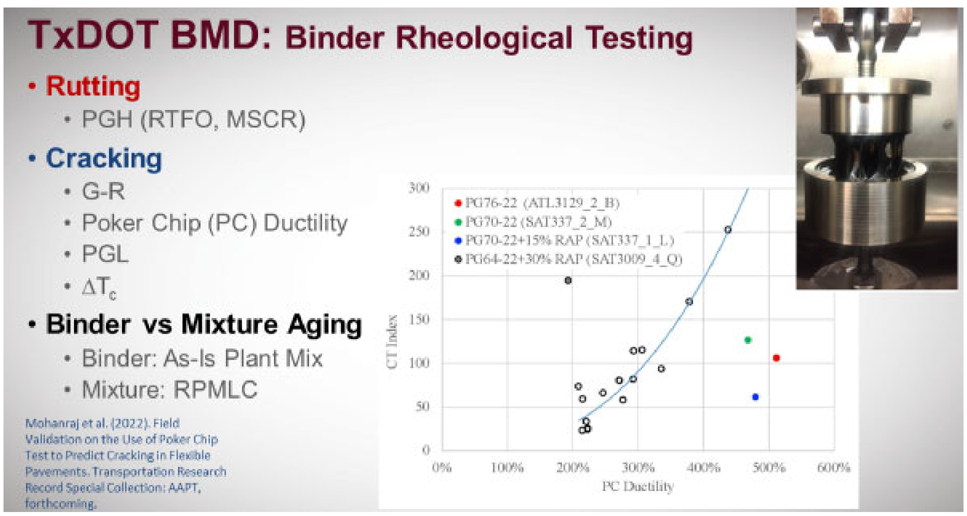


FIGURE 17 Rheological testing in TxDOT BMD Initiative.

failure parameter called poker chip (PC) ductility. The colored outliers shown on Figure 17 correspond to an unmodified binder with heavily aged RAP and a high RBR (gray) and PMA with no or low RAP content (green, red, blue).

A performance threshold of 150% for the PC ductility has also been verified based on field sections across Texas as shown in Figure 18. Based on binders tested on multiple projects, this parameter tracks with laboratory aging (PAV) and field aging (RAP) and is also more variable for PMA (PG 70-22 and PG 76-22) than for unmodified PG 64-22 binders.

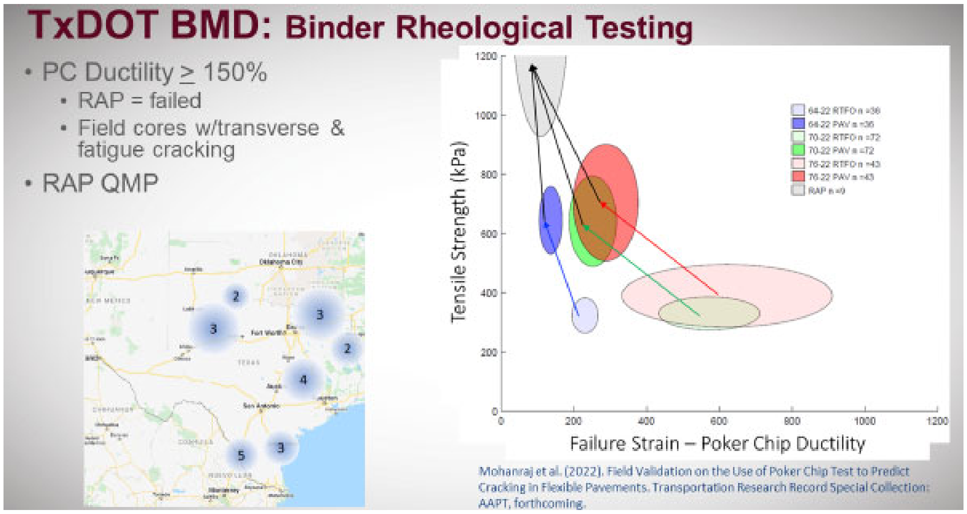


FIGURE 18 Validation of PC ductility performance threshold.

As with all experimental research, especially when field projects are constructed which give the most meaningful results, there are many to acknowledge. Specific thanks are due to the sponsors (NCHRP and TxDOT), the research and implementation teams, the DOTs, the contractors and associated asphalt pavement associations, and the recycling agent suppliers.

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2. Mohanraj et al. Field Validation on the Use of Poker Chip Test to Predict Cracking in Flexible Pavements. AAPT, 2022.

Implementing Asphalt Binder Research Results into a Balanced Mix Design Framework

R. MICHAEL ANDERSON
Asphalt Institute

The content in this presentation relies on information that was compiled from the NCHRP Project 20-44(19), Implementation of Proposed AASHTO Standards for Asphalt Binders and Mixtures. Thanks to the project panel and NCHRP program officers, Ed Harrigan and Roberto Barcena. Thanks also to the research team members from the Asphalt Institute (AI) and National Center for Asphalt Technology (NCAT), the researchers of the asphalt binder research projects discussed in this presentation, and the member companies of the Asphalt Institute for their support.

Figures 1 through 10 are presented to set the stage for an understanding of how asphalt binder properties impact expected asphalt mixture performance properties.

As SHRP ended in 1993, the main product from the asphalt research program was Superpave, which was a combined system including:

- Component materials tests and specifications (PG Asphalt Binder Specification and aggregate consensus properties);
- Mix design based primarily on the analysis and optimization of volumetric properties; and
- Advanced performance-related mixture testing and analysis to evaluate expected performance and allow for optimizing the volumetric design.

The first two items were ready for implementation at the conclusion of the program, which resulted in a coordinated training effort sponsored by the FHWA—NCAT, led by the Asphalt Institute.

In the National Asphalt Training Center training program, the process of designing an asphalt mixture using the volumetric mix design process was communicated to students as being like a pyramid. For purposes of illustration of the intended point, the most recognizable pyramid to the general population of the United States at that time was the US Department of Agriculture's (ADA's) Food Pyramid (Figure 1) because it showed the components inside the pyramid needed to build a balanced, healthy diet. Also shown in the same figure is a

FIGURE 1 USDA Food Pyramid (circa 1992).

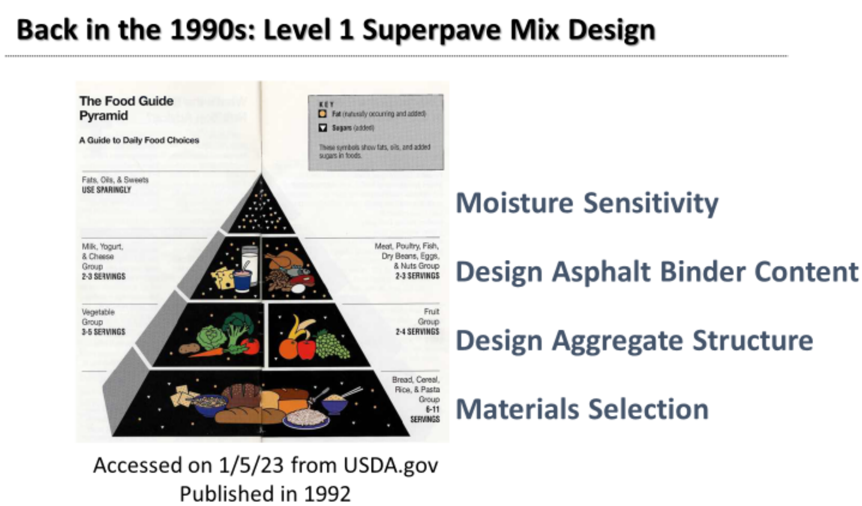

FIGURE 2 Superpave Level 1 Asphalt Mixture Design (circa 1992).

nutrition/cookbook that the presenter used in achieving the goal of losing more than 30 lbs in the late 1980s, generally following the principles shown in the food pyramid. The advice at the time was to base one's diet on high carbohydrates in the form of foods like grains, rice, and pasta.

Figure 2 illustrates how Superpave Level 1 (Volumetric) Mix Design used the principals of building a successful mix design through establishing a strong base (good asphalt binder and aggregate properties), then building on that base to develop a strong aggregate structure with room for air voids and asphalt binder, and then optimizing the volume of asphalt binder to allow the mix to have the best chance of success by being both strong and durable. Moisture sensitivity testing was the last step (the top of the pyramid) to ensure that the design mixture did not perform poorly in the presence of water. In other words, although the hard part of the work was done by the time the mix designer reached the final stages of mix design, they still needed to evaluate if the mixture was potentially susceptible to stripping distress.

Superpave Level 1 (Volumetric) Mix Design was the starting point for the mix design process, but the completion of a volumetric mix design was not intended to be the end of the process—except for pavements with low traffic volume. For readers unfamiliar with the Superpave mix design system, there were two other levels above Level 1 representing increased testing and analysis. The highest level of design, Level 3, was intended for high traffic applications. Level 3 Mix Design relied on performance-based tests and modeling to optimize asphalt binder content based on the mixture's performance in tests that related to expected rutting, fatigue cracking, and low temperature cracking, as shown in Figure 3. It was, in effect, a BMD system. The problem was that the complexity of the equipment, tests, and models was such that it was not readily usable by the asphalt industry.

To understand the impacts of asphalt binder properties on asphalt mixture performance properties and BMD, it is important to first review how asphalt pavements behave at high temperatures and under heavy traffic loads. The distress of interest in these situations is permanent deformation or rutting. Each component, asphalt binder and aggregate, has a role to play in mitigating rutting as does the proper volumetric properties—allowing space for asphalt binder and air voids (Figure 4).

Superpave Level 3 Mix Design

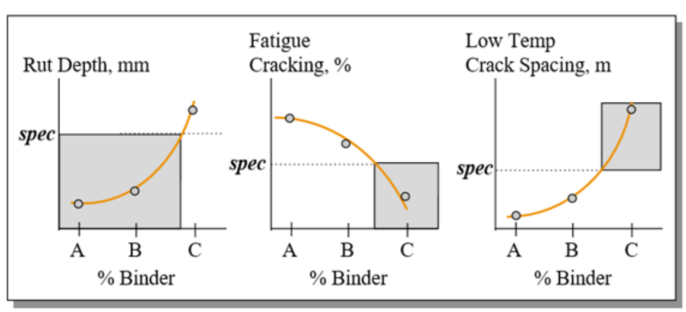

Figure 9.27. Plot of three types of performance vs. binder contents (A,B,C).

NATC II Superpave Mixture Analysis Text, 1996

FIGURE 3 The concept of Superpave Level 3 Mix Design.

How Asphalt Pavements Behave: High Temperature

- Permanent Deformation
  - Mixture is Plastic
    - wheel path rutting
    - shoving at intersections
- Depends on…
  - asphalt cement (some)
  - mineral aggregate (some)
  - volumetric proportioning (some)

FIGURE 4 Behavioral characteristics of asphalt pavements at high pavement temperatures.

The Mohr-Coulomb Failure Theory describes shear strength as related to cohesion and angle of internal friction (Figure 5). In an asphalt mixture, cohesion is largely a function of the asphalt binder properties, while the angle of internal friction is largely a function of aggregate structure including gradation, particle shape (angularity), and texture. The MSCR test described in AASHTO T 350 and used in the PG Asphalt Binder Specification (AASHTO M 332) addresses the asphalt binder contribution to rutting through the cohesion components in the Mohr-Coulomb Failure Theory. Many asphalt technologists believe that the principal parameter resulting from the MSCR test—the non-recoverable creep compliance (J_{nr})—better captures the contribution of the asphalt binder as it is related to rutting.

Principles of Rutting in Asphalt Mixtures

- Mohr-Coulomb Failure Theory
  - Described by Nijboer in 1948
    - Simplification of the rutting model considered in SHRP
    - Separated shear strength of asphalt mixture into three components
      - Internal friction of the aggregate structure (ϕ)
      - Initial resistance or cohesion (c) independent of deformation rate
      - Viscous, or rate-dependent, cohesion
  - Cohesion (c)
    - Largely a function of asphalt binder characteristics
  - Angle of internal friction (ϕ)
    - Largely a function of aggregate structure including gradation, particle shape (angularity), and texture

FIGURE 5 Background of Mohr-Coulomb Failure Theory.

Figure 6 is a graphical representation of the Mohr-Coulomb Failure Theory showing the failure envelope defined as a straight line with “c” (cohesion) as the intercept and “tan φ” (internal friction) as the slope. In this representation, resistance to shear failure, or rutting, can be improved by increasing “c”—improving the high temperature properties of the asphalt binder—and/or by increasing “tan φ”—improving the angle of internal friction, the angularity of the aggregate structure. Both properties have a role to play, but altering the slope of the line (i.e., changing internal friction of the aggregate structure) can have a larger effect resulting from smaller changes than altering the intercept (i.e., changing the high temperature properties of the asphalt binder). Volume of asphalt binder also has a role to play, impacting the cohesion.

Figure 7 illustrates how asphalt pavements behave at low temperatures. The distress of interest at low temperatures is thermal cracking characterized by transverse cracks. Research

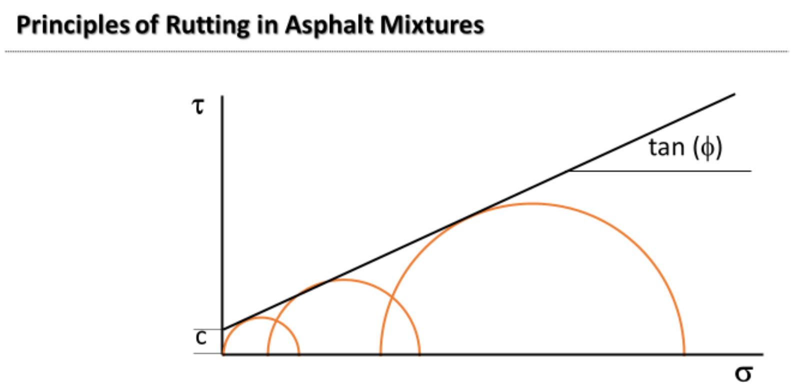

FIGURE 6 Graphical representation of Mohr-Coulomb Failure Envelope for asphalt pavement rutting.

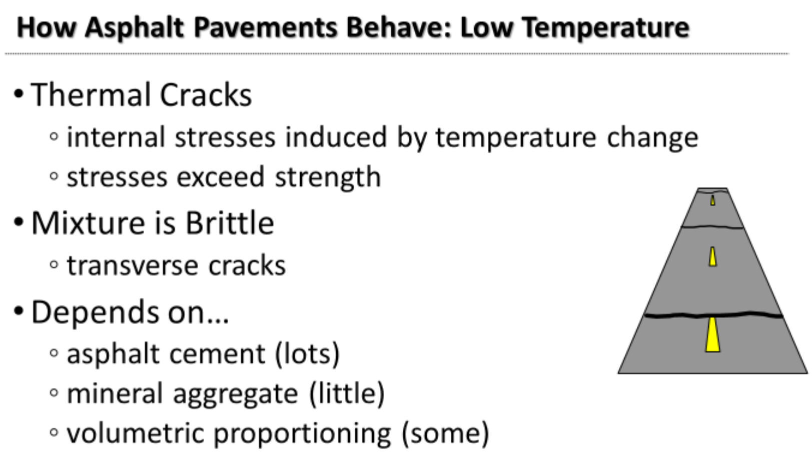

FIGURE 7 Behavioral characteristics of asphalt pavements at low pavement temperatures.

has shown that thermal cracking performance of asphalt mixtures is most strongly affected by the asphalt binder properties. The properties of the aggregate structure have little impact on thermal cracking; considering that the linear coefficient of thermal expansion for asphalt binder is on average about 17 times greater than the coefficient of thermal expansion for aggregate. The volume of the asphalt binder has an effect since it impacts the amount of asphalt binder connecting the aggregate particles.

Research reported in *NCHRP Report 673: A Manual for Design of Hot-Mix Asphalt with Commentary*, indicates that if the asphalt binder used in the mixture has the appropriate low temperature properties for the expected use, then the expectation for conventional asphalt mixtures will be that they will have adequate thermal cracking performance (Figure 8). It is generally accepted by many asphalt technologists that the low temperature properties in the PG Asphalt Binder Specification—stiffness and *m*-value from the BBR—effectively capture the contribution of the asphalt binder to thermal cracking. Instances where the low temperature cracking performance is better than expected in service are often related to conservative selection of grade for the environment (i.e., colder low temperature grade than would be required for the environment) or better strain tolerance, such as that usually imparted by PMA binders.

Figure 9 highlights the area that most asphalt technologists still believe needs work – a description of how asphalt pavements behave due to aging and the impact of oxidation on durability. In this case, the aggregate itself may have little to do with aging and durability (except for absorption of the aggregate and perhaps adhesion at the asphalt-aggregate interface). The volume of the asphalt binder in the mixture relative to the total available void space and the asphalt binder properties will have an impact on durability cracking.

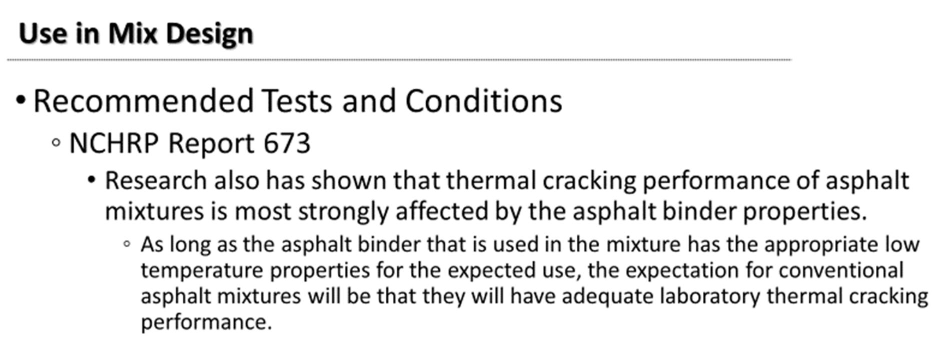

FIGURE 8 From *NCHRP Report 673,* recommendation for controlling low temperature cracking in asphalt mixtures.

How Asphalt Pavement Behaves: Aging

- Durability Cracks
  - Mixture is brittle
  - Random, wandering cracks
  - Longitudinal
  - Depends on
    - asphalt cement (some)
    - mineral aggregate (little)
    - volumetric proportioning (some)

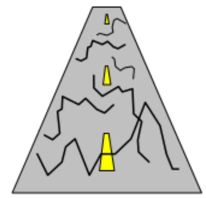

FIGURE 9 Behavioral characteristics of asphalt pavements due to aging.

NCHRP 20-44(19) Activities

- **Implementation of Proposed AASHTO Standards for Asphalt Binders and Mixtures**
  - Key Tasks
    - Assess the technical basis for any new or revised AASHTO standards proposed in the research projects.
      - Identify gaps in supporting data that must be addressed before adoption.
    - Identify and resolve any conflicts between the requirements of the various standards.
    - Assess the impact of the standard's adoption on state DOT and industry operations.
    - Provide technical support to COMP during review and balloting.

FIGURE 10 Purpose of NCHRP Project 20-44(19).

The impact of asphalt binder properties on the expected intermediate temperature durability cracking performance of asphalt mixtures is the focus of the presentation. Figure 10 discusses the research that was recently completed as part of several NCHRP research projects that address aging and intermediate temperature cracking. NCHRP Project 20-44(19), Implementation of Proposed AASHTO Standards for Asphalt Binders and Mixtures, was initiated to review the findings from the recent research projects, including three projects focused on asphalt binders: (1) assess the technical basis for the recommendations; (2) evaluate any potential gaps in data; and (3) assess how the recommendations might impact industry and agency operations (Figure 10).

For this presentation, two of the three asphalt binder research projects—NCHRP Project 09-59 and Project 09-60—are evaluated and their key findings discussed. The research and recommendations from these projects are expected to have an impact on the asphalt binder properties that affect intermediate temperature fatigue and durability cracking. These binder properties in turn are expected to impact how an asphalt mixture performs in a BMD framework. The third project, NCHRP 09-61, is important since it discusses the aging of asphalt binders but will likely have less impact than the findings from the other two projects. As such, it is not discussed in this presentation.

The titles of the three NCHRP projects and principal areas of focus are shown in Table 1.

The main findings and recommendations of the NCHRP 09-59 research were as follows.

- The Glover-Rowe Parameter (GRP) can be used as an intermediate temperature parameter on long-term aged asphalt binder to relate to the fatigue in asphalt mixtures through Fatigue Strain Capacity. The GRP is defined as $G^*\cos^2\delta/\sin\delta$. The proposed criterion is established as 5,000 kPa at a loading frequency of 10 rad/s at the appropriate intermediate specification temperature.
- The *R*-value of the asphalt binder can be calculated from BBR data and included in the specification as an added parameter related to durability. The *R*-value is a rheological representation of the shape of the asphalt binder master-curve at a reference temperature, showing how the modulus of an asphalt binder changes with temperature and/or loading frequency. The proposed limits are 1.5 to 2.5.
- The intermediate temperature to be used for specification testing is more appropriately based on the low temperature grade of the asphalt binder rather than the arithmetic average of the high and low temperatures plus 4°C.

The main findings and recommendations of the NCHRP Project 09-60 research were as follows.

- The durability and relaxation properties of an asphalt binder can be evaluated using the Delta T_c (ΔT_c) parameter, calculated from BBR data on long-term aged asphalt binder. Asphalt binders that have ΔT_c values lower than –6°C (assuming standard PAV aging) fail to meet the proposed criterion. Asphalt binders that have ΔT_c values higher than -2°C (assuming standard PAV aging) meet the proposed criterion without further testing required.

TABLE 1 NCHRP Cracking and Aging Projects

Project	Title	Main Area of Focus
NCHRP 09-59	Relating Asphalt Binder Fatigue Properties to Asphalt Mixture Fatigue Performance	Binder properties related to fatigue cracking
NCHRP 09-60	Addressing Impacts of Changes in Asphalt Binder Formulation and Manufacture on Pavement Performance Through Changes in Asphalt Binder Specifications	Binder properties related to non-load-related cracking and durability
NCHRP 09-61	Short- and Long-Term Binder Aging Methods to Accurately Reflect Aging in Asphalt Mixtures	Aging of asphalt binders in the lab

- Asphalt binders that have ΔT_c values between –2°C and –6°C can be qualified (i.e., meet the specification) by using an additional test and calculation. The ABCD test is used to measure the critical cracking temperature, which can be used with BBR data to calculate a new parameter, ΔT_f. This qualification step is suggested to better capture the strain tolerance of modified asphalt binders, recognizing that they may stretch and thereby handle more strain than an unmodified asphalt binder.

The use of an additional "qualifying test" is like what is currently described in Footnote G of the AASHTO M 320 and AASHTO M 332 specifications. In those specifications an asphalt binder that fails the BBR stiffness criterion of 300 MPa can pass the low temperature grade if: (1) the BBR stiffness does not exceed 600 MPa; (2) the BBR *m*-value does not fall below the minimum criterion of 0.300; and (3) the failure strain at the low test temperature using the DTT meets or exceeds 1%. Asphalt binders that meet the BBR criteria of 300 MPa (maximum) for stiffness and 0.300 (minimum) for *m*-value do not require the use of the DTT as they would be considered passing at that low temperature. Asphalt binders that fail to meet the BBR criteria of 0.300 (minimum) for *m*-value and/or exceed 600 MPa in stiffness do not require the use of the DTT as they would be considered failing at that low temperature.

More details on the findings of the NCHRP 09-59 and 09-60 projects are discussed further.

The NCHRP 09-59 research was published as *NCHRP Research Report 982: Relationships Between the Fatigue Properties of Asphalt Binders and the Fatigue Performance of Asphalt Mixtures*. Its principal authors were Don Christensen (Advanced Asphalt Technologies) and Nam Tran (NCAT). The objectives of the research project were to:

- Determine asphalt binder properties that are significant indicators of the fatigue performance of asphalt mixtures; and
- Identify or develop a practical, implementable binder test (or tests) to measure properties that are significant indicators of mixture fatigue performance for use in a performance-related binder purchase specification such as AASHTO M 320 and M 332.

Figure 11 describes the impact of using GRP as a parameter by examining how asphalt binders age (shown in the small graphic on the left from the Association of Asphalt Paving Technologists P 06-01 research project) and showing the relationship using several PG 64-22 and PG 76-22 asphalt binders tested by the Asphalt Institute lab in 2016. The small graphic on the left of the figure shows data plotted in BS (G* versus phase angle). The white circles represent the same conditions of temperature and loading frequency. As the asphalt binder ages from the unaged condition

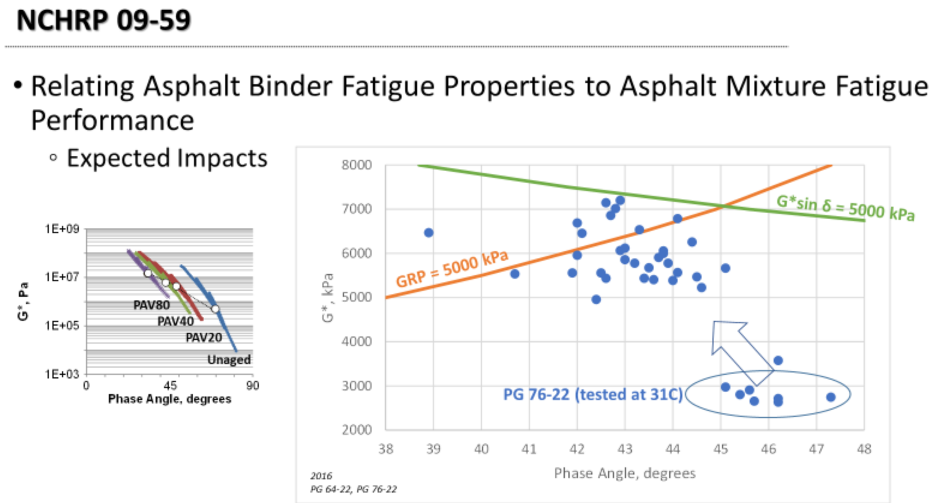

FIGURE 11 BS diagram describing how G-R parameter indicates binder aging.

through PAV20, PAV40, and PAV80 it progresses up (becomes stiffer with higher G*) and to the left (becomes more like an elastic solid with lower phase angle, δ). In the graphic on the right, aging would be expected to follow that same general path, as shown by the large arrow.

The data shows that all asphalt binders would meet the current AASHTO M 320 specification for intermediate temperature performance as represented by the green curve where G*sin δ is equal to 5,000 kPa. The shape of the curve in BS is such that when an asphalt binder ages, as represented by the arrow, it eventually crosses the curve but at an angle. The orange curve represents the case where GRP is equal to 5,000 kPa. The aging of the asphalt binder, represented by the arrow, would cause the asphalt binder to cross the specification curve more directly (i.e., perpendicular). This would appear to be a more rational approach, having a clear transition from passing to failing. The data also shows that there are a few instances where asphalt binders that met the current intermediate temperature specification would not meet the proposed specification using the GRP.

The calculation for *R*-value from BBR data is shown in Figure 12. It is a simple calculation that can be performed using existing test data performed to characterize the low temperature grade of the asphalt binder. A range on *R*-value has been proposed by the NCHRP 09-59 research, with greater emphasis placed on high *R*-values, which are expected to relate to poorer relaxation and poorer cracking performance.

NCHRP 09-59

- Relating Asphalt Binder Fatigue Properties to Asphalt Mixture Fatigue Performance

t Time (s)	P Force (mN)	d Deflection (mm)	Measured Stiffness (MPa)	Estimated Stiffness (MPa)	Difference (%)	m-value	R-value
8.0	978	0.228	346	346	0.000	0.282	1.96
15.0	977	0.273	289	288	-0.346	0.306	1.93
30.0	976	0.341	231	231	0.000	0.332	1.91
60.0	976	0.433	182	182	0.000	0.357	1.91
120.0	975	0.560	140	141	0.714	0.383	1.91
240.0	974	0.734	107	107	0.000	0.409	1.91

$$R = \log(2) * \frac{\log\left(\frac{S}{3000}\right)}{\log(1-m)} = \quad 0.30 * \frac{log\left(\frac{182}{3000}\right)}{log(1-0.357)} = 1.91$$

FIGURE 12 Calculation of *R*-value using BBR results.

NCHRP 09-59

- Relating Asphalt Binder Fatigue Properties to Asphalt Mixture Fatigue Performance
  - Recommendations

Low PG	Intermediate Test Temperature, °C
-10	29
-16	27
-22	25
-28	22
-34	19

FIGURE 13 Asphalt binder intermediate test temperature as a function of low PG.

The NCHRP 09-59 research team also suggested that the intermediate test temperatures used in AASHTO M 320 may not be correct, resulting in temperatures that are too cold being used for most asphalt binders with lower high temperature grades (e.g., PG 52 and PG 58) and temperatures that are too warm being used for asphalt binders with greater high temperature grades (e.g., PG 70 and PG 76). Figure 13 presents the recommendation to use an intermediate temperature based only on the low temperature grade of the asphalt binder instead of the current method which uses the average of the high and low temperature PG and adds 4°C.

The NCHRP 09-60 research has not yet been published but has completed Phases I and II, with an expectation of continuation into Phase III. The research team includes Jean-Pascal Planche (Western Research), Michael Elwardany (WRI), Don Christensen (Advanced Asphalt Technologies), Gayle King (Consultant), Carolina Rodezno (NCAT) and Snehalata Huzurbazar

(Consultant Statistician). The objective of the research project was to propose changes to the current PG Asphalt Binder Specification, tests, and practices to remedy gaps and shortcomings related to the premature loss of asphalt pavement durability in the form of cracking and raveling.

The graphic in Figure 14 shows the conceptual specification proposed in the NCHRP Project 09-60 research which uses ΔT_c as the main parameter to qualify durability cracking resistance of an asphalt binder. Asphalt binders having a ΔT_c value greater than –2°C (or warmer than –2°C) meet the minimum requirement as part of the proposed revision to the PG Asphalt Binder Specification. This is shown in green as Zone 1 in the graphic. Asphalt binders having a ΔT_c value less than –6°C (or colder than –6°C) fail to meet the minimum requirement as part of the proposed revision to the PG Asphalt Binder Specification. This is shown in red as Zone 2 in the graphic. Asphalt binders that fall into either Zone 1 or Zone 2 would require no additional testing. In between the absolute passing (–2°C) and absolute failing (–6°C) values for ΔT_c is an intermediate area represented by Zones 3 (green) and 4 (red) in which the ABCD test can be used to determine the critical cracking temperature (T_{cr}) and use that with the continuous grade temperature based on BBR stiffness ($T_{c,S}$) to calculate a parameter called Delta Tf (ΔT_f). This parameter provides an indication of the relative strain tolerance of the asphalt binder at a given stiffness with higher values of ΔT_f indicating better strain tolerance. Thus, ΔT_f can be used to accept an asphalt binder that otherwise might indicate from ΔT_c that it has potential issues with relaxation that could lead to durability cracking. The line separating Zone 3 (passing) from Zone 4 (failing) is a function of ΔT_c and ΔT_f with higher values of ΔT_f required as ΔT_c decreases towards the failure region (Zone 2).

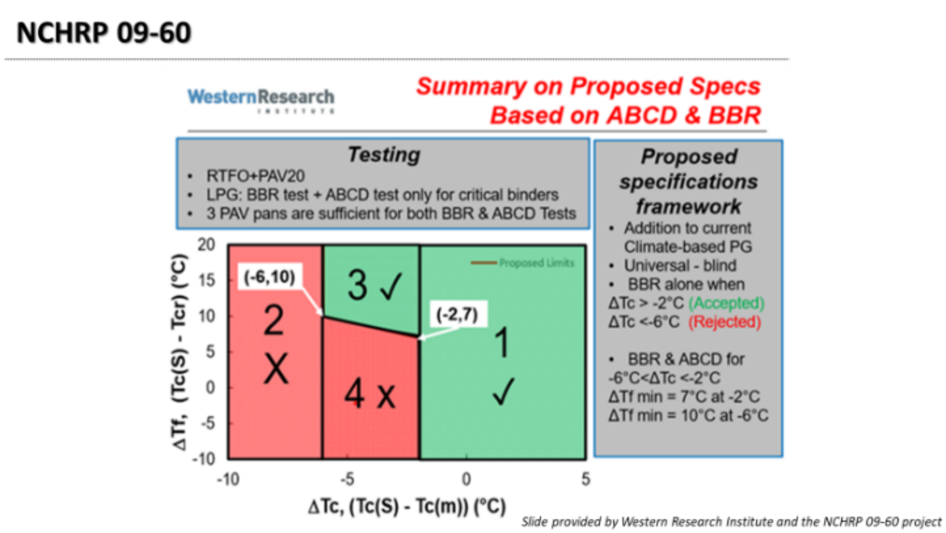

FIGURE 14 Conceptual specification suggested by NCHRP 9-60 using DT_c and DT_f.

Figure 15 shows the ABCD molds and environmental chamber used in the standard test procedure described in AASHTO T 387, Determining the Cracking Temperature of Asphalt Binder Using the Asphalt Binder Cracking Device.

The NCHRP 09-60 draft report shows how asphalt binders used in the research project would fare in meeting the requirements of the proposed specification (Figure 16). In this figure, asphalt binders were subjected to 40-h PAV aging (PAV40) so the proposed ΔT_c and ΔT_f values are a little different than shown in Figure 14, which is based on 20-h PAV aging (PAV20).

FIGURE 15 ABCD apparatus.

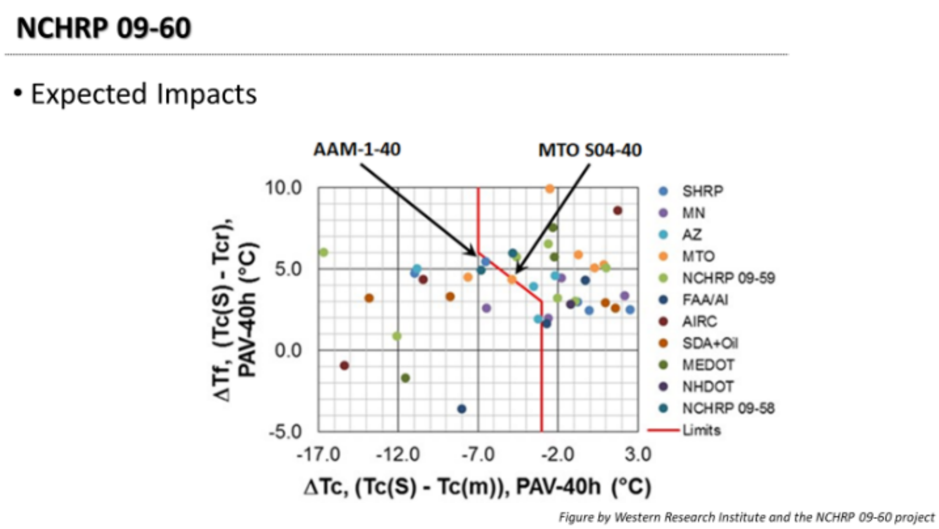

FIGURE 16 Effect of NCHRP 9-60 limits on specification compliance of binders used in that study.

The NCHRP 09-59 and 09-60 research projects have similar objectives in that they both focus on intermediate temperature binder properties and cracking. The NCHRP 09-59 research was focused on recommending an intermediate temperature parameter that provided an indicator of fatigue cracking (load-related) performance. The NCHRP 09-60 research was focused on recommending one or more parameters that were related to the loss of durability in the form of cracking and raveling—likely distress that was not load-related.

The relationships between aging, fatigue cracking, and durability cracking can be seen in a key paper from 1969 published in the *Journal of the Association of Asphalt Paving Technologists*. The performance of asphalt mixtures at the Zaca-Wigmore Test Road was identified in *SHRP Report A-367, Binder Characterization and Evaluation: Volume 1*, as being an important part of the decision by the SHRP researchers to focus on the use of G*sin δ as the fatigue-related performance parameter in the PG Asphalt Binder Specification (Figure 17).

In Figure 18, an excerpt from the conclusions in that paper note that there were two types of failure noted on the project. The most prevalent type of failure was fatigue cracking which appeared to be related to "…the consistency of the recovered asphalt as measured by penetration and viscosity." The other type of failure was block cracking with raveling that was more prevalent in the passing lane (i.e., the lane with expected less traffic loading). That cracking appeared to be related to "…a gain in shear susceptibility during weathering" and a "…marked drop in ductility during service life."

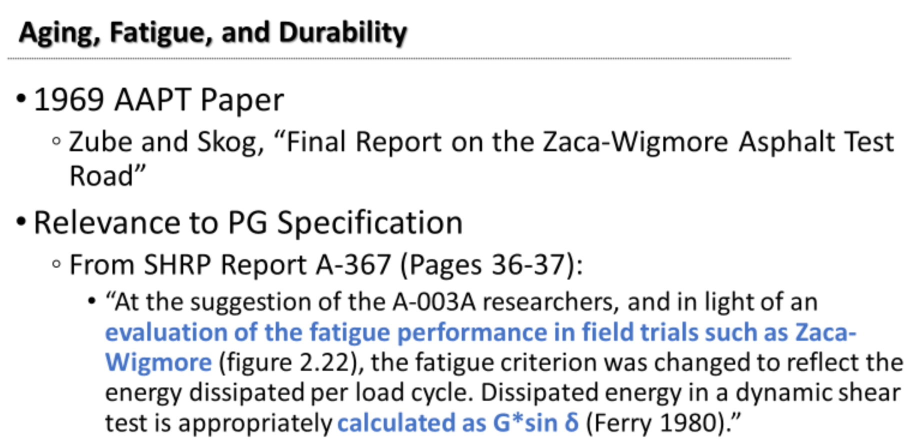

FIGURE 17 Effect of Zaca-Wigmore Test Road research results on PG binders specification.

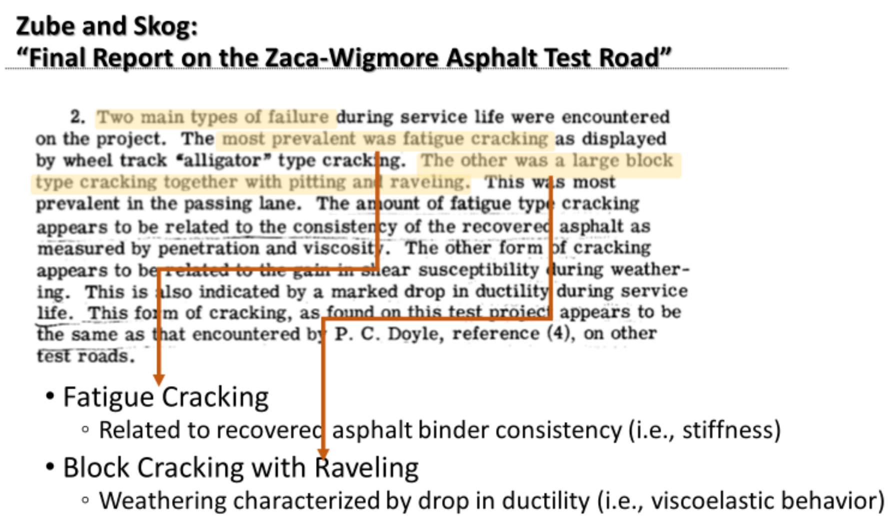

FIGURE 18 Excerpts from the final report of the Zaca-Wigmore asphalt test road.

In other words, fatigue cracking appeared to be related to increased stiffness of the asphalt while block cracking with raveling appeared to be related to decreased ductility. The current PG Asphalt Binder Specification addresses fatigue cracking through the G*sin δ parameter but does not directly address block cracking (Figure 19). The proposed revisions to the specification from the findings of the NCHRP 09-59 and 09-60 projects would address fatigue cracking using the GRP and block cracking using ΔT_c (NCHRP 09-60) or *R*-value (NCHRP 09-59), as shown in Figure 20.

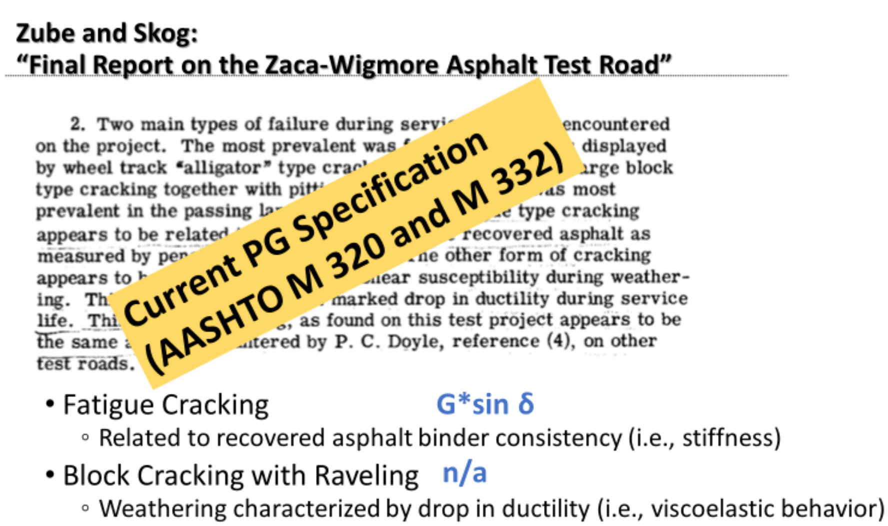

FIGURE 19 How current AASHTO asphalt binder specifications consider intermediate temperature cracking.

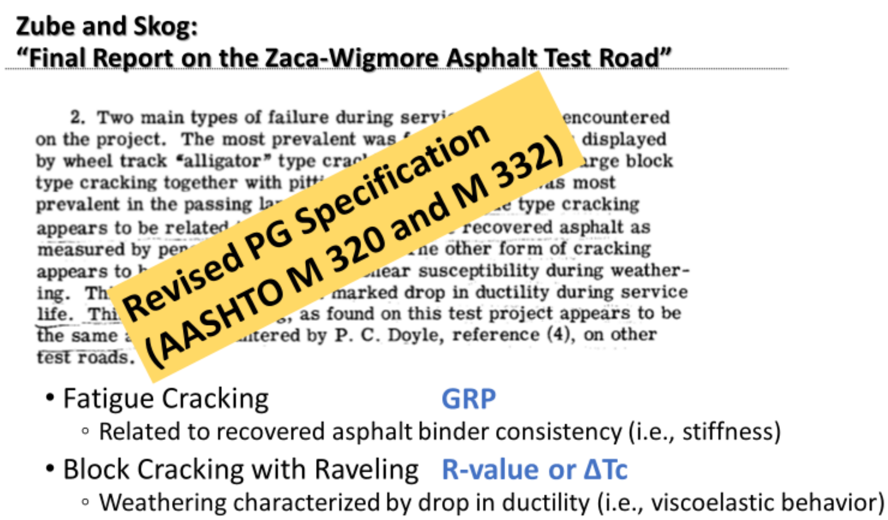

FIGURE 20 How proposed changes from findings of NCHRP 9-59 and 9-60 could consider intermediate temperature cracking.

As noted earlier in Figure 12, *R*-value is calculated from BBR data at one temperature—typically the passing low-grade temperature. To calculate ΔT_c requires data at a passing low-grade temperature as well as a failing low-grade temperature, which is typically just six degrees colder. In cases where ΔT_c is much less than –6°C, an additional colder temperature may be needed to bracket the specification for BBR Stiffness of 300 MPa.

Given that the passing low-grade temperature is used in both *R*-value and ΔT_c calculations, it is not surprising that they are related parameters. Figure 21 shows data mined from various results of unmodified asphalt binder testing conducted by the Asphalt Institute and others. In that figure, the points in orange represent calculated *R*-value and ΔT_c from the data in *SHRP Report A-645, SHRP Materials Reference Library: Asphalt Cements: A Concise Data Compilation*, used in the SHRP studies. The data lies in line with the rest of the data compiled by the Asphalt Institute in other studies. Figure 22 shows the form of the relationship for all the data which suggests that an *R*-value of 1.99 would correspond to a ΔT_c value of 0°C with an *R*-squared value of 0.91, showing a strong correlation between the two parameters.

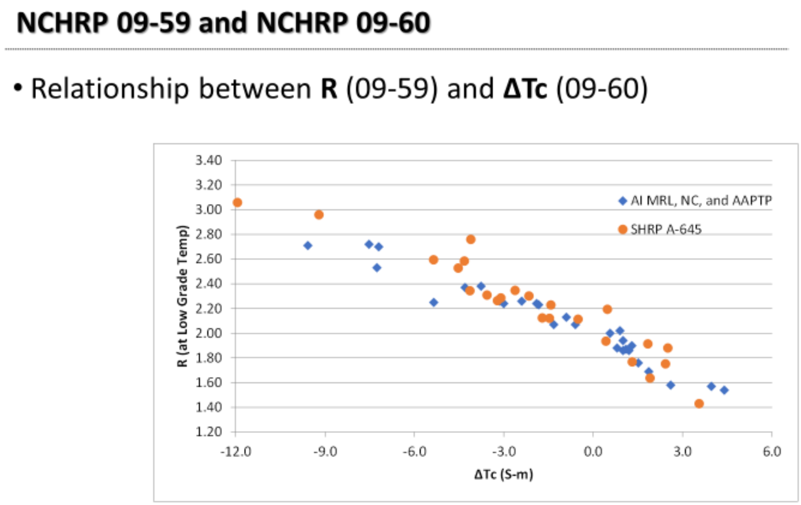

FIGURE 21 Relationship between *R*-value and DT$_c$.

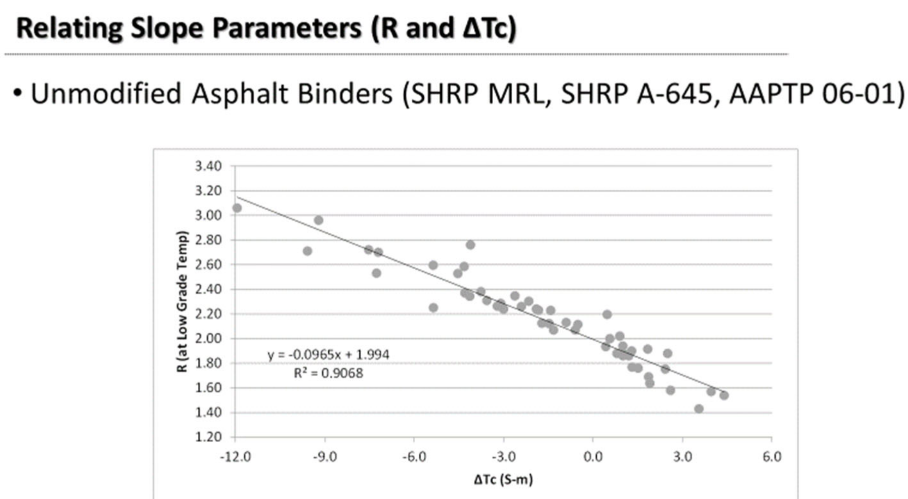

FIGURE 22 Equation describing the relationship between *R*-value and DT$_c$ (combined data from Figure 21).

One of the concerns previously expressed with the use of ΔT_c is that it may show polymer-modified binders to fail the proposed criterion. To address this concern, data was mined from the NCHRP Project 09-10, Superpave Protocols for Modified Asphalt Binders Research Project (*NCHRP Report 459: Characterization of Modified Asphalt Binders in Superpave Mix Design*) on modified asphalt binders. The relationship between *R*-value and ΔT_c (Figure 23) is still apparent and of approximately the same form (similar slope and intercept) as seen for the unmodified

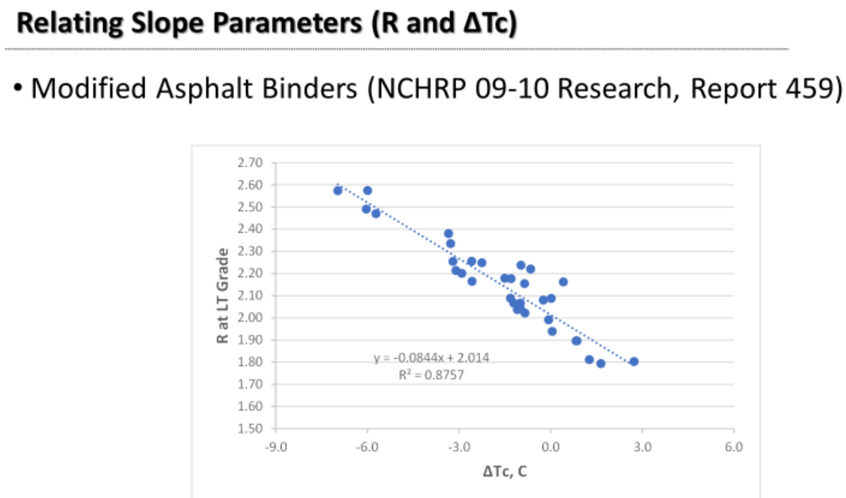

FIGURE 23 Relationship between *R*-value and DT$_c$ for NCHRP 9-10 binders.

asphalt binders in Figure 21 and Figure 22. This suggests that either parameter, *R*-value or ΔT_c, should provide a similar response to addressing durability cracking, although the proposed specification limits are a little different. Although the two parameters appear to address the same distress (durability cracking), it should be noted that strain tolerance, as indicated by ΔT_f, is not addressed except in the NCHRP 09-60 research.

The original question posed in the workshop was how asphalt binder supply (i.e., asphalt binder properties) might affect BMD. To address this, Figure 24 is presented to show how ΔT_c changes with type and amount of RAP used in a blend as well as the virgin asphalt binder used in the blend. The data presented comes from work done by the Asphalt Institute and Purdue University as part of the NCHRP 09-12 research. Although the graphs show data for two different grades of asphalt binder, it also could have represented one grade of asphalt binder from different sources with different values of ΔT_c—one in which the material had a ΔT_c value of +2°C and one in which the material had a ΔT_c value of –2°C. Similarly, although there are two RAP piles that are shown representing RAP from Connecticut and Arizona, it could also have been two different RAP piles from the same state available for use at the plant coming from different projects and with different RAP asphalt binder stiffness. The designer would then have a choice between which asphalt binder to use and which RAP to use.

In this example, assume for the sake of illustration that the user specifies that the blended asphalt binder in the mix cannot have a ΔT_c value lower than –4°C. If the mix designer had the asphalt binder with ΔT_c = –2°C (red data) available, then they would be able to use a maximum of 35% of RAP 1 (CT) or 14% of RAP 2 (AZ) to meet the –4°C limit. If the mix designer had the

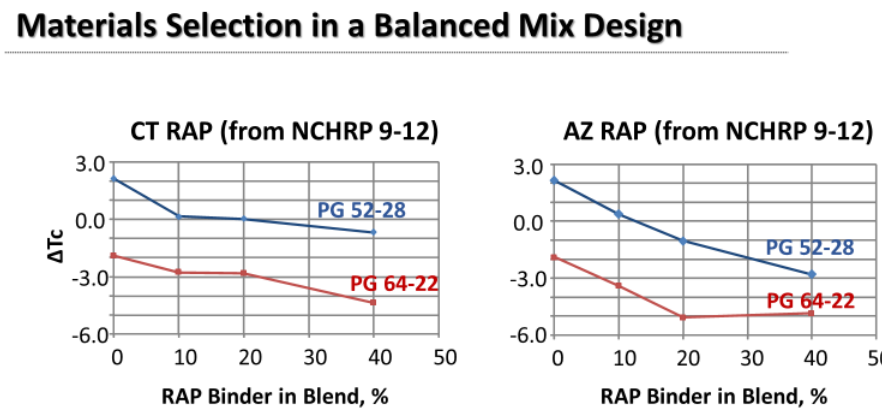

FIGURE 24 DT_c as a function of type and amount of RAP

asphalt binder with ΔT_c = +2°C (blue data) available, then they would be able to use as much as 40% or more of either RAP to meet the limit of –4°C.

The following figures (Figures 25, 26, and 27) were not part of the original presentation but were added as part of a later presentation to attempt to further highlight how asphalt binder properties could impact BMD properties. In the figures, two asphalt mixtures were prepared having the same aggregate structure and asphalt binder content, but two different PG 64-22 asphalt binders. Specimens were compacted to the same target percentage of air voids (7.0 ± 0.5%) and tested at 25°C using the IDEAL-CT after short-term aging (identified as "ST-4" and representing 4 h of loose mix aging at 135°C) and long-term aging (identified as "LT-#" representing loose mix aging at 95°C for the number of days represented by the number following "LT").

The results in Figure 25 show a clear impact of aging but importantly show that two asphalt binders having the same grade could have different performances in a cracking index test. Figure 26 shows data indicating that the G* value of the two asphalt binders at 25°C is virtually identical. The current parameter in AASHTO M 320 and M 332 to characterize intermediate temperature fatigue cracking, G*sin δ, would indicate better cracking performance for the NC-D asphalt binder compared to the NC-F asphalt binder. The CT index shows the opposite. However, when the GRP is calculated, it shows that the NC-F asphalt binder would have better cracking properties than the NC-D asphalt binder.

In addition to a higher GRP value, the NC-D asphalt binder has a lower value of ΔT_c (–4.3°C) and higher *R*-value (2.37) than the NC-F asphalt binder (Figure 27). In all instances, though, the intermediate temperature property values would meet the proposed specification, meaning both asphalt binders would be considered to be equal grades—even though there may be an apparent difference in the CT index values.

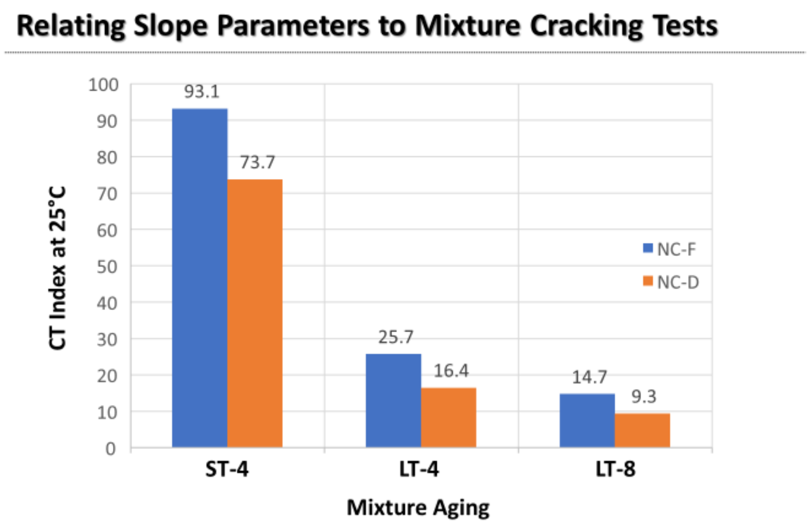

FIGURE 25 Effect of aging and binder source on BMD cracking test results.

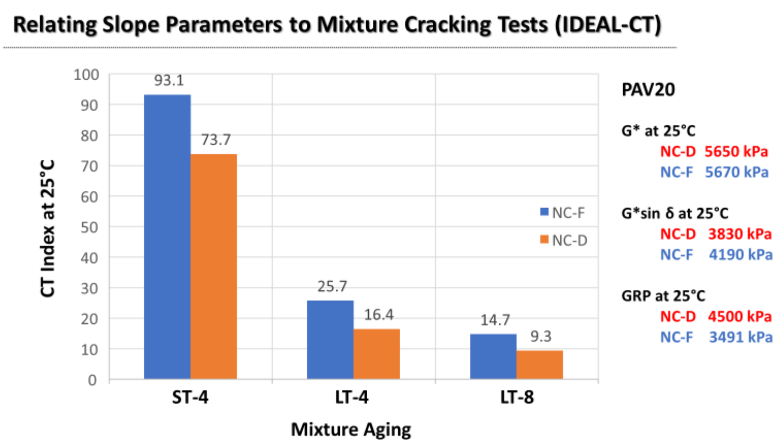

FIGURE 26 Illustration of how GRP binder result validates BMD cracking test results.

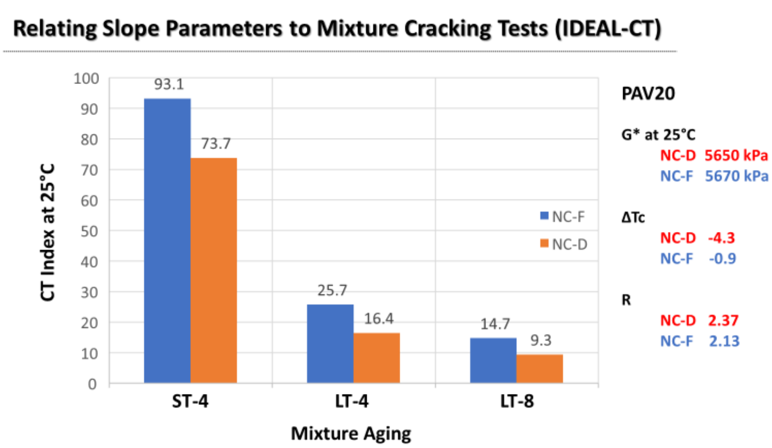

FIGURE 27 Illustration of how DT_c and *R*-value binder results validate BMD cracking test results.

Although there is a difference shown in the CT index values the mix designer will need to ascertain how significant the difference may be and what other factors could affect the values. For instance, how would changing the asphalt binder content or aggregate structure impact the results?

Figure 28 offers a summary of the key points of the presentation, reiterating that: (1) appropriate asphalt binder characteristics contribute to the successful performance of an asphalt mixture; but (2) asphalt binder characteristics are not the only factors that impact performance. Proper aggregate characteristics, good aggregate structure, proper volume of asphalt binder and air voids, and proper use of recycled materials all also contribute to an asphalt mixture's performance from a materials standpoint. The mix designer has those tools available for use in developing a BMD. Ultimately, the mix designer should understand that other factors outside of materials—proper thickness design, production, and construction—also have a role in the successful performance of an asphalt pavement.

The presentation concludes with a call back to the beginning, showing the 1992 USDA Food Pyramid and the nutrition/cookbook that the presenter personally used in achieving the goal of losing more than 30 pounds in 1988, generally following the principles shown in the food pyramid. The advice at the time was to base one's diet on high carbohydrates in the form of foods like grains, rice, and pasta. The advice by some dieticians in 2012 follows the Atkins method which is a low carbohydrate diet that minimizes the consumption of grains, rice, and pasta. Twenty-four years after first achieving a weight loss goal, the presenter was able to again achieve the goal of losing more than 30 lbs using a different approach.

The moral of that illustration (Figure 1) is to remind the audience and reader that there may be more than one way of achieving the same goal—whether in weight loss or BMD.

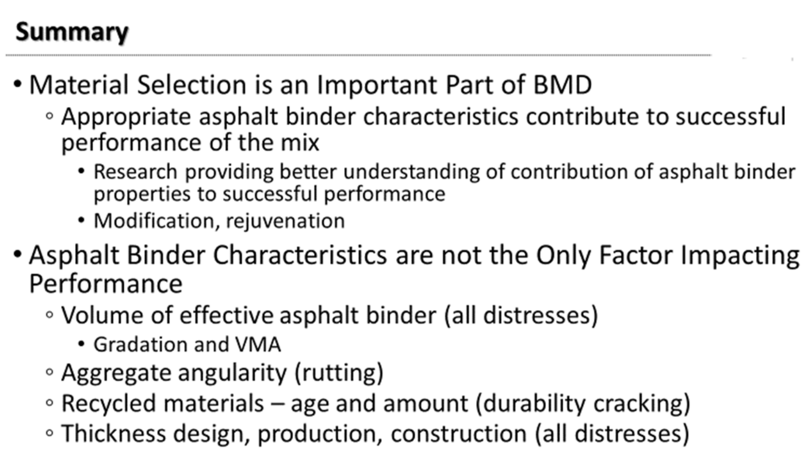

FIGURE 28 Summary of key points in the effect of binder properties on BMD.

Workshop Key Takeaways

From the information presented at the workshop, gaps remain in information available to mix designers that would help them select favorably from an array of asphalt sources with the goal of achieving BMD performance requirements. It was pointed out that factors driving refinery production may produce variability in asphalt characteristics, even within a single supply source. Therefore, physical property tests such as currently used in purchase specifications may not completely (or at all) identify and correctly measure the characteristics that are important in achieving BMD specifications. Current and future research in various chemical analytical tools for asphalt binders may show that chemical characterization is necessary to augment physical property testing or point out the limits to fully mobilize the advantages of different asphalt sources in terms of meeting BMD requirements.

Case studies from New Jersey and Massachusetts showed that asphalt production and source changes can produce a binder meeting current PG specifications, but not necessarily provide the requisite pavement performance. A key point was made that to fully gain the performance benefits of some PMA binders; the asphalt technical community may need to break some of the existing mix design rules to achieve optimum pavement performance. Specifically, to achieve cracking resistance, it will likely be necessary to design at a lower air void content than traditionally used. Although this strategy has nothing to do with asphalt source, it is possible that by giving the mix designer the ability to change some of the traditional design parameters, asphalt source may become less significant. This hypothesis is backed up by decades of French mix design experience, which is entirely based solely on mixture performance testing. It was pointed out that it is important to select performance properties based on asphalt mixture position within the pavement structure. Structural layers need to be optimized with respect to stiffness and fatigue resistance whereas surface layers should be designed to guard against rutting, thermal cracking, and aging and ensure sufficient friction.

The effect of asphalt source on BMD properties is evidently confounded by insufficient knowledge in fundamental interactions between aggregate mineralogy and asphalt binder and the effect of those interactions on performance properties. Consequently, an important tool needed by mix designers is a quick screening test(s) aimed at identifying favorable combinations of asphalt and aggregate to meet BMD requirements.

Binder contained in RAP is a critically important asphalt supply source and thus, there is a need for greater understanding of the interactions that occur between virgin and RAP binders and the effect of those interactions on BMD performance properties. The effect on BMD properties of various existing and new-to-market rejuvenating agents is currently being studied and will likely continue to be. Recommendations for grade dumping (reducing high and low temperature performance grades) and for when hybrid strategies are employed (changing binder and variability in recycled binder availability) are needed. Research outcomes from NCHRP Project 09-58 including an AASHTO Standard Practice are to be implemented moving forward.

Finally, recent research on asphalt binders (NCHRP Projects 09-59, 09-60, and 09-61) pointed out that there remain significant gaps in performance evaluations of asphalt binder alone. Intermediate temperature binder cracking characteristics likely need to be evaluated at different temperatures. The lack of a relevant asphalt binder failure test is a critical gap in the current PG specification. Clearly this gap also translates to a gap for mix designers when evaluating different asphalt sources for cracking resistance. Existing or proposed binder parameters such as DT_c, DT_f, the GRP, and *R*-value show some promise but do not yet represent a tool readily available to mix designers. Although they may offer important upgrades to the current PG specifications, this is still work in progress.

In summary, mix designers transitioning from a volumetrics-only specification environment to BMD-based mix design need tools that allow them to make quick and accurate material selection decisions. Of keen interest are tools that assist mix designers in selecting asphalt binders among various commercial sources that indicate the highest probability of success in terms of required BMD performance properties. Information presented at Workshop Session 1022 at the 102nd Annual TRB meeting and summarized in this E-Circular presents current knowledge and identified existing gaps needed by mix designers. It is the great hope of the Committees that sponsored the workshop that research and practice will continue to move toward identifying the tools that exist as well as facilitate the development of needed tools that will result in reliable asphalt mixtures with adequate field performance.