

**NCAT Report 19-08**

**MIX DESIGN STRATEGIES  
FOR IMPROVING ASPHALT  
MIXTURE PERFORMANCE**

**By**

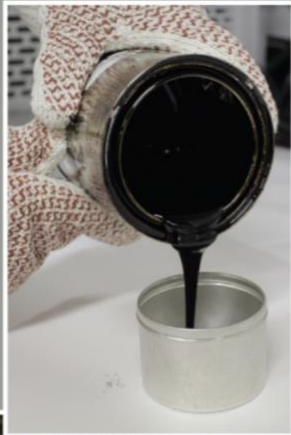
**Nam Tran**

**Gerry Huber**

**Fabricio Leiva**

**Bill Pine**

**Fan Yin**



**October 2019**



**277 Technology Parkway ■ Auburn, AL 36830**

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Nam Tran, PhD, PE  
Assistant Director and Research Professor  
National Center for Asphalt Technology  
Auburn University, Auburn, Alabama

Gerry Huber, PE  
Associate Director of Research  
Heritage Research Group

Fabricio Leiva, PhD  
Assistant Research Professor  
National Center for Asphalt Technology  
Auburn University, Auburn, Alabama

Bill Pine, PE  
Quality Control Director of Asphalt Technology  
Heritage Construction and Materials

Fan Yin, PhD, PE  
Assistant Research Professor  
National Center for Asphalt Technology  
Auburn University, Auburn, Alabama

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### **DISCLAIMER**

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## **1 INTRODUCTION**

The original vision of the Superpave mix design system was to include performance tests in addition to volumetric requirements. However, the proposed performance tests were not implemented primarily because they were not practical for routine use. In the early years of Superpave implementation, the primary focus was on rutting resistance. Most state highway agencies (SHAs) now report that rutting is not a significant problem. However, there have been increasing concerns that asphalt mixtures being produced may not have an adequate amount of asphalt binder, and thus, are susceptible to durability and cracking issues. For this reason, SHAs have been making adjustments to the mix design procedure with the intent of improving mixture durability while evaluating mixture performance tests related to rutting and cracking for future implementation.

### **1.1 Objective and Scope**

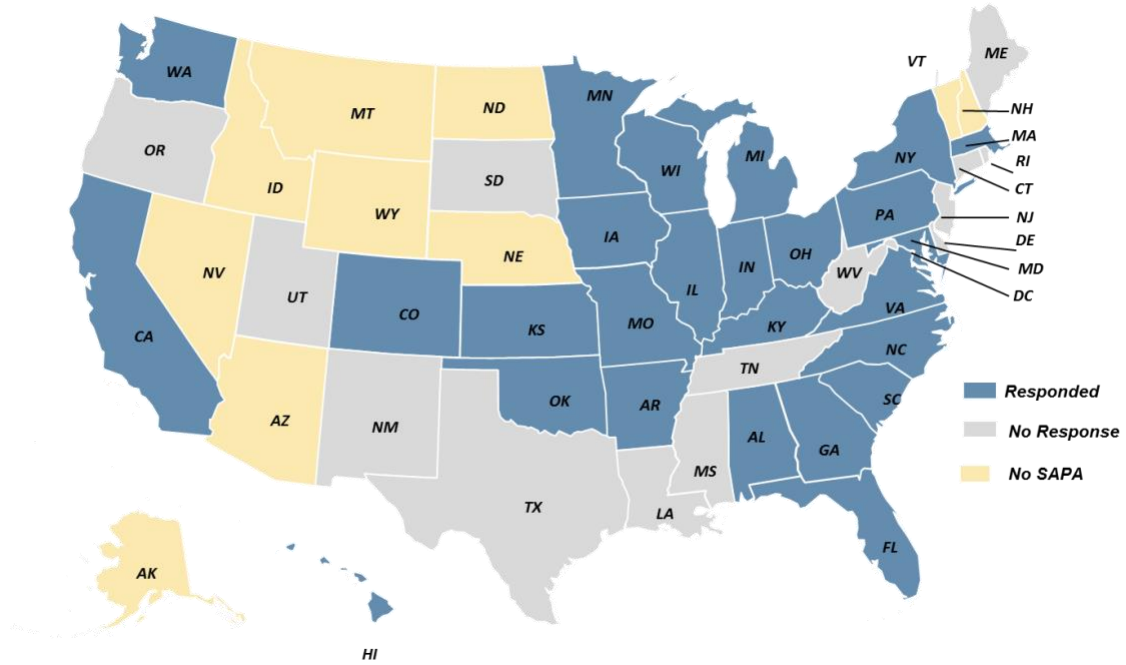
The objective of this study was to document adjustments made by SHAs over the past decade to the Superpave mix design procedure and understand how they may improve pavement performance. The focus of this study was placed on the mix design strategies without mixture performance testing.

The study included a survey of state asphalt pavement associations (SAPAs) to document the adjustments that have been made to the Superpave volumetric mix design system and materials specification by SHAs. Based on the survey results, three adjustments were identified as potentially providing the greatest improvement in pavement performance. A literature review was then conducted to gather information about the impact of these changes on the pavement performance. This report summarizes the findings of that effort.

In addition, the report also briefly discusses the Superpave5 mix design method and the Bailey method. The Superpave5 method was designed to improve the in-place density. The Bailey method can be used to better control the volumetric properties of asphalt mixtures. When combined with the adjustments to the mix design procedure identified in the survey, these methods can have positive impacts on mixture performance.

## **2 SURVEY OF STATE ASPHALT PAVEMENT ASSOCIATIONS**

An online survey of SAPA representatives was conducted at the beginning of this study to document adjustments to the volumetric mix design system that can potentially improve asphalt pavement performance. Specific objectives of the survey were to (1) identify potential changes that can improve asphalt mixture durability without mixture performance testing, (2) find out how many of these changes have been implemented by SHAs, and (3) determine the availability of historical data for evaluating the impact of specification changes on asphalt mixture durability in the future. The survey was sent to SAPAs representing contractors in 40 states, with 26 responses received as shown in Figure 1. Ten other states do not have SAPAs. A copy of the survey questionnaire is provided in Appendix A.



**Figure 1. U.S. Map of SAPA Survey Responses**

In the survey, SAPA representatives were given a list of potential changes to the volumetric mix design and asked to select the top five changes they thought would provide the greatest improvement in asphalt pavement performance. Based on the changes selected by each representative, the survey responses are compiled in Table 1. Increasing the use of polymer-modified binders was the most selected response by SAPA representatives, followed by adopting the regressed air voids approach and making changes to mix design specifications to increase in-place density. Other changes that received more than five responses include decreasing design compaction effort ( $N_{design}$ ), targeting lower design air voids, increasing minimum voids in the mineral aggregate (VMA), and setting a minimum effective binder content. In addition, several survey respondents indicated that mixture performance testing in conjunction with volumetric testing has the potential to improve the long-term durability and cracking resistance of asphalt mixtures.

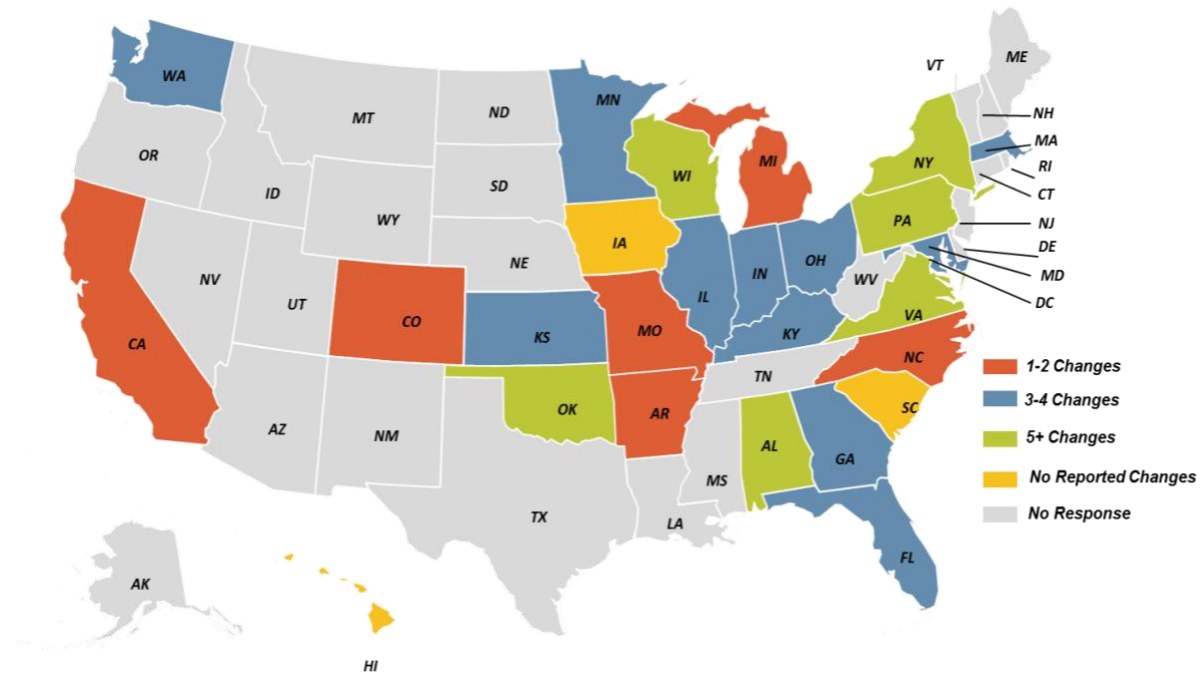
**Table 1. Selection of Top Five Changes to Potentially Improve Asphalt Mix Durability**

<b>Changes to Volumetric Mix Design System</b>	<b>No. of Responses</b>
Increasing use of polymer-modified binders	15
Adopting regressed air voids approach	13
Making changes in mix design to potentially increase in-place density	13
Decreasing design compaction effort ( $N_{\text{design}}$ )	12
Targeting lower design air voids	9
Increasing design voids in mineral aggregate (VMA)	9
Setting a minimum effective binder content	9
Allowing or requiring recycling agents	5
Changing other requirements for recycled materials	4
Requiring WMA technology and lower mixture production temperatures	4
Requiring higher or lower PG grades (either the high or low temperature)	3
Adopting $\Delta T_c$ specification for asphalt binders	3
Setting or verifying specific gravity of aggregate	3
Decreasing recycled asphalt shingles (RAS) content allowed	3
Setting a minimum total binder content	3
Adopting multiple-stress creep recovery (MSCR) specification	2
Eliminating RAS	2
Setting minimum asphalt film thickness	2
Increasing moisture susceptibility requirements or use of antistrip	2
Decreasing reclaimed asphalt pavement (RAP) content allowed	1

SAPA representatives were then asked to indicate which of the potential changes to the volumetric mix design have been adopted by their SHAs. Based on the survey responses, a list of specification changes is compiled in Table 2. The top five changes in the list include (1) adopted multiple-stress creep recovery (MSCR) specification for asphalt binders, (2) increased use of polymer-modified asphalt binders, (3) decreased  $N_{\text{design}}$ , (4) decreased design air voids, and (5) increased design VMA. The first two changes focused on improving the quality of asphalt binder, while the latter three changes were intended to increase the amount of asphalt binder in the total mix. Figure 2 and Table 3 present the number of specification changes made by these SHAs and when the changes were implemented, respectively. As shown, six SHAs implemented one or two changes, eleven agencies implemented three to four changes, and six agencies implemented more than five changes.

**Table 2. Summary of Specification Changes Implemented by State Highway Agencies**

Specification Changes Implemented by State Highway Agencies	No. of Responses
Adopted MSCR specification for asphalt binders	9
Increased use of polymer-modified binders	8
Decreased $N_{design}$	8
Decreased design air voids target	8
Increased design VMA	6
Set a minimum total binder content	5
Required higher or lower PG grades (either the high or low temperature)	4
Adopted regressed air voids approach	4
Set or verified specific gravity of aggregate	4
Decreased RAS content allowed	4
Changed other requirements for recycled materials	4
Made changes in mix design to potentially increase in-place density	4
Eliminated RAS	3
Increased moisture susceptibility requirements or use of antistrip	3
Decreased RAP content allowed	2
Allowed or required recycling agents	2
Set a minimum effective binder content	2
Set a minimum asphalt film thickness	2
Adopted $\Delta T_c$ specification for asphalt binders	1
Required WMA technology and lower mixture production temperatures	1



**Figure 2. U.S. Map of Specification Changes Implemented by State Highway Agencies**



**Table 3. Time when Specifications Changes were Implemented by State Highway Agencies**

<b>Specifications Changes</b>	<b>Year Implemented (state)</b>
Required higher or lower binder grades	1998 (VA), 2015 (WI), 2018 (CA, KS)
Increased use of polymer-modified binders	1993 (OH), 1996 (VA), 2005 (FL, IL), 2010 (PA), 2016 (MA), 2017 (KY, NY)
Adopted MSCR specification for asphalt binders	2014 (MD), 2015 (FL, MN, NY, PA, VA), 2017 (OK, WI), 2018 (WA)
Adopted $\Delta T_c$ specification for asphalt binders	2019 (FL - to be implemented)
Decreased $N_{design}$	1998 (VA), 2008 (GA, MD, NY), 2010 (AL, OH), 2012 (IL, OK), 2015 (PA), 2016 (VA)
Decreased design air voids target	2000 (MD), 2008 (NY), 2010 (OH), 2015 (AL), 2016 (MN, VA), 2017 (KS), 2018 (AR)
Adopted regressed air voids approach	2012 (MI), 2014 (PA), 2015 (MI), 2017 (WI)
Increased design VMA	2012 (IL, PA), 2014 (WI), 2016 (VA), 2017 (IN), 2018 (WA)
Set/Verified specific gravity of aggregate	1998 (VA), 2014 (PA), 2017 (IN), 2018 (IN)
Decreased RAP content allowed	2017 (IN, KY)
Decreased RAS content allowed	2016 (MA), 2017 (IN, KY), 2018 (AL)
Eliminated RAS	2012 (OK), 2016 (CO), 2018 (AL)
Changed other requirements for recycled materials	2012 (GA, MD), 2015 (WI), 2016 (NC)
Allowed or required recycling agents	2008 (MO), 2015 (KS)
Set a minimum total binder content	2004 (OK), 2010 (AL), 2012 (OK), 2016 (VA), 2017 (KY)
Set a minimum effective binder content	2010 (AL), 2014 (PA)
Set a minimum asphalt film thickness	2012 (GA), 2016 (MN), 2017 (MN)
Increased moisture susceptibility requirements or use of antistrip	2017 (PA, WI), 2018 (AR)
Required WMA technology and lower mixture production temperatures	2016 (MA)
Made changes in mix design to potentially increase in-place density	2008 (NY), 2016 (VA), 2017 (WI), 2018 (WA)

SAPA representatives were also asked to identify the impact of each proposed specification change (listed in Table 3) to volumetric mix design system on mix durability, bid costs, staffing requirements, and use of recycled asphalt materials. Their responses are summarized in Table 4.

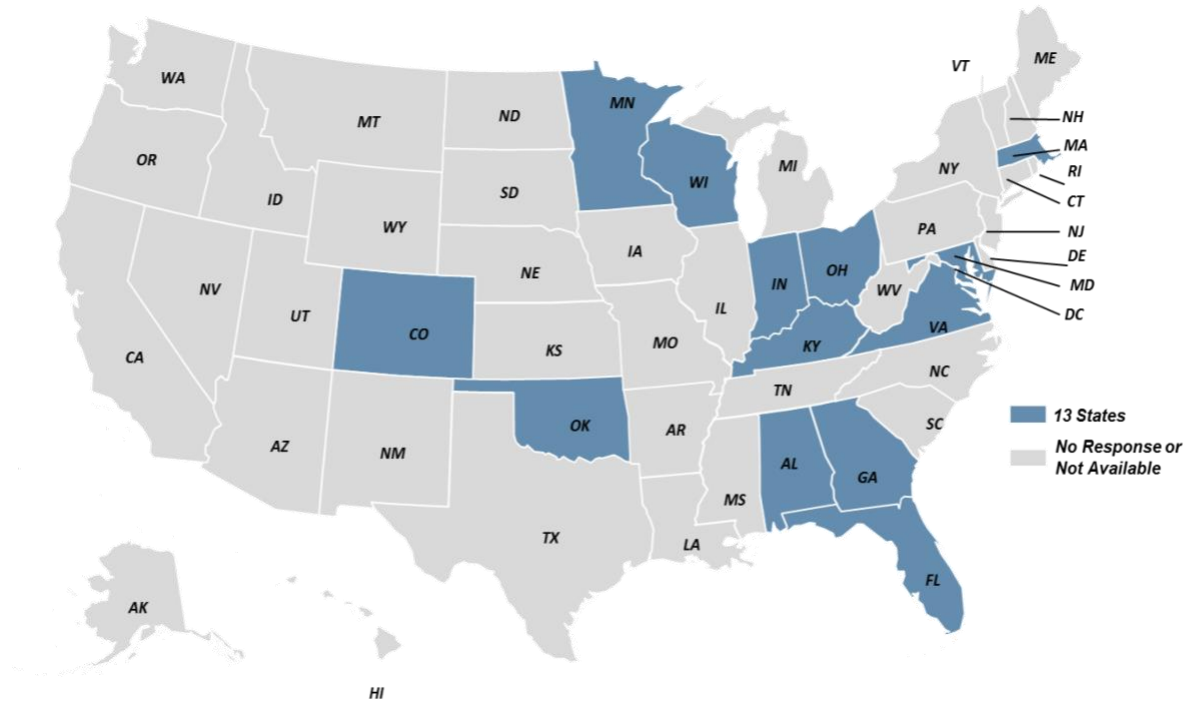
- Decreased  $N_{design}$  (with 9 states selecting this option) and increased use of polymer-modified binders (with 8 states selecting this option) were identified as having the most significant impacts on mix durability, followed by decreased design air voids and increased design VMA (with six states selecting this option).

- The two changes that are likely to have a significant impact on mix bid price are increased design VMA and increased use of polymer-modified binders. In addition, adopting MSCR specification for asphalt binders, setting minimum total binder content, and increasing moisture susceptibility requirements or mandating the use of antistrip agents are also selected as they can increase the mix bid price.
- Based on the survey results, the expected impact of the specification changes on staffing requirements is negligible.
- Finally, decreasing the allowable limit for RAS can reduce its use in asphalt mixtures. Strategic changes of binder grade and use of recycling agents (or rejuvenators) may increase the use of RAP and/or RAS materials. However, the effects of these changes are different for RAP and RAS materials, so they should be separately specified and managed.

**Table 4. Number of SAPA Responses Indicating Impact of Each Specification Change on Mix Durability, Bid Costs, Staffing Requirements, and Recycled Materials Usage**

Changes to Volumetric Mix Design System	Number of Responses Indicating Impact on...			
	Mix Durability	Bid Costs	Staffing Requirements	Recycled Materials Use
Decreased $N_{design}$	9	2		
Increased use of polymer-modified binders	8	5		2
Decreased design air voids target	6	1		
Increased design VMA	6	6	1	2
Required higher or lower binder grades	4	2		3
Adopted MSCR specification for asphalt binders	4	3	1	
Set a minimum total binder content	4	3		
Made changes in mix design to potentially increase in-place density	4	2	1	1
Adopted regressed air voids approach	3	1		1
Eliminated RAS	3	2		2
Changed other requirements for recycled materials	3	1		1
Set minimum effective binder content	3	2		
Increased moisture susceptibility requirements or use of antistrip	3	3	1	1
Set/verified specific gravity of aggregate	2	1	1	
Decreased RAS content allowed	2	2		3
Adopted $\Delta T_c$ specification for asphalt binders	1			
Decreased RAP content allowed	1	2		2
Allowed or required recycling agents	1	2		3
Set minimum asphalt film thickness	1	1		1
Required WMA technology and lower mixture production temperatures	1	1		1

The survey results also identified 13 states with historical data (i.e., field performance data and/or lab test results) available that can be used to evaluate the impact of specification changes to volumetric mix design system on asphalt mix durability, if needed, in the future (Figure 3).



**Figure 3. U.S. Map of SHAs with Historical Data Available to Evaluate the Impact of Specification Changes on Asphalt Mix Durability**

The key findings of the SAPA survey are summarized as follows:

- Based on the SAPA representatives' responses, the top three changes that can provide the most improvement in asphalt mix durability are:
  1. Increased use of polymer-modified binders
  2. Regressed air void method to determine the optimum binder content
  3. Changes to mix design to increase in-place density
- As reported by survey respondents, the top three changes implemented by SHAs are:
  1. Adopting MSCR specifications for asphalt binders
  2. Increased use of polymer-modified binders
  3. Two other changes, including decreased  $N_{design}$  and decreased design air voids, having equal responses and tying for the third.
- Among the potential changes to the volumetric mix design system, the top three adjustments that may impact the mix bid price are:
  1. Increased design VMA
  2. Increased use of polymer-modified binders
  3. Four other changes, including adopting MSCR specifications for asphalt binders, setting minimum total binder content, increasing moisture susceptibility requirements, and mandating the use of antistripping agents, having equal responses and tying for the third.

- The survey respondents also reported that 13 states have historical data that can be used to evaluate the impact of specification changes on asphalt mix durability (Figure 3).

In summary, the changes suggested by the SAPA representatives generally agreed with those implemented by SHAs, and they can be grouped in the following three categories. The changes that have been implemented to improve asphalt mixture performance are further discussed in the next section.

- Improving the quality of asphalt binder through the increased use of polymer.
- Making other changes to mix design to increase in-place density, such as lowering the  $N_{\text{design}}$  requirement(s).
- Increasing the binder content by lowering the design air voids, adopting the air void regression method, or increasing the minimum VMA requirement to determine the optimum binder content.

### **3 CHANGES IN VOLUMETRIC MIX DESIGN TO IMPROVE PERFORMANCE**

The Superpave volumetric mix design procedure was established to ensure sufficient space for asphalt binder to provide long-term mix durability while maintaining adequate aggregate structure to resist densification and rutting (1). The implementation of Superpave mix design has significantly improved performance, especially the rutting resistance, of asphalt pavements and overlays. However, there have been increasing concerns among SHAs over the last several years that the asphalt binder content of many Superpave mix designs has been below the levels desired for durability (2, 3). In other words, mixtures designed utilizing the current procedure may not have an adequate amount of asphalt binder, and thus, are susceptible to durability and cracking issues. To overcome these issues, highway agencies have implemented changes in their asphalt mix design specifications to improve asphalt mixture durability. The adjustments identified in the survey are discussed in the following subsections. Each subsection starts with background information about an adjustment to the volumetric mix design system followed by a brief summary of research showing how the change can improve asphalt mixture performance and a volumetric mix design example to illustrate how the change can affect the mixture volumetric properties.

#### **3.1 Increased Use of Polymer Modified Asphalt**

The asphalt industry has a long history of using polymer modified asphalt (PMA) to mitigate the major forms of pavement distresses, including rutting, fatigue cracking, and thermal cracking, while extending the service life of asphalt pavements and overlays. It has become common practice for SHAs to specify polymer modified binders in mixtures subjected to high traffic volumes primarily to improve rutting resistance. Some agencies, such as Nevada and Louisiana Departments of Transportation (DOTs), require polymer modified binders in all surface course mixtures.

The commonly used polymers for asphalt modification can generally be classified into two categories: plastomers and elastomers, as shown in Table 5. Plastomers are typically used to improve the high-temperature properties of asphalt binders, and thus, are often specified in projects where rutting is a concern. However, plastomers have little or no elastic component,

usually resulting in reduced strain and deformation tolerance. As a result, binders modified with plastomers are more susceptible to cracking due to increased embrittlement and reduced relaxation properties. The most commonly used plastomers for asphalt modification include polyethylene (PE), polypropylene (PP), and ethylene-vinyl-acetate (EVA). Unlike plastomers, elastomers can stretch under load and elastically recover once the load is removed. Because of this behavior, elastomers are more often used in asphalt modification to reduce rutting and improve fatigue and thermal cracking resistance of asphalt binders. Styrene-butadiene-styrene (SBS) and styrene-butadiene rubber (SBR) are the two most frequently used elastomers. A number of studies have demonstrated that polymer modification could improve rheological and mechanical properties of asphalt binders, leading to improved asphalt mixture performance in the field.

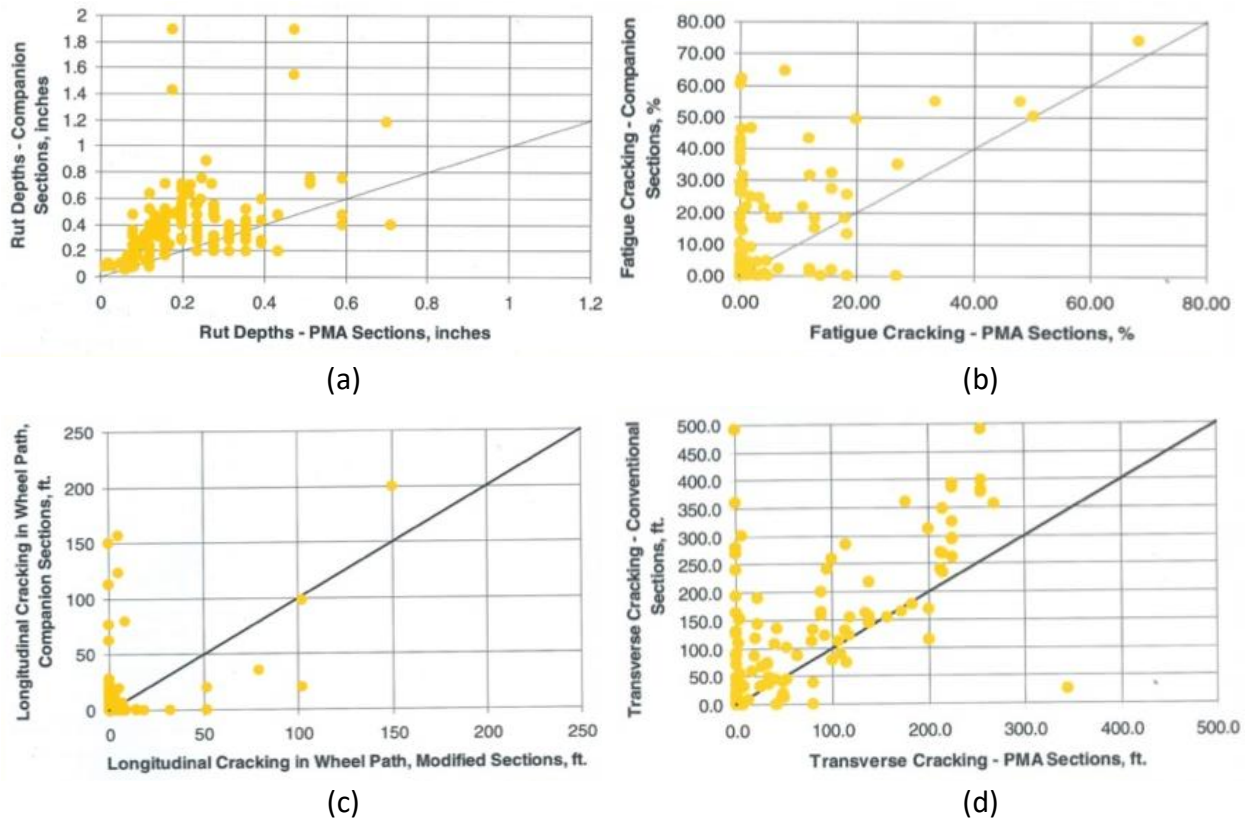
**Table 5. Commonly Used Polymers for Asphalt Modification (4)**

Category	Examples	Advantages	Disadvantages
Plastomers	Polyethylene (PE); Polypropylene (PP)	Good high-temperature properties; Relatively low cost.	Limited improvement in elasticity; Phase separation problems.
	Ethylene-vinyl acetate (EVA); Ethylene-butyl acrylate (EBA)	Relatively good storage stability; High resistance to rutting.	Limited improvement in elastic recovery; Limited enhancement in low-temperature properties.
Elastomers	Styrene-butadiene-styrene (SBS); Styrene butadiene rubber (SBR); Styrene-isoprene-styrene (SIS)	Increased stiffness; Reduced temperature sensitivity; Improved elastic response.	Compatibility problems in some binders; Poor resistance to heat, oxidation and ultraviolet; Relatively high cost.
	Styrene-ethylene/butylene-styrene (SEBS)	Good resistance to heat, oxidation and ultraviolet.	Storage stability problems; Relatively reduced elasticity; High cost.

### 3.1.1 Effect of Polymer Modified Asphalt on Mix Performance

The Asphalt Institute document IS-215 summarizes a study conducted by the Applied Research Associates, Inc. (ARA) to quantify the effects of PMA for reducing pavement distresses using the Long-Term Pavement Performance (LTPP) and non-LTPP test sections (5). As part of the study, expert opinions on the benefits of PMA were gathered by interviewing experienced agency individuals. Approximately 70 percent of the interview respondents believed in the benefits of using PMA to extend asphalt pavement service life. The top three selections on reasons why the agencies use PMA mixtures were (1) increased rutting resistance, (2) reduced thermal cracking, and (3) improved durability. Furthermore, all participating agencies indicated they used PMA in the wearing course when the performance grade (PG) binder specification dictated the need.

Figure 4 presents the direct comparisons of measured pavement distresses for PMA sections versus the companion sections with similar pavement structure, traffic, and climate conditions. Pavement distresses considered in the analyses were rutting, fatigue cracking, longitudinal cracking, and transverse cracking. In the figure, the pavement distress of the PMA sections is plotted on the x-axis, and that of the companion sections is plotted on the y-axis. For all comparisons, most of the data points fall above the line of equality, which indicated that the distresses in PMA sections were not as severe as the companion sections. Most of the PMA sections had rut depths of less than 0.5 inches [Figure 4(a)], no fatigue or longitudinal cracking [Figure 4(b) and Figure 4(c)], and no transverse cracking [Figure 4(d)].



**Figure 4. Direct Comparisons of Measured Pavement Distresses for PMA Sections Versus the Companion Sections; (a) Rut Depth, (b) Percent Fatigue Cracking in Wheel Paths, (c) Length of Longitudinal Cracking in Wheel Paths, (d) Length of Transverse Cracking (5)**

In addition to performance comparisons, the study also computed the expected increase in the service life of asphalt pavements and overlays with PMA using the M-E damage-based performance analyses. Table 6 summarizes the computation results for various traffic and climate conditions, existing pavement conditions, and site features. As shown, the expected increase in the life span of asphalt pavements and overlays using PMA ranged from two to ten years.

**Table 6. Expected Increase in Service Life for Pavements and Overlays with PMA (5)**

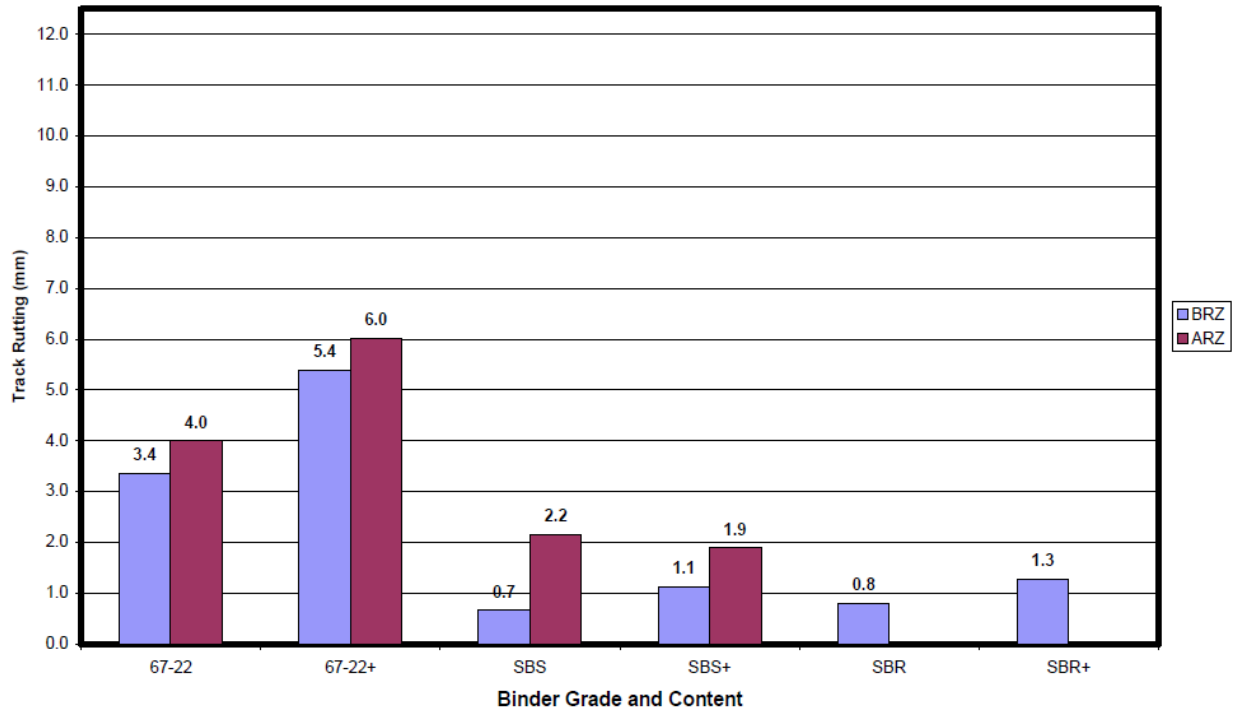
Site Feature	Condition Description	Increase in Service Life, Years <sup>(1)</sup>
Foundation Soils	Non-expansive, coarse-grained soils	5-10
	Expansive soils; moderately to highly plastic soils (Plasticity Index > 35)	2-5
	Frost susceptible soils in cold climates; moderately to highly frost susceptible (Class 3 and 4) <sup>(2)</sup>	2-5
Water Table Depth	Deep	5-10
	Shallow; adequate drainage	5-8
	Shallow; inadequate drainage	0-2
Traffic	Low volumes, Stop & Go/Intersections	5-10
	Low volumes, Thoroughfares	3-6
	Low volumes, Heavy roads/Special containers	5-10
	Moderate volumes	5-10
	High volumes	5-10
Climate	Hot	5-10
	Mild	2-5
	Cold	3-6
Existing Pavement Condition	HMA; Good condition	5-10
	HMA; Poor condition, extensive cracking <sup>(3)</sup>	1-3
	PCC/JPCP; Good condition <sup>(3)</sup>	3-6
	PCC/JPCP; faulting & mid-panel cracking	0-2
Notes:		
<ol style="list-style-type: none"> <li>1. The range of the increase in service life is based on the M-E damage-based analyses, comments from the experts, and engineering judgement.</li> <li>2. Without sufficient thickness of non-frost susceptible materials to prevent frost from penetrating frost susceptible soils.</li> <li>3. Without the use of any reflection cracking mitigation techniques.</li> </ol>		

In the 2000 NCAT Test Track research cycle, an experiment involving ten test sections was designed to assess the effect of PG grade (i.e., polymer modification), asphalt content, and aggregate gradation on the rutting resistance of asphalt mixes (6). Three asphalt binders were included: a unmodified binder (PG 67-22), a styrene-butadiene-styrene (SBS) modified binder (PG 76-22), and a styrene-butadiene-rubber (SBR) modified binder (PG 76-22).

One objective of this study was to evaluate the rutting resistance of these mixtures when additional asphalt binder is added above the optimum design binder content to improve mixture cracking resistance. Thus, each mix evaluated in the experiment was produced at two asphalt contents: optimum and optimum plus 0.5 percent.

Figure 5 presents the rut depths of the test sections after being trafficked for 10 million equivalent single axle loads (ESALs). As can be seen, mixes containing SBS and SBR modified binders had similar rut depths, which were significantly lower than those of mixes with

unmodified binders. As shown in Figure 5, increasing asphalt content by 0.5% resulted in an increase of approximately 50% in the rutting of unmodified mixes. However, the increase in rutting for polymer modified mixes was not significant (i.e., less than 1 mm). Based on the results, the study concluded that using a slightly higher asphalt content for polymer modified binders to improve mixture durability could be done without detrimentally impacting its rutting resistance while it could be a concern for unmodified binders.



**Figure 5. Effect of Binder Grade and Content on Pavement Rut Depth (Note: “+” represents 0.5% above optimum binder content, “BRZ” represents mixes with a gradation below the Superpave restricted zone, and “ARZ” represents mixes with a gradation above the Superpave restricted zone) (6)**

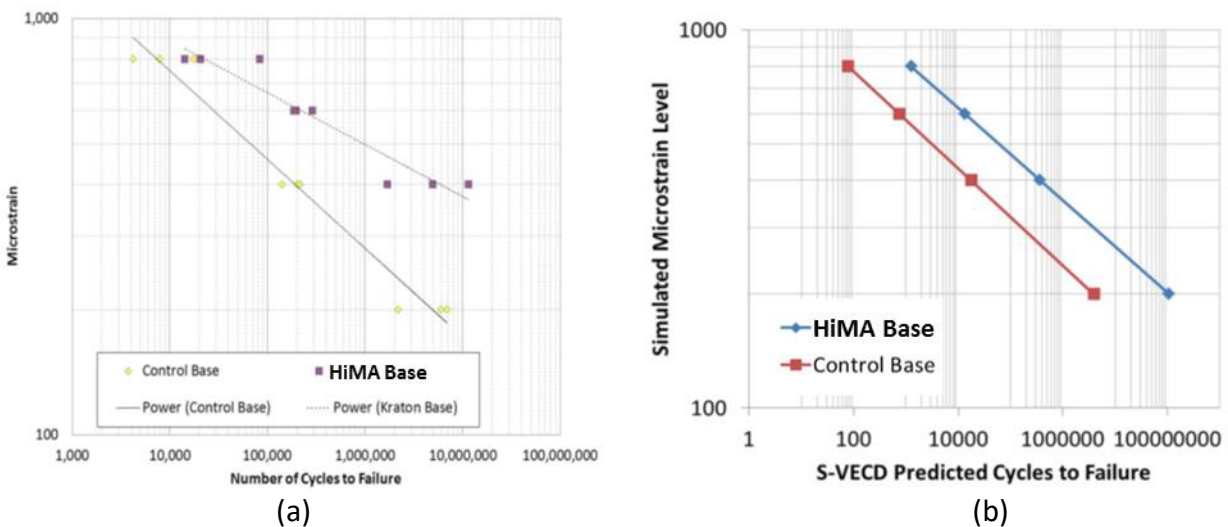
In the 2009 NCAT Test Track research cycle, two companion test sections were constructed to evaluate the structural and performance benefits of using highly polymer-modified (HiMA) binders (7). The HiMA binder was designed with a significantly higher dosage rate (i.e., 7.5%) of SBS polymer than conventional modified binders with approximately 2% to 4% SBS. Both sections had a 6-inch aggregate base. The asphalt layer of the HiMA section was placed in three lifts and had a total thickness of 5.75 inches. All three lifts used a PG 88–22 HiMA binder. The control section also had an asphalt layer consisting of three lifts; the top two used a PG 76–22 SBS modified binder while the bottom lift used a PG 67–22 unmodified binder. The total thickness of the asphalt layer for the control section was 7 inches. The asphalt layer of the HiMA section was designed 1.25 inches thinner to offset the cost of the HiMA binder. During construction, plant mixes were sampled from the Test Track, transported to the research lab, and reheated to prepare plant-mixed, lab-compacted (PMLC) specimens for a full sweep of performance testing.



The laboratory test results showed that the HiMA mixtures consistently outperformed the control mixtures in terms of resistance to rutting, cracking, and moisture damage. Table 7 summarizes the rutting test results of all the mixes tested in the study. As shown, the HiMA mixes had significantly lower Asphalt Pavement Analyzer (APA) rut depth, lower Hamburg Wheel-Tracking Test (HWTT) rutting rate, and higher flow numbers than the corresponding control mixes, indicating better rutting resistance. Figure 6 compares the fatigue cracking resistance of the two base mixes in the bending beam fatigue (BBF) and direct tension cyclic fatigue tests. The HiMA mix had a higher predicted fatigue life than the control mixture across all strain levels in both tests.

**Table 7. Comparison of Mixture Rutting Test Results (7)**

Mix Type	APA Rut Depth, mm	Flow Number	HWTT Rutting Rate, mm/hr
Control surface	3.07	150	0.94
Control base	4.15	125	1.36
HiMA surface	0.62	4600	0.30
HiMA base	0.86	950	0.42



**Figure 6. Fatigue and Cracking Resistance Comparison of HiMA Mix Versus Control Mix; (a) BBF Test, (b) Direct Tension Cyclic Fatigue Test (7)**

After approximately 20 million ESALs were applied in two three-year research cycles, the HiMA section had a final wireline rut depth of approximately 4.0 mm, which was significantly lower than that of the control section (i.e., approximately 8.0 mm). The control section had cracking in 10.0 percent of the lane area while the HiMA section had only 6.0 percent of the lane area. In addition, forensic coring showed that the HiMA section only had near surface hairline cracks while the control section had fatigue cracking propagating through the asphalt layer (8). In summary, the field performance data along with the laboratory test results demonstrated the benefits of using HiMA binders to improve asphalt mixture resistance to both rutting and cracking and increase pavement structural capacity.

In addition to the above studies, numerous research projects have been conducted to evaluate the effect of polymer modified binders on the long-term field performance of asphalt pavements.

Since the late 1980s, many field test sections with polymer modified binders were constructed and their performance was continuously monitored. More information about these studies is included in Table 8.

**Table 8. Field Studies on Polymer Modified Binders**

Location of Sites	Polymer Information	Age When Investigated	Conclusions
Over 30 sites in US, Canada and Austria	Various polymers including PE and EVA SBR and SBS	Less than 5 years	No significant difference was observed in performance between most test sections and the control sections (9).
Six sites in US	Various polymers including EVA, SBR and SBS	Various, but no longer than 6 years	No distinctive trend was found between the performance of modified and unmodified asphalts, nor among the performance of the same modified asphalt types, when compared between different sections (10).
Twenty sites in US and Canada	Various polymers including LDPE, some unspecified polyolefin, EVA, SBR and SBS	Various, but no longer than 9 years	EVA modification has a tendency for brittle behavior as seen by the reports of premature cracking. There were no consistent trends in rutting resistance for any of the reported modifiers (11).
One site in Mississippi, US	Various polymers including SBS, SB latex, LDPE and GTR	Various, but no longer than 5 years	Initial performance test results for the pavement test sections were low roughness and low deflection readings and high skid values. Results to date indicate that all the modified binders are providing superior rutting resistance as compared to the control binder (12).
All sites in US	Various polymers including LDPE, SBR and some styrene-butadiene block copolymers	11 years	For most test sections, the use of PMA improved the field cracking resistance over the unmodified asphalt. However, LDPE increased the brittleness of the asphalt and mixture, leading to extensive cracking. PMA is not necessary to control rutting. Properly designed and constructed mixture can perform under heavy traffic without rutting (13).
One site in Alabama, US	Various polymers including SBS and SBR	No longer than 1 month	Unmodified asphalt mixtures had a rut depth of 6.0 mm. The modified sections had an average rutting of 2.7 mm (14).
Seven sites in Canada	Various polymers including SBS, SB and RET	8 years	Asphalt modified with RET and PPA performed as desired, without cracking after eight years of service. One of the two SBS modified bitumen sections cracked at a moderate amount, with intermittent full width transverse cracks of moderate severity. The remaining sections all experienced severe and excessive cracking (15).

### 3.1.2 Effect of Polymer Modified Asphalt on Mix Volumetric Properties

Table 9 shows volumetric properties of two Superpave mixtures designed using the same aggregate gradation with 20 percent RAP and a design compaction effort of 80 gyrations for the Cracking Group Experiment at the NCAT Test Track (16). One mix was designed with an unmodified PG 67–22 binder and mixed at a temperature between 300 and 310°F. The other was designed with a HiMA binder and mixed at a temperature between 335 and 345°F, as recommended by the polymer supplier. The HiMA mix design had a slightly higher asphalt binder content and a higher VMA. It was observed that the HiMA binder was stiffer than the unmodified binder, making the HiMA mixture more resistant to compaction in the gyratory compactor mold, leading to higher VMA and air voids than the unmodified mixture at a binder content of 5.7 percent. The additional HiMA binder (0.2 percent) was needed to obtain the 4.0 percent design air voids required for Superpave mix design. After approximately 14 million ESALs were applied, the test section surfaced with the unmodified asphalt mixture had cracking in 10.0 percent of the lane area while the test section surfaced with the HiMA mixture had no cracking.

**Table 9. Effect of PMA on Mix Volumetric Properties**

Mix	V <sub>a</sub> (%)	P <sub>b</sub> (%)	VMA (%)	VFA (%)	DP	V <sub>be</sub> (%)	P <sub>2.36</sub> (%)
PG 67–22 (unmodified)	4.0	5.7	15.6	75.0	1.2	11.6	51
HiMA (highly SBS-modified)	4.0	5.9	16.0	75.0	1.2	12.0	51
<b>M323 requirements</b>	<b>4.0</b>		<b>≥ 15</b>	<b>73–76</b>	<b>0.6–1.2</b>		<b>32–67</b>

### 3.2 Lowering Design Compaction Effort

Lowering N<sub>design</sub> was identified in the survey of SAPAs as one of the top three changes to the Superpave mix design that could effectively improve asphalt mixture durability. A survey of state highway agencies, conducted by the research team for NCHRP Project 20-07/Task 412, showed that 26 states have reduced the design compaction efforts used for their mix designs, most with the goal of increasing asphalt content (17). Table 10 summarizes the current N<sub>design</sub> levels used by these SHAs. Although most agencies found that lowering N<sub>design</sub> could result in an increased asphalt content, a few reported that they did not see a sustainable increase over time. They commented that the asphalt content increased initially, but returned to earlier levels after a year or two. The following discussion of past studies on the effect of the laboratory design compaction effort on mix performance and volumetric properties can help explain the phenomenon reported by SHAs participating in the survey.

**Table 10. List of SHAs That Have Decreased  $N_{\text{design}}$  Levels (17)**

Design ESALs (Million)	< 0.3	0.3 – 3	3 – 30	> 30
AASHTO R 35	50	75	100	125
AL	60	60	60	60
CA	85	85	85	85
CO	50/75	75/100	75/100	125
CT	50	75	100	100
DE	75	75	75	75
GA	65	65	65	65
IA	ST (standard traffic): 50; HT (high traffic): 75; VT (very high traffic): 95			
IL	30	50-70	70-90	90
MD	50	65	80	100
ME	50	50	75	75
MO	50	75	80/100	125
MT	75	75	75	75
NC	50	50	65	100
ND	65/75	65/75	75	75
NE	SPS (shoulder mix): 40; SPR (high recycle mix): 65; SPH (heavy truck applications): 95			
NJ	50	50	50	50
OH	50	50	65	65
OK	50	50	65	80
OR	65	80	80/100	100
PA	50	75	100	100
RI	50	50	50	50
SC	50	75	75	75
SD	50	60	80	80
UT	50	75	75/100	75/100
VA	Surface mix: 50; Intermediate mix: 65; Base mix: 65			
VT	50	65	80	80
WV	50	65	80	100

### 3.2.1 Effect of a Lower Design Compaction Effort on Mix Performance

The Alabama Department of Transportation (ALDOT) is one of 26 SHAs that have decreased  $N_{\text{design}}$  levels in the Superpave mix design system. The agency first reduced  $N_{\text{design}}$  for high volume roads (i.e., over 30 million design ESALs) from 125 to 100 gyrations and then further to 85 gyrations with an intention of increasing the asphalt content. They later revised the  $N_{\text{design}}$  level based on the concept of locking point, which is defined as the gyration at which the aggregate skeleton “locks” together and further compaction results in aggregate degradation and very little additional compaction. ALDOT found that most of their Superpave mixes “locked up” in the range of 45 to 55 gyrations, and thus, set the  $N_{\text{design}}$  at 60 gyrations for all design traffic levels. ALDOT

has found no effect of the lower  $N_{\text{design}}$  level on field rutting performance. In addition, the lower  $N_{\text{design}}$  mixes were easier to compact in the field.

The Virginia Department of Transportation (VDOT) is another SHA that has decreased its  $N_{\text{design}}$  levels. The agency had been requiring 65 gyrations for all Superpave mixes. A laboratory study was conducted by Katicha and Flintsch in 2016 to evaluate if additional asphalt binder (as much as 0.5 percent) could be added to 65-gyrations mixes to further improve mixture durability (18). The study modified four VDOT-approve plant-produced mixes to increase the asphalt contents and evaluated the changes in mixture rutting resistance using the flow number (FN) and indirect tensile (IDT) strength tests. One of the modifications evaluated was lowering  $N_{\text{design}}$  from 65 to 50 gyrations along with reducing design air voids from 4.0 to 3.5 percent. This modification resulted in an increase in the asphalt content by approximately 0.37 to 1.0 percent among the four mixes. The test results indicated that decreasing  $N_{\text{design}}$  in conjunction with decreasing design air voids, which yields increased asphalt binder content, could help improve mixture cracking resistance without detrimentally affecting the rutting resistance. As shown in Figure 7, two out of the four mixes (i.e., Mix C and Mix D) showed performance enhancement in both rutting and cracking resistance due to the modification of decreasing  $N_{\text{design}}$ . Based on this study, VDOT further reduced the  $N_{\text{design}}$  of all surface mixes to 50 gyrations with an expectation to achieve improved mixture durability.

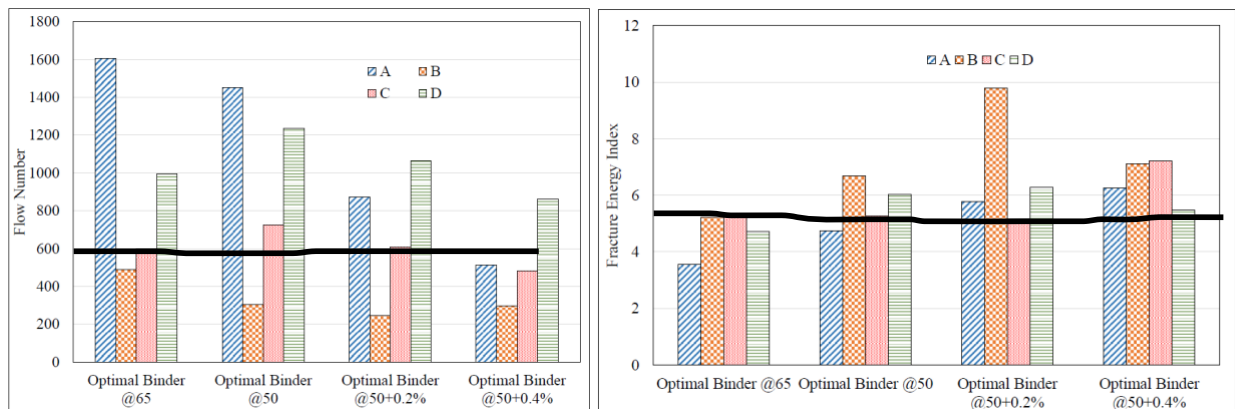


Figure 7. Flow Number and IDT Strength Test Results (18)

### 3.2.2 Effect of a Lower Design Compaction Effort on Mix Volumetric Properties

Theoretically, when aggregate gradation is fixed, lowering  $N_{\text{design}}$  can result in increased VMA and air voids for a given asphalt content, so a higher optimum asphalt binder content will be needed to meet the 4.0 percent design air void requirement. However, in practice, the contractor, driven by the low bid environment, intends to design a cost-effective mix with the lowest possible asphalt content that satisfies the volumetric requirements. Thus, if the agency does not require increased VMA and/or reduced design air voids to go along with decreased  $N_{\text{design}}$ , the contractor can adjust the aggregate gradation to meet all volumetric requirements without necessarily increasing the asphalt content.

Table 11 shows three mix designs using the same absorptive aggregate sources and unmodified binder with 20 percent RAP (17). The first mix was designed with an  $N_{\text{design}}$  of 100 gyrations and had an optimum binder content of 6.8 percent. The second mix was designed with the same

gradation as the first mix, but the  $N_{\text{design}}$  was decreased from 100 gyrations to 75 gyrations. With the decreased  $N_{\text{design}}$ , the second mix had a higher VMA, requiring a higher optimum binder content of 7.2 percent to achieve the 4.0 percent design air voids. For the third mix, the gradation was adjusted so that its VMA would be the same as that of the first mix, resulting in the same optimum binder content and volumetric properties as those of the first mix design.

The results shown in Table 11 explain the above-mentioned phenomenon reported by several SHAs in the survey. The asphalt content increased right after the change (i.e., a decreased  $N_{\text{design}}$ ) was made but then returned to earlier levels once the contractors started adjusting the gradations of their mix designs. While a decreased  $N_{\text{design}}$  level may be more representative of the field compaction, potentially leading to higher in-place density, it has a minimum effect on volumetric properties, especially the design binder content.

**Table 11. Effect of PMA on Mix Volumetric Properties (17)**

Mix	V <sub>a</sub> (%)	P <sub>b</sub> (%)	VMA (%)	VFA (%)	DP	V <sub>be</sub> (%)	P <sub>2.36</sub> (%)
$N_{\text{design}} = 100$	4.0	6.8	15.8	74.7	1.0	11.8	38.9
$N_{\text{design}} = 75$ using same gradation as $N_{\text{design}} = 100$	4.0	7.2	16.6	75.9	0.9	12.6	38.9
Redesign using $N_{\text{design}} = 75$	4.0	6.8	15.7	74.5	1.1	11.7	41.7
<b>M323 requirements</b>	<b>4.0</b>		<b>≥ 15.0</b>	<b>73-76</b>	<b>0.6-1.2</b>		<b>32-67</b>

### 3.3 Lowering Design Air Voids

This approach requires decreased design air voids, which are reduced from 4.0 percent as required in AASHTO M323 to 3.0 or 3.5 percent (19). Table 12 lists seven SHAs identified in the survey conducted as part of NCHRP Project 20-07/Task 412 that have decreased design air voids with the goal of increasing the design binder content (17).

**Table 12. A List of SHAs That Have Decreased Design Air Voids (17)**

State	Target Design Air Voids
KS	3.0%
MO	3.5% to 4.0%
NE	3.5%
NY	3.5%
PA	3.5% to 4.0%
UT	3.5%
VA	2.5% (base mix), 3.5% (polymer mix), 4.0% (surface mix and intermediate mix)

A very similar approach to lowering the design air voids is the air void regression approach. In this approach, a mix is first designed with a target air void content of 4.0 percent to meet all of the volumetric requirements. The mix design can be reviewed or verified and then accepted if all the volumetric requirements are satisfied at 4.0 percent design air voids. The asphalt binder content is then increased to achieve lower target air voids of 3.5 or 3.0 percent, and this asphalt

binder content is used for production. This approach does not require a significant change in the mix design and acceptance specification, except the target binder content, laboratory compacted air voids and those volumetric properties that are required for acceptance testing.

According to the NCHRP Project 20-07/Task 412 survey, four SHAs have implemented the air void regression approach. Colorado, Michigan, and Wisconsin currently require a “regressed” or higher binder content to achieve 3.0 percent air voids, and South Carolina specifies a regressed binder content to obtain an air void content ranging from 2.5 to 4.0 percent depending on the mix type (17).

A one-percent change in design air voids without changing the VMA requirement can increase the effective binder volume ( $V_{be}$ ) by 1.0 percent, resulting in an increase between 0.4 to 0.5 percent in the design binder content. The increased asphalt binder content is expected to improve mixture durability and cracking resistance as well as its workability and compactability.

### 3.3.1 Effect of Lower Air Voids on Mix Performance and Volumetric Properties

Since 2016, the Wisconsin Department of Transportation (WisDOT) has worked with the asphalt pavement association and contractors in the state to evaluate and implement the air void regression approach to increase the design binder content in Superpave asphalt mixtures (20).

In 2018, a study was conducted to help WisDOT evaluate the air void regression approach in combination with the balanced mix design methodology (21). Table 13 includes the test results for one of the asphalt mixtures evaluated in the study. This mix was designed at 4.0 percent design air voids and met all the volumetric requirements for a 12.5 mm asphalt mixture. The asphalt binder content was then increased to achieve 3.5 and 3.0 percent air voids. As shown in Table 13, targeting a lower air void content would result in a higher binder content and VFA with small changes in VMA and dust proportion (DP). With a higher binder content achieved, the air void regression approach can lead to improved mixture cracking resistance as indicated by a higher flexibility index (FI). Higher rut depths measured in the Hamburg wheel tracking test were also observed with higher binder contents. WisDOT has implemented the air void regression approach in its specifications; however, its impact on field performance has yet to be determined.

**Table 13. Effect of Targeting Lower Design Air Voids on Mix Properties (21)**

Mix	V <sub>a</sub> (%)	P <sub>b</sub> (%)	VMA (%)	VFA (%)	DP	V <sub>be</sub> (%)	FI	Rut Depth* (mm)
Medium Traffic (12.5 mm, PG 58–28, 20% RAP, 75 gyrations)	4.0	5.7	15.4	74.0	0.8	11.4	6.0	4.4
	3.5	5.9	15.3	77.2	0.8	11.8	9.6	6.1
	3.0	6.1	15.2	80.3	0.8	12.2	13.0	7.2
<b>WisDOT Requirements</b>	<b>4.0</b>		<b>14.0</b>	<b>65–75</b>	<b>0.6–1.2</b>			

\*The average rut depth was measured at 10,000 passes in the Hamburg wheel tracking test conducted at 46°C.

### 3.4 Increasing Minimum Requirement for Voids in the Mineral Aggregate

Voids in the mineral aggregate represents the total volume of intergranular space between aggregate particles of a compacted mix. For a given design compaction effort (i.e.,  $N_{design}$ ), VMA is influenced by the aggregate structure. To increase VMA without changing the design air voids, a change in the packing of aggregate particles is needed to create voids that will be filled with more asphalt binder. A one-percent increase in VMA without changing the design air voids results in a one-percent increase in  $V_{be}$  of the mixture, which would increase the design asphalt content by approximately 0.4 to 0.5 percent. The key to achieving the true increase in asphalt content is to ensure the correct aggregate bulk specific gravity ( $G_{sb}$ ) is used in the mix design and production.

To help SHAs address the mix durability concern, FHWA recommends increasing the minimum VMA limit by 0.5 percent for each NMAS level to increase the binder content assuming the aggregate structure is sufficient for the traffic conditions (1). The mix design manual developed in NCHRP Project 9-33 recommends increasing the design VMA by 1.0 percent to produce mixtures with improved durability (22). According to the NCHRP Project 20-07/Task 412 survey (17), several SHAs have changed the minimum VMA requirements for their Superpave mixtures as summarized in Table 14.

**Table 14. A List of SHAs That Have Increased Minimum VMA (17)**

Description	Minimum VMA (%) by NMAS			
	19 mm	12.5 mm	9.5 mm	4.75 mm
AASHTO M 323	13.0	14.0	15.0	16.0
AL	13.5	14.5	15.5	16.5
CA	13.5	14.5	15.5	16.5
CO	13.6–13.8	14.6–14.8	15.6–16.9	N/A
DE	13.5	14.5	15.5	16.5
GA	14.0	15.0	16.0	N/A
IL	13.5	N/A	15.0	18.5
MA	14.0	15.0	16.0	17.0
ME	14.0	15.0	16.0	16.0
MT	13.0	14.5	15.5	N/A
NC	13.5	N/A	15.5	16.0
PA	13.5	14.5	15.5	16.0
RI	14.5	15.5	16.5	17.5
SC	13.5	14.5	15.5	17.5
SD	N/A	14.5	N/A	N/A
VA	13.0	15.0	16.0	16.5
VT	14.5	15.5	16.5	17.5
WI	13.0	14.0/14.5	15.0/15.5	16.0
WV	13.5	14.5	15.5	16.5

VMA is one of the mixture volumetric properties that can decrease significantly from mix design to production because there is more aggregate breakdown and dust generated in the asphalt



plant compared to the mix design process. VMA typically decreases from 0.2 percent to 0.5 percent depending on aggregate hardness. While VMA for production mix can be lower than that of the mix design, it should not be lower than the minimum VMA requirement for durable asphalt mixtures. To avoid the VMA collapse, mix designers can either target a higher VMA than the minimum or add baghouse fines during the mix design process to simulate the effects of breakdown on volumetric properties.

### 3.4.1 Effect of Increased VMA on Mix Performance and Volumetric Properties

Table 15 shows testing results for two mix designs using the same component materials placed on the NCAT Test Track. The S11 mixture was designed first to meet the Texas Department of Transportation (TxDOT) requirements for volumetric mix design. This mix also met the maximum rut depth requirement of 12.5 mm; however, it failed the proposed cracking resistance requirement with a  $\beta$  parameter of at least 0.45. An asphalt mixture with a lower  $\beta$  parameter determined by the overlay test is expected to have better cracking resistance. The aggregate gradation of the S11 mix was then adjusted to design the S10 mixture. With the adjusted aggregate gradation, the S10 mixture showed a VMA increase of 1.6 percent, resulting in a design binder content increase of 0.8 percent compared to the S11 mixture. The S10 mixture had a higher rut depth than the S11 mixture, but both mixtures met the TxDOT maximum rut depth requirement. With respect to the  $\beta$  parameter determined by the overlay test, the S10 mix met the proposed TxDOT requirement, but the S11 mixture did not. The field performance of the two mixtures is currently being evaluated at the NCAT Test Track. While the two mixtures were designed to validate the cracking and rutting criteria for a balanced mix design method, it shows that an increase in VMA without changing the design air void requirement will yield a higher binder content, and VMA can be adjusted by changing the aggregate gradation.

**Table 15. Effect of Increased VMA on Mix Properties**

Mix	Va (%)	Pb (%)	VMA (%)	VFA (%)	DP	Rut Depth* (mm)	$\beta$ ** Parameter
S10	4.0	5.5	16.6	76	0.9	7.6	0.37
S11	4.0	4.7	15.0	73	1.0	4.9	0.57
<b>TxDOT Requirements</b>	<b>4.0</b>	<b>—</b>	<b>≥ 15.0</b>	<b>-</b>	<b>0.6–1.2</b>	<b>≤ 12.5</b>	<b>≤ 0.45</b>

\*The average rut depth was measured at 15,000 passes in the Hamburg wheel tracking test conducted at 50°C. \*\*The  $\beta$  parameter was determined using the overlay test at 25°C.

In summary, several changes to the Superpave mix design method as identified in the survey of SAPAs are discussed in this section. The goals of these changes are to have sufficient (or better performing) asphalt binder in the mix, which is considered important for long-term pavement performance.

While these changes can be the first priority for many agencies, the survey of SHAs also suggests that other adjustments can be made to the mix design procedure to increase in-place density, which can in turn further improve the field performance of asphalt mixtures. To this end, the following section discusses one of the adjustments that can be considered by SHAs.

#### 4 SUPERPAVE5 VOLUMETRIC MIX DESIGN

The recently developed Superpave5 mix design method (23) is an adjustment to the current Superpave mixture design system specified in AASHTO M323. Compared to the current Superpave mix design method, the Superpave5 mix design includes the following changes:

- The design air voids in the Superpave5 mix design method are increased by one percent, from four percent to five percent. As a result, the design density requirement is changed from 96 percent (= 100% – 4% air voids) to 95 percent (100% – 5% air voids).
- To maintain the same effective asphalt binder volume ( $V_{be} = VMA - V_a$ ) with the one-percent increase in air void content, the VMA criteria are also increased by one percent.
- The design compaction effort for the Superpave5 mix design method is reduced. Asphalt mixtures currently designed at 125, 100, or 75 gyrations would be compacted to 70, 50, or 30 gyrations, respectively, in the Superpave5 mix design method.
- Finally, the in-place density requirement for a Superpave5 mixture is targeted at 95 percent, which is the same as the laboratory design density requirement as previously described.

Except for the changes described above, the Superpave5 mix design requires the same Superpave gyratory compactor, aggregate consensus properties for different traffic levels, typical lift thicknesses, and other practices as in the current Superpave mix design system.

##### 4.1 Motivation for Adjustments in Superpave5 Mix Design

Making changes to the current Superpave mix design system to increase in-place density was identified by SAPAs as one of the top three strategies that could effectively improve asphalt mixture durability in the field. Historically, air voids, both during the design phase and during the in-service phase, have been recognized as an important parameter contributing to asphalt mixture performance. If air voids are too low, the asphalt mixture, especially one with unmodified binder, can be susceptible to permanent deformation and the development of wheel path rutting. If air voids are too high, the pavement can be susceptible to cracking and disintegration caused by ingress of air, which accelerates aging of the asphalt binder, and from water expanding during freezing.

A consensus had developed that design air voids (laboratory-compacted asphalt mixture) should be approximately four percent (three to five percent has been used as a range) and in-place air voids after construction should be about six to eight percent. It was also thought that traffic would compact the asphalt mixture to the design level (laboratory-compacted) air voids. This consensus of air void evolution throughout the asphalt mixture life was first incorporated in the Marshall asphalt mix design method (23). When the Superpave mixture design system was developed in the mid-1990s, the same concept was carried forward; hence, the design air voids specified in AASHTO M323 is four percent. In most SHA specifications for field compaction, the lower density limit is between 91.0 and 93.0 percent of maximum theoretical specific gravity ( $G_{mm}$ ) with an upper specification limit between 97.0 and 98.0 percent (24).

To increase in-place density, especially to the same level achievable during the design of an asphalt mixture, simply increasing compaction effort (i.e. size of rollers and number of passes) is not sufficient. Using current rollers, compaction practice, lift thickness selection, and with

consistent asphalt production, the achievable air voids after compaction are typically six to eight percent. Therefore, the Superpave mix design system needs to be adjusted to achieve the same air voids during design and after compaction.

Research was conducted to determine design gyration levels for designing asphalt mixtures at five percent design air voids such that they could be compacted to a final density of 95 percent  $G_{mm}$  at a lift thickness of four times NMAS using approximately the same rolling effort (roller size, weight, and number of passes) as currently used (23). Research results indicated that mixtures currently designed at 125, 100, or 75 gyrations should be compacted with 70, 50, or 30 gyrations, respectively, in the Superpave5 mix design method.

#### **4.2 Implementation of Superpave5 Mix Design**

The Indiana Department of Transportation (INDOT) is in the process of implementing the Superpave5 mix design method. Several pilot projects were let in 2018, and 2019 is a transition year as additional pilot projects are constructed. Contractors were allowed to opt-in to the Superpave5 method on projects for 2019, and starting that fall, projects will be let using Superpave5 specifications.

INDOT has selected two design gyration levels. For mixtures with less than three million ESALs, the design compaction level is 30 gyrations. For mixtures designed for all other traffic levels, the design compaction effort is 50 gyrations. The design air void content is increased from four percent to five percent. The design VMA is increased by 1.0 percent, meaning the effective binder volume remains the same in the Superpave5 mixtures as in the current Superpave mixtures. Final compaction on the road is targeted to be five percent air voids (i.e., 95 percent  $G_{mm}$ ) instead of seven percent air voids (i.e., 93 percent  $G_{mm}$ ).

The net result of these adjustments is that stiffness and rut resistance of Superpave5 mixtures as compacted on the road are about the same or slightly higher than current Superpave mixtures based on the rut depths measured on trial sections, one of which has been in service for five years (25). In addition, the Superpave5 section showed less cracking than the control section (current Superpave mixture) in the five-year-old experiment. Also, the true high and low performance grades of the asphalt binder recovered from field cores for the Superpave5 mixture (i.e., 94.0 – 21.0) were approximately one grade lower compared to those of the control section (i.e., 100.0 - 16.2) in the experiment.

In summary, Superpave5 mixtures designed at five percent air voids and compacted to 95 percent  $G_{mm}$  density were found to have the same stiffness and rut resistance as current Superpave mixtures designed at four percent air voids and compacted to 93 percent  $G_{mm}$  density. Also, with a higher in-place density, the Superpave5 mixture is less susceptible to field aging, resulting in improved long-term durability.

In addition to the changes made to the mix design specifications, the Bailey method has been used during design and production to better control the volumetric properties and compactability of asphalt mixtures, improving mixture performance. The following section provides a brief introduction to that method.

## 5 USING THE BAILEY METHOD TO CONTROL VOLUMETRIC PROPERTIES

Neither the Superpave nor Marshall mix design method provides a means to design the aggregate structure for an asphalt mixture. The design aggregate gradation is traditionally selected based on trial and error along with experience and historical data. In addition, while increasing the amount of new binder in an asphalt mixture can improve its durability, it may have an adverse effect on the mix stability (i.e., rutting resistance) and/or its volumetric properties, potentially making the mix design unacceptable based on the current specifications. In this case, the Bailey method can provide the mix designer a set of tools to develop, evaluate and adjust the aggregate blend and other volumetric properties, such as VMA and air voids. It can be used to quantify aggregate packing and its relationship with volumetric properties. The Bailey method is applicable to all dense-graded asphalt mixtures with different aggregate sizes (i.e., coarse-graded and fine-graded mix designs) as well as gap-graded asphalt mixtures, such as stone matrix asphalt (SMA). Following the Bailey method, the mix designer can evaluate the relationship between aggregate gradation and mixture volumetric properties by first determining the primary control sieve (PCS) that separates the coarse and fine fractions of the aggregate blend and then evaluating the degree of packing for the coarse aggregate, the coarse fraction of fine aggregate, the fine fraction of fine aggregate, and their blend (26).

### 5.1 Primary Control Sieve

The primary control sieve is defined as the closest sized sieve to the result of Equation 1. It separates the coarse and fine aggregate fractions of an aggregate blend. Within the aggregate blend, coarse aggregate includes large aggregate particles that create voids while fine aggregate consists of aggregate particles that fill voids created by coarse aggregate.

$$PCS = NMPS \times 0.22 \quad (1)$$

where:

PCS = primary control sieve for the overall blend; and

NMPS = nominal maximum particle size (one sieve larger than the first sieve that retains more than 10%).

### 5.2 Aggregate Packing

Since aggregate particles do not completely fill all volume in a compacted mix, there is space between the aggregate particles (i.e. VMA) that is dependent on the degree of packing and is influenced by the following factors:

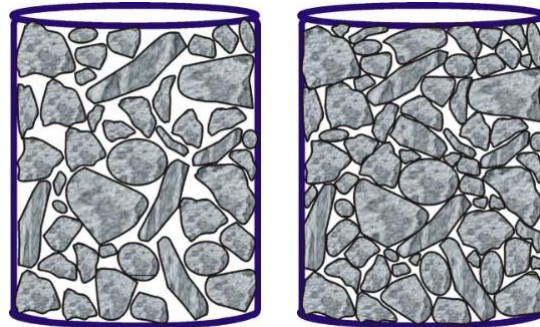
- *Type and amount of compactive energy.* Aggregate particles orient differently to Marshall hammer blows versus Superpave compactor gyrations. For each type of compactor, aggregate particles pack more densely as the number of applications increases.
- *Particle shape.* Irregular elongated particles are more difficult to pack than cubical particles.
- *Particle surface texture.* Smooth texture particles orient and pack more densely than rough surface particles.
- *Gradation.* Particle size distribution impacts the degree of packing.

- *Strength of the particles.* Softer aggregates allow denser packing because of degradation.

These factors apply to both coarse and fine aggregates. The final combination of coarse and fine aggregates and their corresponding individual properties determines the packing characteristics of the overall blend.

### 5.3 Loose and Rodded Unit Weights of Aggregate

The volumes of coarse and fine aggregates are evaluated based on their loose and rodded unit weights. Loose unit weight is the amount of aggregate required to fill a unit volume by pouring it into a container without any compactive effort. This represents the beginning of particle to particle contact of the coarse aggregate. The rodded unit weight of aggregate is the amount of aggregate that fills a unit volume with compactive effort applied. The compactive effort increases the particle to particle contact. Loose and rodded unit weights are depicted in Figure 8 and are expressed as pounds per cubic foot or kilograms per cubic meter.

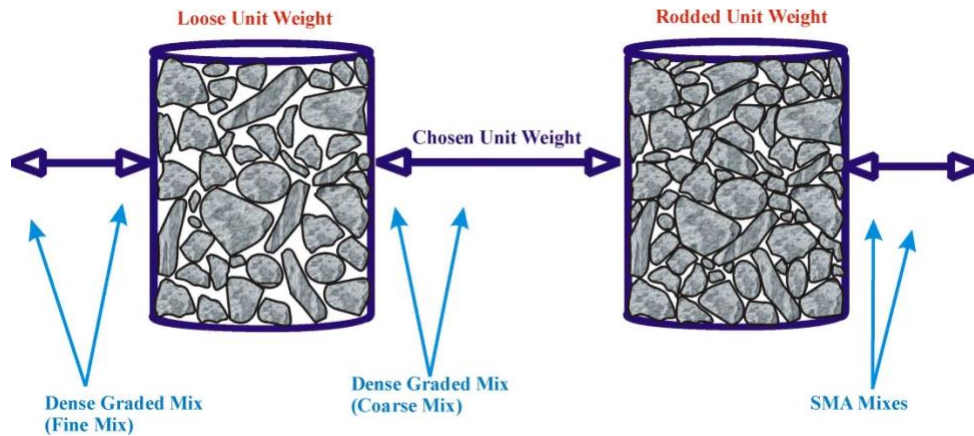


**Figure 8. Aggregate Loose and Rodded Unit Weight**

### 5.4 Design and Analysis of Aggregate Gradation

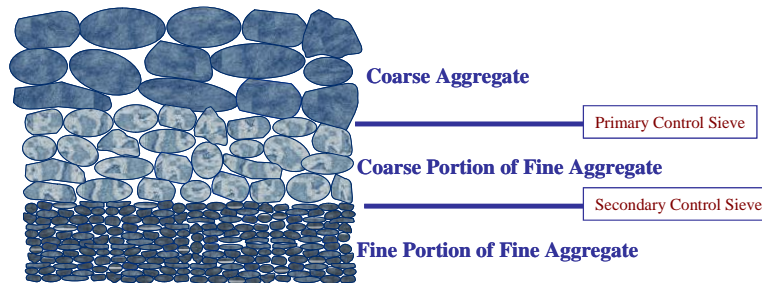
The design and analysis of an aggregate blend with the Bailey method can be conducted following four steps: (1) select a chosen unit weight (CUW) for coarse aggregate based on mix type; (2) analyze the coarse aggregate; (3) analyze the overall fine aggregate; and (4) analyze the fine portion of the fine aggregate.

As shown in Figure 9, a CUW is selected in the first step based on the corresponding coarse aggregate unit weights. For a dense graded mixture, the CUW is selected relative to the loose unit weight, and it is selected based on the rodded unit weight for a SMA mixture. The CUW establishes the volume of coarse aggregate in the mix design.



**Figure 9 Suggested Chosen Unit Weight Ranges for Coarse Aggregate**

The combined blend is then divided into three fractions, and each fraction is evaluated individually. The coarse fraction of the combined blend is from the largest sieve size to the primary control sieve. The fine fraction of the combined blend is evaluated with two different ratios utilizing a secondary control sieve ( $SCS = PCS \times 0.22$ ) and a tertiary control sieve ( $TCS = SCS \times 0.22$ ). A schematic of the gradation proportions is shown in Figure 10



**Figure 10 Overview of The Divisions That Allows an Analysis of Gradation**

Within each fraction, a ratio is used to characterize packing of the aggregates. These ratios help the mix designer estimate an increase or decrease in VMA when changes are made to the blend gradation.

- Coarse Aggregate Ratio (CA) is used to evaluate how the coarse aggregate particles pack together and how they compact fine aggregate within them.
- Fine Aggregate Coarse Ratio ( $FA_c$ ) is used to evaluate packing of the overall fine aggregate.
- Fine Aggregate Fine Ratio ( $FA_f$ ) is used to evaluate packing of the fine portion of the fine aggregate.

Changes to any of these parameters will affect VMA (and air voids), along with constructability of the asphalt mixture. Changing stockpile blends can affect several parameters that may cancel each other or accentuate their effects. Also, changes to stockpile blends may affect aggregate shape or texture. For example, when decreasing natural sand and increasing manufactured sand, not only will gradation change affect air voids and VMA, but shape and texture will also influence these volumetric properties.

In summary, this section provides a brief introduction to the Bailey method. The Bailey method can be used during mix design and during production to better optimize volumetric properties and compactability.

## **6 SUMMARY**

As SHAs are making adjustments to the volumetric mix design system with the intent of improving mixture durability, it is important to keep the industry up to date with the changes that have been implemented and how they can help improve pavement performance. Several changes to the volumetric mix design system were identified through a survey of State Asphalt Pavement Associations (SAPAs). The adjustments identified as potentially providing the greatest improvement in pavement performance are discussed in this report.

The most important changes identified in the survey of SAPAs are (1) to use more polymer modified asphalt binder; (2) to increase the amount of new binder in the mixture by lowering the design air voids, including the air void regression method, or increasing the minimum VMA requirement; and (3) to make changes to mix design to increase in-place density, such as lowering the  $N_{\text{design}}$  requirements. For each adjustment to the volumetric mix design system, background information about the adjustment is first discussed, followed by (1) a brief summary of research showing how the adjustment can improve asphalt mixture performance and (2) a volumetric mix design example to illustrate how the change can affect the mix volumetric properties.

In addition, the report also includes sections for the Superpave5 mix design method and the Bailey method to offer additional options that users may consider for use in improving mixture performance. The Superpave5 method can significantly help improve the in-place density while the Bailey method can be used during both design and production to better control the volumetric properties of asphalt mixtures. When combined with the adjustments to the volumetric mix design system discussed above, these methods can have positive impacts on mixture performance, leading to a longer pavement service life.

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## APPENDIX A SURVEY QUESTIONNAIRE

This survey is part of an effort in a NAPA/SAPA-sponsored project entitled “Mixture Design Strategies for Improving Asphalt Mixture Performance.” The objective of this survey is to understand and document the adjustments to the volumetric mix design system that may provide the greatest improvement in pavement performance. This information will help position the industry to respond to agency and owner needs while the development and implementation of balanced mix design is further refined.

This survey has five questions and should take about 10 to 15 minutes to complete. Your response is important for the success of this project. We will share a summary of survey responses and other research findings in a future report.

1. Please provide your contact information so that we can contact you with any follow-up questions:
  - Name:
  - Company
  - Title:
  - State:
  - E-mail:
  - Phone:
  
2. Below is a list of changes made to the volumetric mix design procedure to potentially improve asphalt mixture durability. Based on your experience, please select five changes that you think can provide the greatest improvement.

Changes	Select Top 5 Changes
Increased or decreased binder grades	
Increased use of polymer-modified binders	
Adopted MSCR specification for asphalt binders	
Adopted $\Delta T_c$ specification for asphalt binders	
Lowered $N_{design}$	
Lowered design air voids target	
Lowered air voids with regression (added AC)	
Increased design VMA	
Set/Verified Specific Gravity of Aggregate	
Lowered RAP %	
Lowered RAS %	
Eliminated RAS	
Changed other requirements for Recycled Materials, please specify	
Allowed or required recycling agents (rejuvenators)	
Set minimum total binder content ( $P_b$ )	
Set minimum effective binder content ( $P_{be}$ )	
Set minimum asphalt film thickness	

Increased in-place density	
Increased moisture susceptibility requirements or mandated antistrip utilization	
Required WMA technology and lower mixture production temperatures	
Changed quality acceptance procedures, please specify	
New or improved ride quality requirements	
Other, please specify	

3. What changes have been made to the volumetric mix design procedure in your state to potentially improve asphalt mixture durability? When were they implemented? Did these changes have any significant impact on mixture durability and contractors' operation, please specify? Please check all that apply.

Changes	Year Implemented	These Changes Have Significant Impact on...				
		Mix Durability	Bid Costs	Staffing Requirements	Recycled Mats Use	Others, Please Specify
Increased or decreased binder grades						
Increased use of polymer-modified binders						
Adopted MSCR specification for asphalt binders						
Adopted $\Delta T_c$ specification for asphalt binders						
Lowered $N_{design}$						
Lowered design air voids target						
Lowered air voids with regression (added AC)						
Increased design VMA						
Set/Verified Specific Gravity of Aggregate						
Lowered RAP %						
Lowered RAS %						
Eliminated RAS						
Changed other requirements for Recycled Materials (as provided in Question 2)						
Allowed or required recycling agents (rejuvenators)						
Set minimum total binder content ( $P_b$ )						
Set minimum effective binder content ( $P_{be}$ )						
Set minimum asphalt film thickness						
Increased in-place density						
Increased moisture susceptibility requirements or mandated antistrip utilization						

Required WMA technology and lower mixture production temperatures						
Changed quality acceptance procedures (as provided in Question 2)						
New or improved ride quality requirements						
Other (as provided in Question 2)						

4. Does your state's transportation agency have historical data (i.e., field performance data and/or lab test results) to show how the mix durability has changed over the years, especially before and after changes were implemented?
  - a. Yes (Go to Q5)
  - b. No (Skip to End)
  
5. Can you provide the historical data or provide the contact information for someone at the agency who can provide the information?
  - a. Yes, historical data are attached to the questionnaire
  - b. Yes, please contact: \_\_\_\_\_
  - c. No