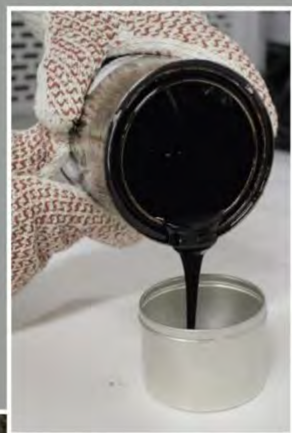
NCAT Report 18-03

PERFORMANCE AND LIFE-CYCLE COST BENEFITS OF STONE MATRIX ASPHALT



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August 2018

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Performance and Life-Cycle Cost Benefits of Stone Matrix Asphalt

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DISCLAIMER

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1. INTRODUCTION

Stone matrix asphalt (SMA), also called stone mastic asphalt, is a durable and rut-resistant asphalt mixture that relies on stone-on-stone contact to offer strength and a rich mortar binder to provide durability (Hughes 1999). SMA was introduced into the United States in the early 1990s mainly through the efforts of a Technical Working Group established by the Federal Highway Administration. The first SMA project in the United States was constructed in Wisconsin in 1991. Ever since, SMA has gained popularity among highway agencies as a premium asphalt mixture to enhance field performance and extend life expectancy of asphalt pavements and overlays. However, SMA is generally more expensive than the conventional Superpave dense-graded mixture, mainly due to higher asphalt contents, requirements for more durable aggregates, and inclusion of fibers as stabilizers.

This study was undertaken to objectively and comprehensively quantify and compare the performance and life-cycle cost benefits of SMA versus those of polymer-modified Superpave dense-graded mixtures used on similar trafficked highways. To accomplish the objective, market analysis was first conducted to determine the current usage of SMA through surveys of state highway agencies (SHAs), state asphalt pavement associations (SAPAs), and knowledgeable individuals in the asphalt pavement industry. Performance analysis was then conducted to compare the long-term field performance of pavement sections with SMA and polymer-modified Superpave dense-graded mixtures. Information gathered from the market analysis and performance analysis was then used as inputs to compare the life-cycle cost between these two mixtures. Finally, a comprehensive review of literature was conducted to summarize the engineering properties and field performance of SMA. Results obtained from this study provide highway agencies with additional guidance regarding the use of SMA as a premium asphalt mixture.

2. MARKET ANALYSIS

A market analysis was conducted to collect information regarding the use of SMA through surveys of SHAs and SAPAs, and direct correspondence with knowledgeable individuals in the asphalt pavement industry. Email inquiries were first sent out to SAPAs to identify states that use SMA. Information gathered to-date indicates that SMA is currently being used on a routine basis by at least 18 SHAs; these agencies are highlighted in the map below (Figure 1).

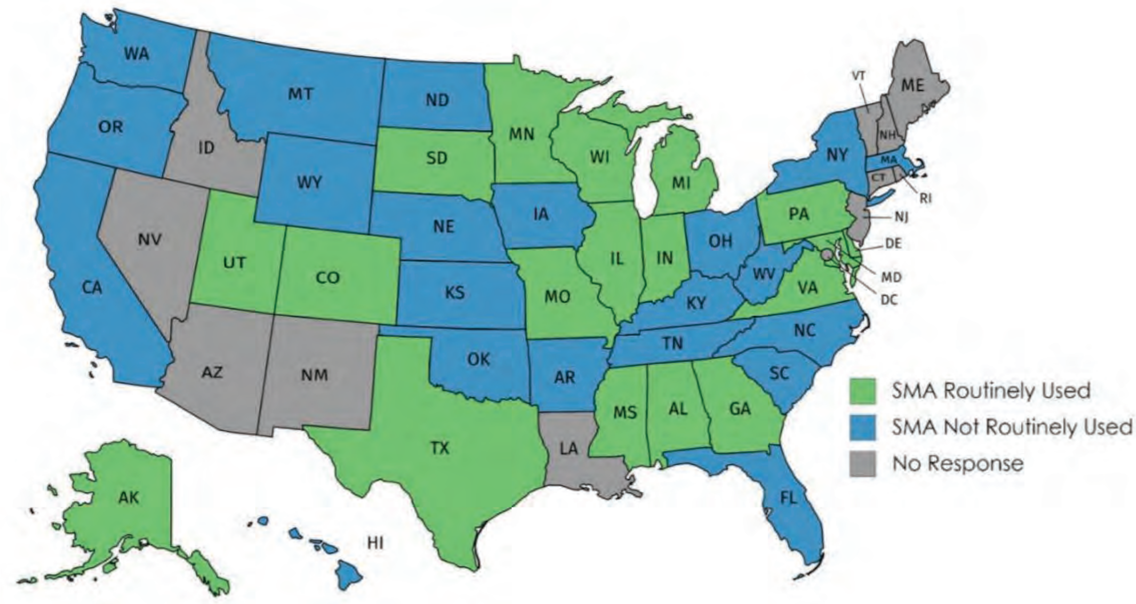


Figure 1. SMA Usage in the United States

In July 2016, an email-based survey questionnaire was then sent to representatives from the 18 state highway agencies highlighted in Figure 1, Illinois Tollway Authority (ITA), and Kansas Department of Transportation (DOT). Questions included in the survey are as follows:

- Mixture Selection Policy – please provide a copy or link to policies that identify when SMA (or a similar mixture) should be selected for a project.
- Does your agency follow the AASHTO Standard Specification R 46-08 to design SMA mixtures? If your state requires a different procedure, please send us the procedure or a link to the method.
- Please list below the bid item numbers for SMA and Superpave dense-graded surface mixtures for the same traffic level(s) used for SMA.
- Please list the quantities (tons/yr.) of SMA and Superpave dense-graded surface mixtures for the same traffic level for the past five years.
- Please provide the weighted mix bid price for SMA and Superpave dense-graded surface mixtures used for the same traffic level for the past five years.
- Please provide any reports that detail the statewide field performance of SMA mixtures.
- Please provide the contact information for your state's Pavement Management Engineer. We would like to contact him/her to see if he/she can help provide information on the average service lives of SMA and Superpave dense-graded surface mixtures for the same traffic levels.

As shown in Figure 2, responses from 16 highway agencies (including both the ITA and Illinois DOT) were received with an 80% response rate (16 of 20). These responses are briefly summarized in the following subsections with more details provided in Appendix A.

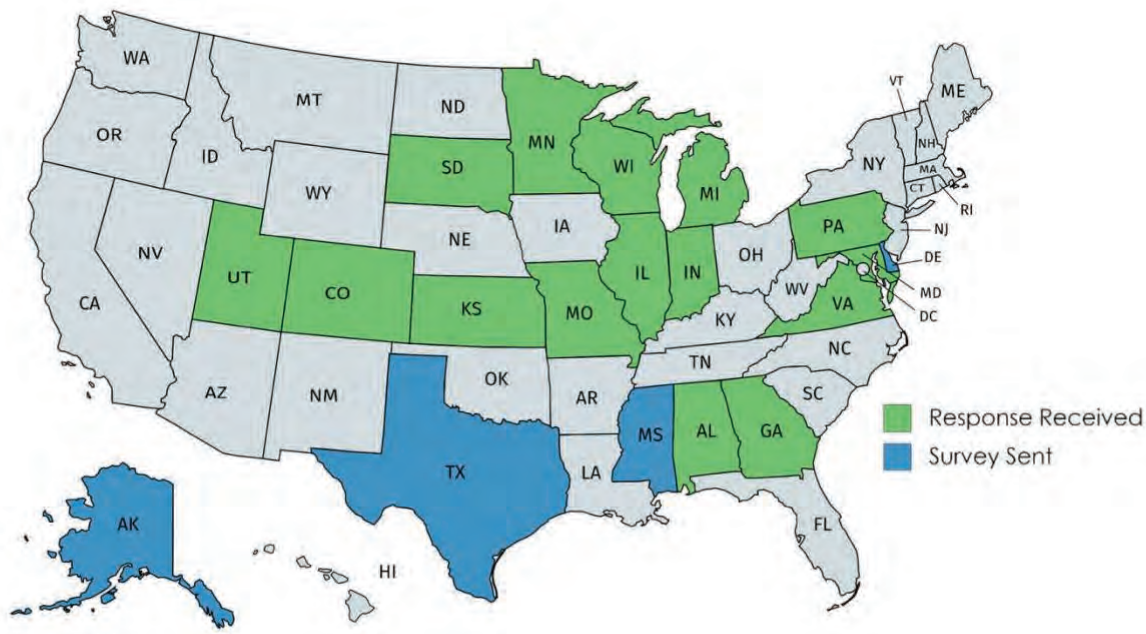


Figure 2. SMA Survey of Highway Agencies

2.1 Mixture Selection Policy

Table 1 summarizes the policy used by SHAs to identify when SMA should be used. 62.5% (i.e., 10 out of 16) of the agencies that responded to the survey have specific mixture selection policy for using SMA, while the rest indicated that the use of SMA is a decision by the state or district pavement engineer. In general, SMA is typically used on state and interstate routes and projects with high traffic volumes. SMA is also considered on projects where frequent maintenance is costly and projects where the higher cost can be justified by the improved performance.

2.2 Mixture Design Procedure

Table 2 summarizes the SMA mix design procedures used by SHAs. Nine agencies design SMA following AASHTO R 46-08, *Standard Practice for Designing Stone Matrix Asphalt (SMA)*, or a modified version of it. Five agencies have their own specifications while the other two agencies follow AASHTO R 35, *Standard Practice for Superpave Volumetric Design for Asphalt Mixtures*.

2.3 SMA Tonnage

Figure 3 compares the total tonnage of SMA and polymer-modified Superpave dense-graded mixtures from 2011 to 2015. As can be seen, the five-year total tonnage of SMA ranged from approximately 68,000 to 1,872,000 tons. The three agencies with the highest SMA tonnage were Maryland SHA, Alabama DOT, and Utah DOT, respectively. Over this five-year period, only Alabama DOT, Illinois DOT, and Maryland SHA produced comparable or more SMA than polymer-modified Superpave mixtures used on similar trafficked highways.

Table 1. Survey Responses of SMA Mixture Selection Policy

Highway Agency	Survey Response
Alabama DOT	Projects with 20-year design traffic greater than 30 million equivalent single axle loads (ESALs); projects with rutting concerns (such as intersections).
Colorado DOT	No criteria, but typically used on projects with high traffic volumes.
Georgia DOT	State and interstate routes with ADT greater than 50,000; state routes with ADT between 10,000 and 50,000 only when recommended by Office of Materials and Testing.
Illinois DOT	Projects with ADT greater than 35,000.
Illinois Tollway	All mainline pavements.
Indiana DOT	Decision by the Pavement Designer.
Kansas DOT	Project-by-project decision, but rarely used.
Maryland State Highway Administration (SHA)	Projects with 20-year design traffic greater than 30 million ESALs; projects with a functional class of Principal Arterial or greater.
Michigan DOT	Projects with 20-year design traffic between 10 and 100 million ESALs.
Minnesota DOT	No criteria, but typically used on projects with high traffic volumes.
Missouri DOT	Interstate routes and other freeways.
Pennsylvania DOT	Interstates, interstate look-alike highways, and high-speed freeways; projects with a minimum quantity of 50,000 square yards; roadways with greater than 30 million ESALs.
South Dakota DOT	Most four-lane roads and interstate routes.
Utah DOT	No criteria, but typically used on interstate routes.
Virginia DOT	Projects with greater than 3 million ESALs; Heavy to extreme heavy traffic volume routes where the higher cost can be justified with improved performance over other mixtures.
Wisconsin DOT	Projects with 20-year design traffic greater than 5 million ESALs; Projects where low maintenance is beneficial (such as high-traffic areas); Projects where SMA is economically feasible.

Table 2. Survey Responses of SMA Mixture Design Procedure

Highway Agency	Survey Response
Alabama DOT	ALDOT Procedure 395
Colorado DOT	AASHTO R 46-08, with 50-blow Marshall design
Georgia DOT	GTD 123
Illinois DOT	AASHTO R 46-08, with modifications
Illinois Tollway	Illinois Tollway SMA special provision
Indiana DOT	AASHTO M 325 and AASHTO R 46-08
Kansas DOT	KDOT special provision
Maryland SHA	AASHTO R 35
Michigan DOT	AASHTO R 46-08
Minnesota DOT	AASHTO R 46-08
Missouri DOT	AASHTO R 46-08
Pennsylvania DOT	AASHTO R 46-08, with modifications
South Dakota DOT	AASHTO R 46-08
Utah DOT	AASHTO R 46-08
Virginia DOT	Virginia Test Method 99
Wisconsin DOT	AASHTO R 35 and AASHTO M 323

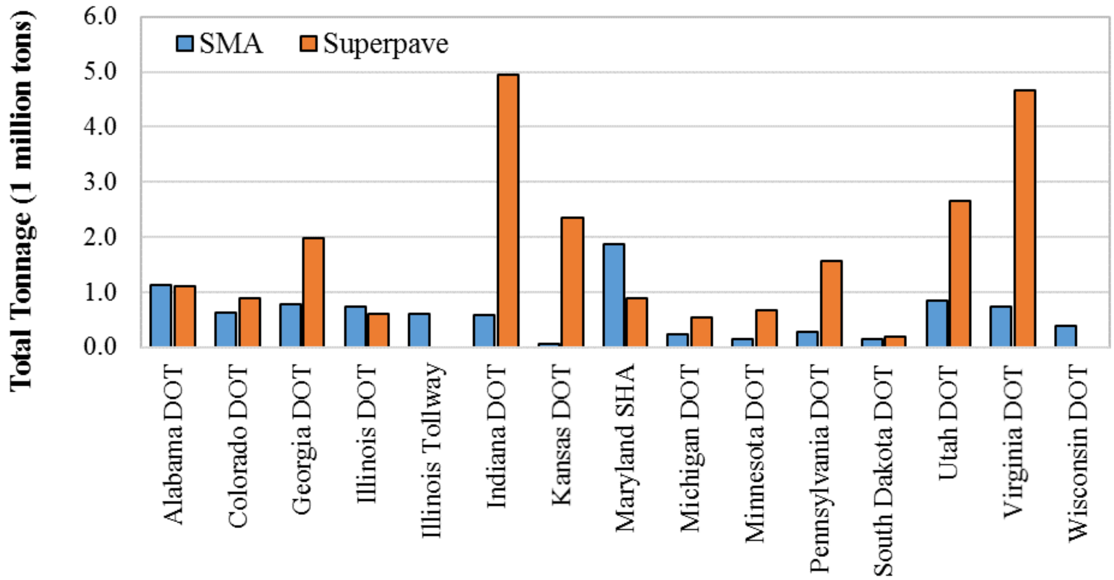


Figure 3. Total Tonnage of SMA and Polymer-Modified Superpave Mixtures from 2011-2015

2.4 SMA Cost

Figure 4 compares the five-year average weighted bid price of SMA and polymer-modified Superpave dense-graded mixtures from 2011 to 2015, where the weighted bid price is calculated as the sum of project bid price times the project tonnage divided by the total tonnage for that mixture for the year (Equation 1). As shown in the figure, the cost of SMA was consistently higher than that of comparable Superpave mixtures. The difference in the weighted bid price of these two mixtures ranged from $6 to $31 per ton. The higher cost of SMA was likely due to higher asphalt contents, requirements for more cubical and durable aggregates, and inclusion of fibers as stabilizers. In addition, several agencies noted that recycled materials [i.e., reclaimed asphalt pavements (RAP) and recycled asphalt shingles (RAS)] are not permitted in SMA but are allowed in Superpave mixtures. As shown in Figure 5, for SHAs that allow the use of RAP and RAS in SMA, the average cost difference between these two mixtures was approximately $17 per ton [(12+31+6+21+10+24)/6 = 17], which was slightly lower than that of agencies not allowing the use of RAP and RAS in SMA [i.e., (23+27+16+28+12)/5 = $21 per ton]. Additional factors that could also contribute to the higher cost of SMA include reduced plant versatility due to not being able to easily switch to other mix types since the production of SMA often uses special aggregates in the cold feed bins, and shortened paving windows due to traffic control restrictions on projects where SMA mixtures are typically used.

$$Weighted\ Bid\ Price = \frac{\sum T_i P_i}{\sum T_i} \tag{1}$$

where

T_i = tonnage of project *i*; and

P_i = unit bid price of project *i*.

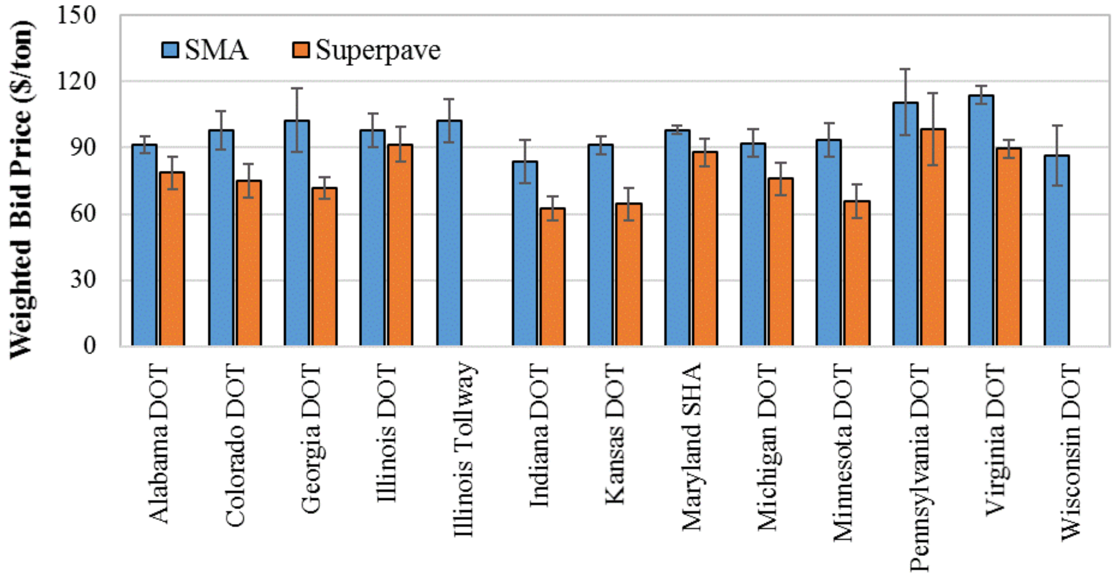
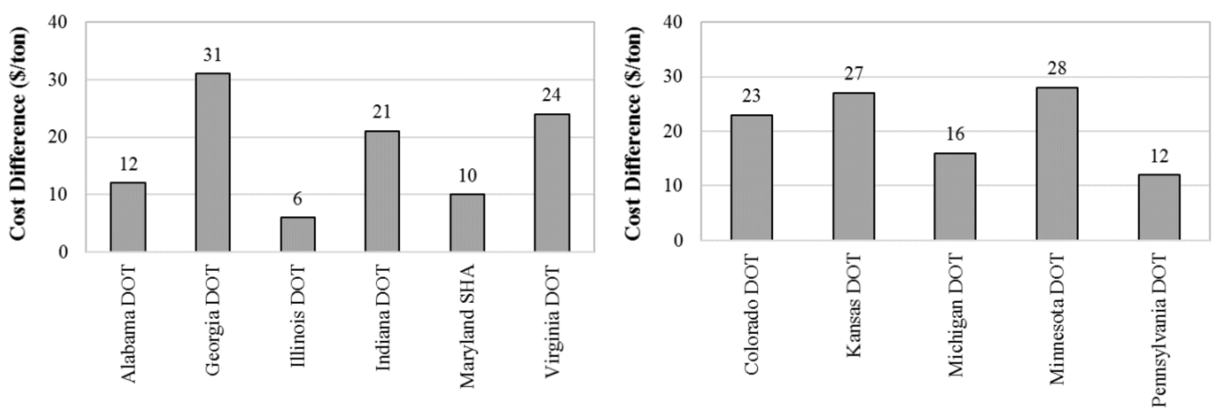


Figure 4. Weighted Bid Price of SMA and Polymer-Modified Superpave Mixtures from 2011-2015



(a) (b)

Figure 5. Difference in Weighted Bid Price Between SMA and Polymer-Modified Superpave Mixtures; (a) States Allowing RAP/RAS in SMA; (b) States Not Allowing RAP/RAS in SMA.

2.5 Summary

Currently, at least 18 SHAs use SMA on a routine basis. Ten out of 16 (62.5%) agencies that provided survey responses have a specific mixture selection policy for using SMA, while the other six (37.5%) agencies indicated that the use of SMA is a decision by the state pavement engineer. In general, SMA is used on state and interstate routes with high traffic volumes and projects where frequent maintenance is costly and disruptive to high traffic volumes. With regard to SMA mixture design procedure, 56.3% of the survey respondents (nine agencies) follow AASHTO R 46-08, *Standard Practice for Designing Stone Matrix Asphalt (SMA)*, or a modified version of it, while 31.2% (five agencies) and 12.5% (two agencies) use specific DOT standards or AASHTO R 35, *Standard Practice for Superpave Volumetric Design for Asphalt Mixtures*, respectively. The five-year average weighted bid price of SMA ranged from 7% to 43% higher than that of polymer-modified Superpave mixtures used on similar trafficked highways. The difference ranged from $6 to $31 per ton among the states. The higher cost of SMA was mainly due to higher asphalt contents, requirements for more cubical and durable aggregates, and inclusions of fibers. Additional factors such as reduced recycled materials contents, reduced plant versatility, and shortened paving windows could also contribute to the higher cost of SMA.

3. PERFORMANCE ANALYSIS

Pavement management system (PMS) data from nine highway agencies were received and analyzed to compare the long-term field performance of SMA versus polymer-modified Superpave dense-graded mixtures used for equivalent road categories and pavement types. Performance analyses were conducted using the network-level analysis approach to determine the life expectancy of these two mixtures. As will be discussed subsequently, most pavement sections included in the analyses were constructed within the past ten years, and thus, their long-term performance data is not available and needs to be predicted using a performance deterioration model. In most cases, an s-shaped logistic performance prediction model (Equation 2) was used because it could simulate the general development trend of pavement conditions (Jackson et al. 1996; Wang 2016). As shown in Figure 6, asphalt pavement condition typically deteriorates slowly during the first few years, but afterwards, drops at a significantly faster rate, and finally shows a steady decrease to approach a low boundary.

$$y(t) = a - \frac{b}{1+ce^{-dt}} \tag{2}$$

where
$y(t)$ = pavement condition at time t;
a, b, c, and d = model coefficients; and
t = pavement age.

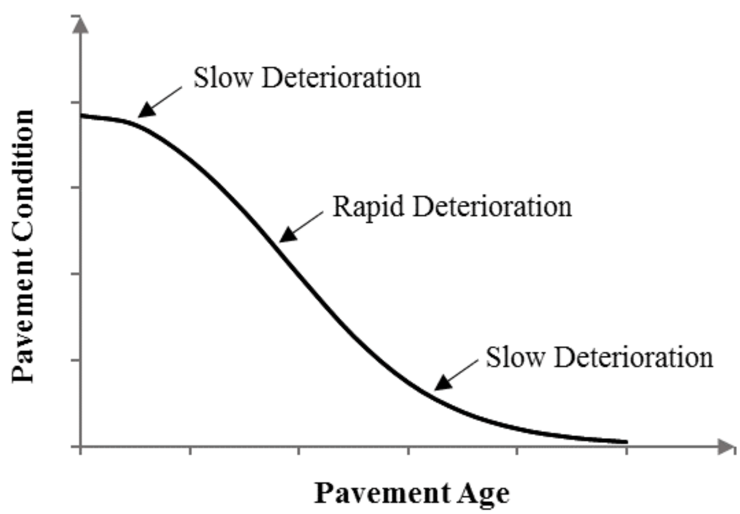


Figure 6. Illustration of S-shaped Logistic Pavement Performance Model

For data analysis, the collected PMS data was first used to calibrate the selected performance models, which were then used to predict the service life of pavement sections with SMA and Superpave dense-graded mixtures. For agencies using individual pavement distresses (e.g., rutting, cracking, and roughness) for pavement maintenance and rehabilitation decisions, performance was evaluated with regard to each distress. Otherwise, PMS data was analyzed using composite pavement condition indexes, such as Distress Index, Surface Rating, PACES Rating, etc. In this study, PMS data from a total of 407 SMA and 807 Superpave pavement sections were analyzed. The analysis results are presented subsequently.

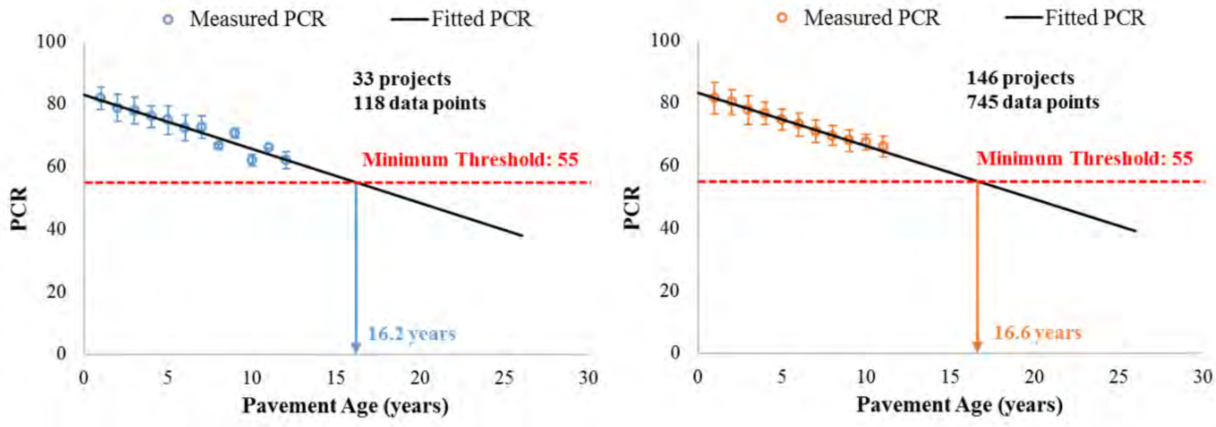
3.1 Agencies Using Composite Pavement Condition Indexes

3.1.1 Alabama DOT

The Alabama DOT currently uses automated data collection methods to perform network-level pavement assessment. According to ALDOT-414-04, collected information for flexible pavements include transverse cracking, load associated cracking, non-load associated cracking, rutting, high severity raveling, patching, and macrotexture. All cracking data are measured and reported in terms of the number of linear feet within each 0.01-mile road segment. The collected distress data are then analyzed to determine a composite pavement condition index termed Pavement Condition Rating (PCR). As expressed in Equation 3, PCR is defined as the arithmetic average of four index metrics: pavement roughness, wheelpath cracking, rutting, and age of overlay, respectively (ALDOT 2015). PCR is on a zero to 100 scale, with 100 indicating a distress-free condition and zero for a completely failed pavement. Typically, pavement sections with a PCR value of 55 or lower are considered in a “marginal” condition that require rehabilitation or reconstruction.

$$PCR = \frac{Index_{roughness}+Index_{cracking}+Index_{rutting}+Index_{age}}{4} \tag{3}$$

Figure 7 presents the PCR data of 179 flexible pavement sections; the dots represent the average PCR of pavement sections with the same age, and the error bars denote one standard deviation from the average values. Thirty-three of these sections had SMA as the surface layer and the rest (146 sections) used polymer-modified Superpave dense-graded mixtures. Both SMA and Superpave sections had a design traffic level of greater than 10 million equivalent single axle loads (ESALs). As shown in Figure 7, the PCR data shows a relatively consistent reduction with pavement age; thus, a linear performance model was selected to project the future development of pavement condition. For data analysis, the performance model was first used to fit the measured PCR data. Once the model coefficients were determined, the pavement service life was then predicted using a minimum PCR threshold of 55. Based on the results shown in Figure 7, flexible pavement sections with SMA and polymer-modified Superpave mixtures showed comparable predicted performance and were predicted to last for 16.2 and 16.6 years, respectively.



(a) (b)

Figure 7. Alabama DOT Pavement PCR Data; (a) SMA, (b) Polymer-Modified Superpave Mixtures

3.1.2 Georgia DOT

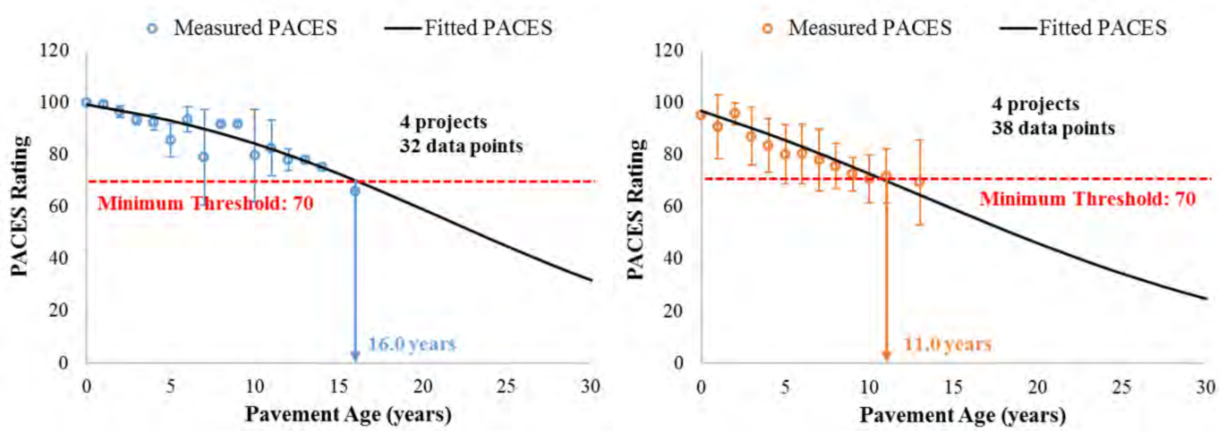
The Georgia DOT uses the Pavement Condition Evaluation Survey (PACES) as a manual to identify individual pavement distresses and rate the pavement condition (GDOT 2005). Collected distresses for flexible pavements include rutting, raveling, load cracking, edge distress, block cracking, bleeding/flushing, reflection cracking, corrugations/pushing, patches and potholes, and loss of section. For each type of pavement distress, a deduct value is determined based on its severity and extent. These deduct values are then totaled and subtracted from 100 to compute the PACES rating (Equation 4). The PACES rating ranges from zero to 100, with 100 indicating a distress-free condition and zero for a completely failed condition. A minimum rating of 70 is currently used by the Georgia DOT as the trigger for pavement resurfacing; thus, this threshold was used in the analysis to predict the life expectancy of SMA and polymer-modified Superpave dense-graded mixtures.

$$PACES\ Rating = 100 - \Sigma^{D_i} \tag{4}$$

where

D_i = deduct value for each individual pavement distress.

In this study, PMS data of four SMA and four polymer-modified Superpave sections on flexible pavements were provided by the Georgia DOT and included in the performance analysis. Although all of these sections have an open-graded friction course (OGFC), OGFC is not considered as a structural pavement layer. Thus, the data could still be used to compare the field performance of SMA versus polymer-modified Superpave mixtures. Figure 8 presents the PACES ratings of these sections; the dots represent the average PACES ratings of pavement sections with the same age, and the error bars refer to one standard deviation from the average values. For performance analysis, an s-shaped logistic model (Equation 2) was first used to fit the PACES rating results versus pavement age. The service lives of SMA and Superpave mixtures were then predicted using a terminal PACES rating of 70. As shown in Figure 8, SMA was predicted to last for 16.0 years, which was approximately five years longer than that of comparable Superpave mixtures (i.e., 11.0 years). It should be noted that the performance analysis presented here was based on a limited number of pavement sections; thus, the results should be interpreted with caution.



(a) (b)

Figure 8. Georgia DOT Pavement PACES Rating Data; (a) SMA, (b) Polymer-Modified Superpave Mixtures

3.1.3 Illinois Tollway

The Illinois Tollway uses video inspection vehicles (VIVs) and computerized workstations to perform pavement survey and analysis. The VIVs collect images of the roadways and sensor data including rutting, faulting, and longitudinal profile at highway speeds. The data is then analyzed to identify pavement distresses and calculate a Condition Rating Survey (CRS) to indicate the overall pavement condition. CRS has a scale of 0 to 9, with nine indicating a distress-free condition and zero for a completely failed condition. A minimum threshold value of 6.5 is specified for interstate highways and thus, this threshold was used to predict the service lives of SMA and polymer-modified Superpave mixtures in this study.

Islam et al. (2017) presented the recalibrated performance models for a variety of pavement types used by the Illinois Tollway. Two pavement sections with SMA and polymer-modified Superpave dense-graded overlays on top of jointed plain concrete pavement (JPCP) were included in the study. For data analysis, an iterative performance model (Equation 5) was first used to fit the measured CRS data, from which the model coefficients were determined based on non-linear regression analysis. The pavement service life was then predicted using the following assumptions: initial traffic of 4.0 million ESALs, traffic growth rate of 3%, an initial CRS value of 8.9, and a terminal CRS value of 6.5. Based on the results shown in Figure 9, the SMA section had a predicted service life of 13.5 years, which was approximately five years longer than that of the Superpave dense-graded pavement section. It should be noted that the analysis presented here was based on a limited number of pavement sections; thus, the results should be interpreted with caution.

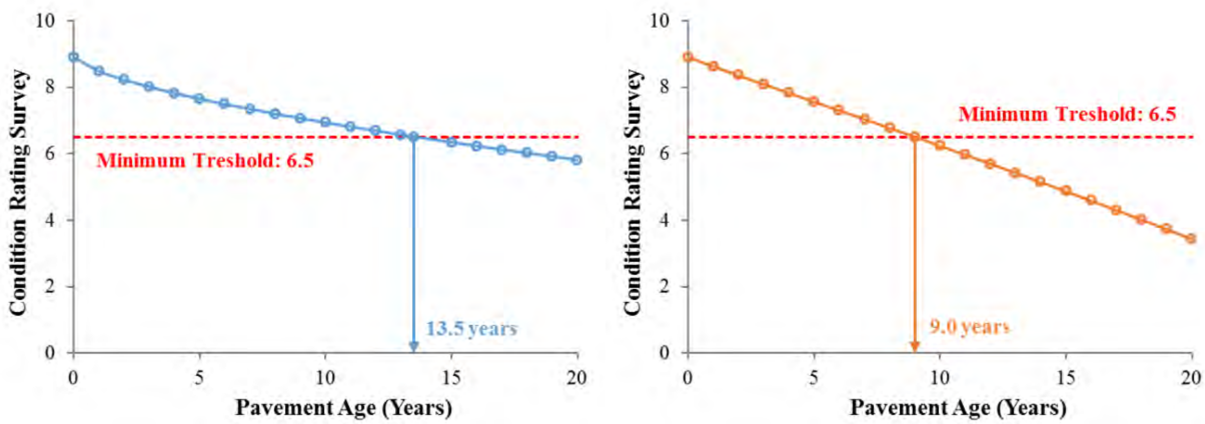
$$CRS = 9 - 2a*(Thick*TAF)^{b}*(C_1 + \Delta Year)^{c}*(C_2 + \Delta ESAL)^{d} \tag{5}$$

$$C_1 = ((9 - CRS_i)/(2a*(Thick*TAF)^{b}*CESAL^{d}))^{\frac{1}{c+d}}$$

$$C_2 = C_1 * CESAL$$

where

TAF = thickness adjustment factor;
Thick = AC overlay thickness;
ΔYear = change in pavement age;
ΔESAL = accumulated ESALs over the time period *ΔYear*;
CESAL = current annual ESALs; and
a, b, c, d = model coefficients.



(a) (b)

Figure 9. Illinois Tollway Pavement CRS Data; (a) SMA, (b) Polymer-Modified Superpave Mixtures (Islam et al. 2017)

3.1.4 Michigan DOT

The Michigan DOT conducts pavement distress survey by videotaping the pavement surface. The videos are analyzed to identify distress type, extent, and severity, which are then used to compute a composite pavement condition rating termed Distress Index (DI). The DI starts at zero for a distress-free condition and increases as the pavement deteriorates. A DI of 50 or higher indicates the need for rehabilitation. This DI threshold also corresponds to a remaining service life of zero.

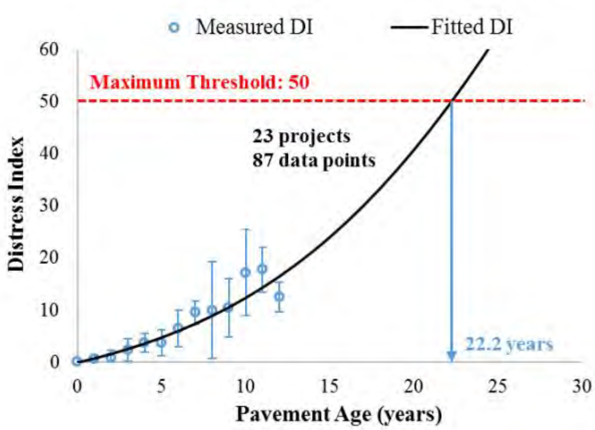
Since most of the SMA sections identified by the Michigan DOT in this study were composite pavements, a performance comparison between SMA and polymer-modified Superpave dense-graded mixtures for flexible pavements was not available. Figure 10 presents the DI data of 113 composite pavement sections; the dots represent the average DI of pavement sections with the same age, and the error bars denote one standard deviation from the average values. Twenty-three of these sections had SMA as the surface layer and the rest used comparable Superpave dense-graded mixtures. The asphalt layer of both SMA and Superpave sections had similar thickness ranging from 3.5 to 5.0 inches. The average daily truck traffic (ADTT) of these sections was between 1,000 and 6,000. For data analysis, an s-shaped performance model (Equation 6) was first used to fit the measured DI data based on non-linear regression. This model has been used by the Michigan DOT to predict the development of pavement distresses since 1995 (Kuo 1995). Once the model coefficients were determined, the pavement service life was then predicted using a DI threshold of 50. Based on the results in Figure 10, composite pavement sections with SMA and polymer-modified Superpave dense-graded mixtures showed similar performance and were predicted to last for 22.2 and 21.3 years, respectively.

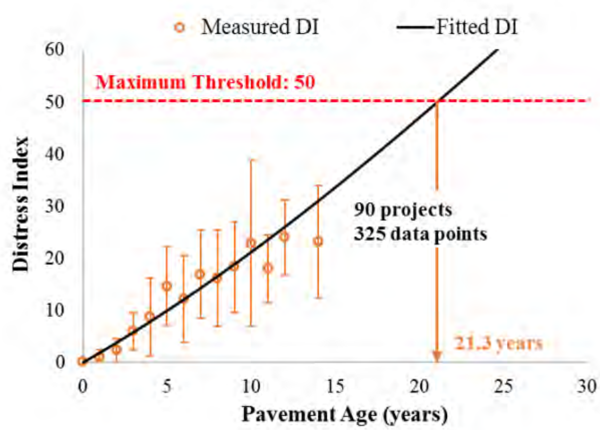
$$DI = m\left(\frac{1}{1+ce^{-\gamma * t}} - \frac{1}{1+c}\right) \tag{6}$$

where

t = pavement age; and

m, γ, c = model coefficients.





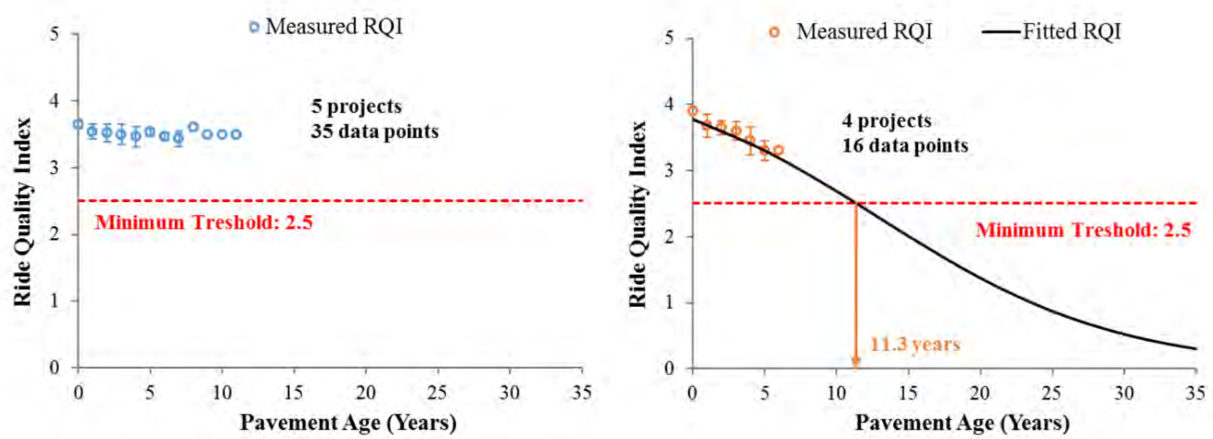
(a) (b)

Figure 10. Michigan DOT Pavement DI Data; (a) SMA, (b) Polymer-Modified Superpave Mixtures

3.1.5 Minnesota DOT

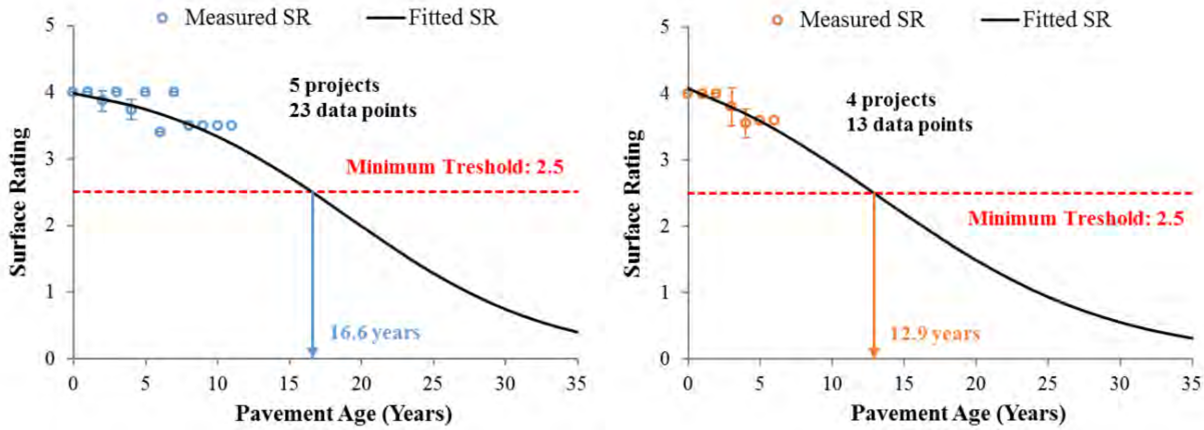
The Minnesota DOT collects pavement roughness and surface distress data using a digital inspection van. The van is equipped with digital cameras and lasers that generate pavement surface images and measure the longitudinal pavement profile. The collected pavement condition data are then analyzed to compute two performance indexes, namely Ride Quality Index (RQI), and Surface Rating (SR). The RQI is a smoothness index with a scale of 0 to 5. A higher RQI value indicates a smoother pavement. The SR index provides an overall indication of pavement surface distresses. It ranges from 0 to 4 and a higher SR represents a better surface condition. Pavement sections in need of major rehabilitation or reconstruction generally have a terminal RQI and SR of 2.5. In this study, both RQI and SR were used to compare the performance of SMA versus polymer-modified Superpave dense-graded mixtures used on similar trafficked highways.

PMS data of 10 SMA (including five flexible pavements and five composite pavements) and 14 polymer-modified Superpave pavement sections (including four flexible pavements and ten composite pavements) were identified by the Minnesota DOT. However, the five SMA composite pavement sections were only two to four years old, which was considered insufficient for predicting service lives. Thus, a performance comparison between SMA and Superpave dense-graded mixtures for composite pavements was not available. Figure 11 and Figure 12 present the RQI and SR data of five SMA and four Superpave flexible pavement sections, respectively; the dots represent the average RQI and SR of pavement sections with the same age, and the error bars denote one standard deviation from the average values. Note that in cases where there is only one pavement section at a particular age, no error bars would be shown for the corresponding RQI and SR results. All these sections consist of 2 to 4 inches of asphalt surface layer with SMA or polymer-modified Superpave dense-graded mixtures on top of an aggregate base. For data analysis, an s-shaped logistic model (Equation 2) was first used to fit the RQI and SR data. The pavement service life was then predicted using a terminal RQI and SR of 2.5. As shown in Figure 11(a), the RQI data of SMA pavement sections showed no deterioration with time; thus, additional data is needed for the performance model to predict the development of RQI. Based on the SR results in Figure 12(a), SMA was predicted to last for 16.6 years. The comparable Superpave dense-graded mixtures had a predicted service life of 11.3 years using a terminal RQI [Figure 11(b)] and SR [Figure 12(b)] of 2.5. In general, SMA was predicted to have approximately five years of life extension as compared to polymer-modified Superpave dense-graded mixtures. It should be noted that the analysis presented here was based on a limited number of pavement sections; thus, the results should be interpreted with caution.



(a) (b)

Figure 11. Minnesota DOT Pavement RQI Data; (a) SMA, (b) Polymer-Modified Superpave Mixtures



(a) (b)

Figure 12. Minnesota DOT Pavement SR Data; (a) SMA, (b) Polymer-Modified Superpave Mixtures

3.1.6 Pennsylvania DOT

The Pennsylvania DOT uses Automated Road Analyzer (ARAN) vans to collect pavement condition data. The vans are equipped with digital cameras, sensors, and accelerometers to record pavement surface distresses and measure pavement roughness. Distresses collected for flexible pavements include rutting, fatigue cracking, transverse cracking, miscellaneous cracking, edge deterioration, patching, and raveling/weathering. The collected data are then processed through automated distress programs as well as visual rating of pavement images to derive severity and extent of different pavement distresses. For each type of distress, individual distress index (DI) is determined using Equation 7. The overall pavement index (OPI) is then computed as a 0-100 index that combines IRI-based Roughness Index and individual DI (Equation 8). An OPI of 100 represents a distress-free condition and it decreases as the severity and extent of pavement distresses increase. To compare the long-term performance of SMA versus comparable Superpave dense-graded mixtures, an s-shaped logistic model (Equation 2) was used to fit the OPI data with pavement age. The pavement service life was then predicted using a preliminary minimum threshold of 80.

$$DI = 100 - D_{high} - \left(\left(1 - D_{high}/100\right) * D_{med}\right) - \left(\left(1 - D_{high}/100\right) * (1 - D_{med}/100\right) * D_{low} \quad (7)$$

where
D = distress deduct values.

$$OPI = 0.25RUF + 0.15FCI + 0.125TCI + 0.10MCI + 0.10EDI + 0.05BPI + 0.05RWI + 0.175RUT \quad (8)$$

where
RUF = roughness index;

FCI	=	fatigue cracking index;
TCI	=	transverse cracking index;
MCI	=	miscellaneous cracking index;
EDI	=	edge deterioration index;
BPI	=	bituminous patching index;
RWI	=	raveling/weathering index; and
RUT	=	rut depth index.

Figure 13 presents the OPI data of 22 composite pavement sections on interstate highways; the dots represent the average OPI of pavement sections with the same age, and the error bars denote one standard deviation from the average values. All these sections had 1.5 to 3.0 inches of asphalt layer on top of Portland cement concrete. Five of these sections used SMA as the surface layer and the rest had Superpave dense-graded mixtures. The truck traffic volume of both SMA and Superpave sections had a range of approximately 300 to 7,000 ADTT. The database provided by the Pennsylvania DOT only included two SMA flexible pavement sections on interstate routes, and thus, a performance comparison between SMA and Superpave dense-graded mixtures was not conducted for this pavement type. As shown in Figure 13, composite pavement sections with SMA and Superpave mixtures showed comparable performance. The predicted service lives of both mixtures were slightly over 20 years. It should be noted that the analysis for SMA was based on a limited number of pavement sections; thus, the results should be interpreted with caution. Additionally, the pavement sections included in the analysis covered a wide range of traffic volumes, which could affect the performance of SMA and Superpave pavement sections.

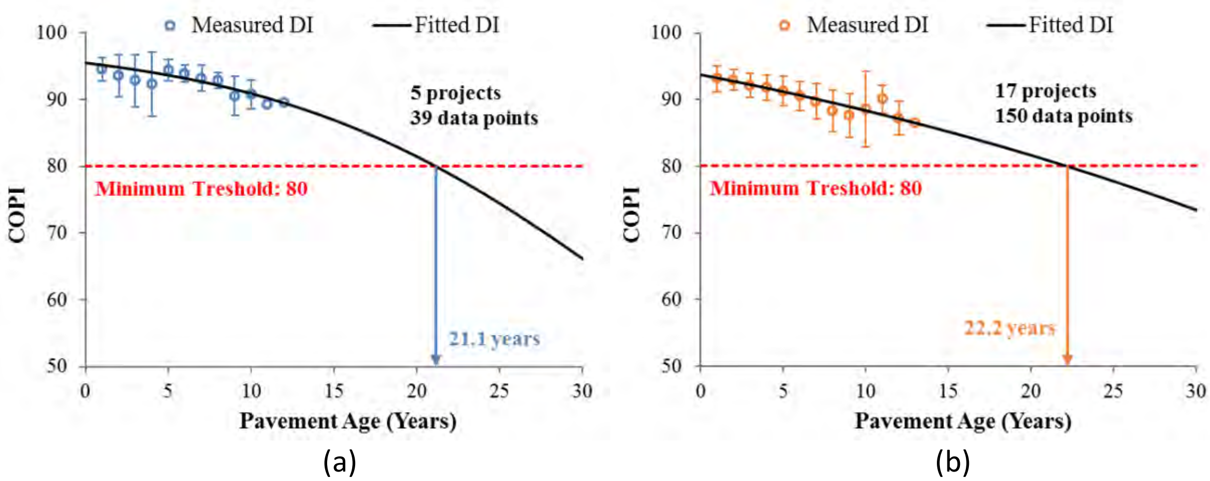
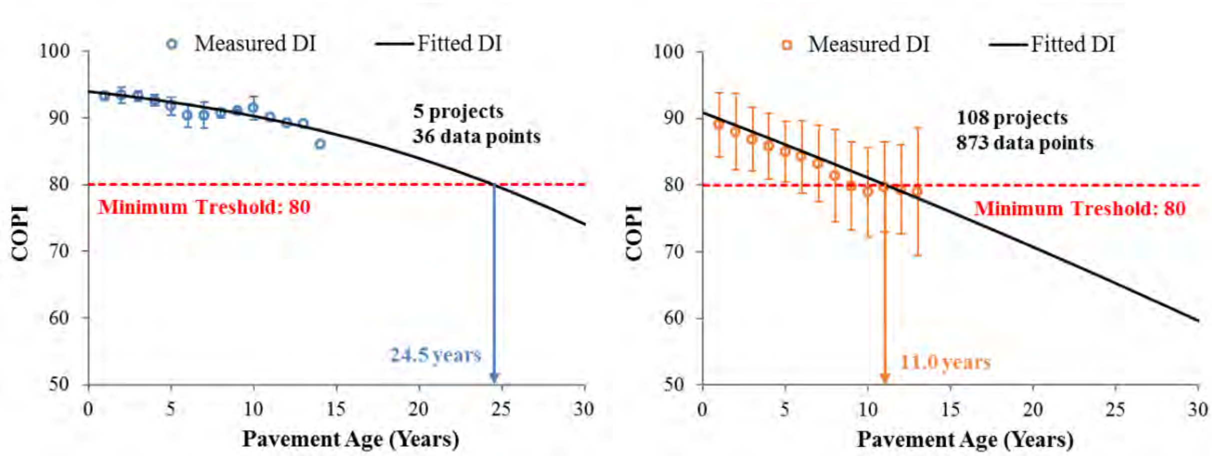


Figure 13. Pennsylvania DOT OPI Data of Composite Pavements on Interstate Routes; (a) SMA, (b) Polymer-Modified Superpave Mixtures

Figure 14 presents the OPI data of 113 composite pavement sections on NHS non-interstate routes. Five of these sections used SMA as the surface layer and the rest had comparable Superpave dense-graded mixtures. The truck traffic volume of these sections had a range of approximately 100 to 3,500 AADTT. Since the database provided by the Pennsylvania DOT only included three SMA flexible pavement sections on NHS non-interstate routes, a performance comparison between SMA and Superpave dense-graded mixtures was not conducted for this pavement type. As shown in Figure 14(a), composite pavement sections with SMA were predicted to last for 24.5 years until the OPI reached the minimum threshold of 80. Pavement sections with Superpave mixtures, however, showed a significantly faster deterioration of OPI and had a predicted service life of 11.0 years. These results indicated that SMA yielded an approximately 13 years of life extension as compared to polymer-modified Superpave mixtures when used on NHS non-interstate routes. Again, the analysis for SMA was based on a limited number of pavement sections; thus, the results should be interpreted with caution.



(a) (b)

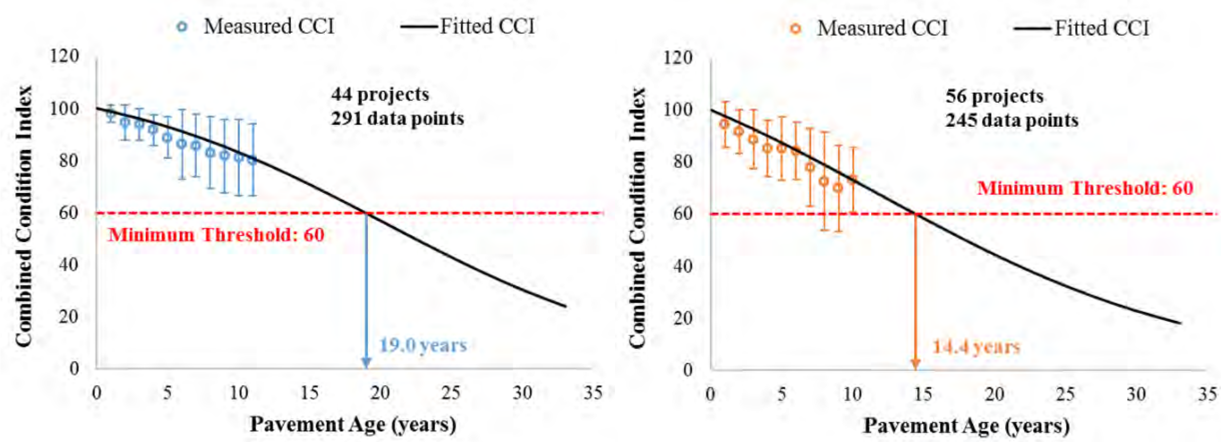
Figure 14. Pennsylvania DOT OPI Data of Composite Pavements on NHS Non-Interstate Routes; (a) SMA, (b) Polymer-Modified Superpave Mixtures

3.1.7 Virginia DOT

The Virginia DOT uses an ARAN van to collect pavement data based on digital images and automated crack detection methodology. The ARAN is equipped with a distance measuring instrument, a laser rut measuring system, a laser longitudinal profiling system, a global positioning system, and downward facing cameras. Data collection is conducted on approximately 13,000 directional miles of interstate and primary state highways on a yearly basis (VDOT 2012). The collected pavement distress data are then analyzed to calculate the Load Related Distress Rating (LDR) and Non-load Related Distress Rating (NDR). The LDR is determined based on alligator cracking, wheel path patching, and rutting, and the NDR considers longitudinal and transverse cracking, non-wheel path patching, and bleeding. The lower of the two ratings is defined as the Critical Condition Index (CCI). The CCI has a scale of zero to 100, with 100 indicating a distress-free condition and zero for a completed failed condition. Pavement sections with a CCI of 60 or lower are considered “deficient” and are in need of immediate rehabilitation and reconstruction.

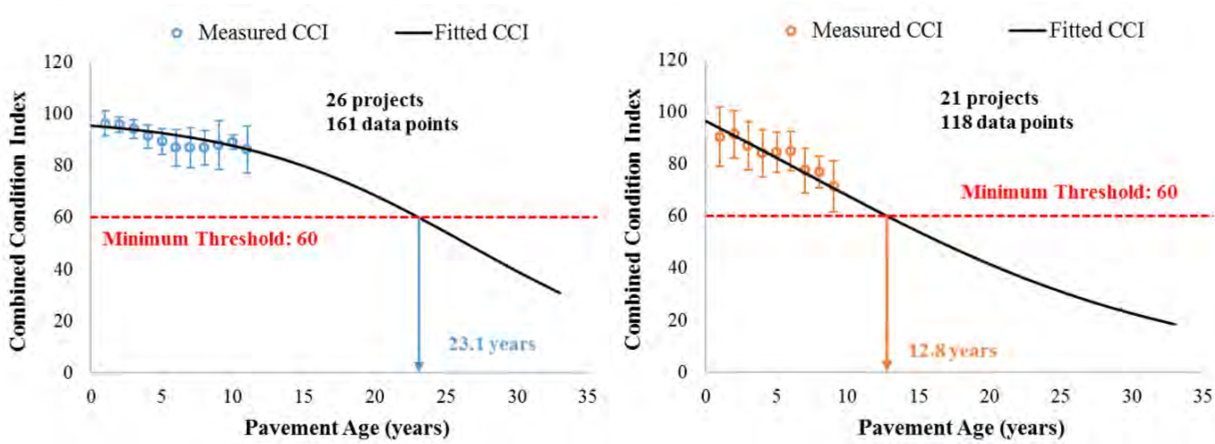
Figure 15 and Figure 16 present the CCI results of 100 flexible pavement sections and 47 composite pavement sections, respectively; the dots represent the average CCI of sections with the same age, and the error bars refer to one standard deviation from the average values. Both

SMA and Superpave pavement sections had similar design traffic levels. The thickness of the surface layer ranged from 1.5 to 3 inches. For performance analysis, an s-shaped logistic model (Equation 2) was first used to fit the measured CCI data versus pavement age. The pavement service life was then predicted with a minimum CCI threshold of 60. As shown in Figure 15, flexible pavement sections with SMA had a predicted service life of 19.0 years, which was approximately five years longer than that of polymer-modified Superpave dense-graded mixtures (i.e., 14.4 years). A greater life extension of approximately ten years was observed for composite pavement sections in Figure 16, where SMA and Superpave mixtures were predicted to last for 23.1 and 12.8 years, respectively. It should be noted that the predicted service lives of SMA and comparable Superpave mixtures discussed above were determined based on extrapolation using a non-linear performance model, which might not necessarily represent the observed service lives in the field.



(a) (b)

Figure 15. Virginia DOT Flexible Pavement CCI Data; (a) SMA, (b) Polymer-Modified Superpave Mixtures



(a) (b)

Figure 16. Virginia DOT Composite Pavement CCI Data; (a) SMA, (b) Polymer-Modified Superpave Mixtures

3.2 Agencies Using Individual Pavement Distresses

3.2.1 Colorado DOT

The Colorado DOT collects pavement condition data using automated photo survey and laser profilometer equipment. Collected data includes ride quality in terms of International Roughness Index (IRI), rutting, fatigue cracking, transverse cracking, and longitudinal cracking. All pavement distresses are reported in 1/10-mile increments and are collected in accordance with the FHWA-HRT-13-092 *Distress Identification Manual for the Long-Term Pavement Performance Project* (FHWA 2014). The overall pavement index (OPI) was historically used to evaluate the overall pavement condition of the state highway network, but previous experience indicated that OPI replied heavily on pavement surface condition and underestimated the impact of ride quality. From 1999 to 2013, the Colorado DOT had been using the Remaining Service Life (RSL) as the indicator of overall pavement condition. For each type of pavement distress, RSL was calculated using a specified threshold. In 2013, a new performance index termed Drivability Life (DL) was adopted, which focused on the overall driving condition of the pavement by considering smoothness, distress, and safety. Since most of the pavement sections included in the study were constructed between 1999 and 2013, the performance comparison between SMA and Superpave dense-graded mixtures was conducted using the RSL procedure.

PMS data of 163 flexible pavement sections were included in the performance analysis; 52 of these sections had SMA as the surface layer and the rest used Superpave dense-graded mixtures. All these sections had average annual daily truck traffic (AADTT) of 500 to 9,500 in 2015. The thickness of the surface layers ranged from 2 to 4 inches. The analysis method proposed by Shuler and Schmidt (2008) was followed largely in this study to predict and compare the RSL of SMA and Superpave mixtures. Pavement distress data was first organized by pavement section and in-service time. The average pavement distress of both SMA and Superpave pavement sections was then calculated for each pavement age (i.e., in-service time). After that, the changes in the average pavement distress between every two consecutive years were determined, which were then used to calculate the cumulative change in pavement distress with time, as shown in Table 3. Finally, an exponential function was employed to fit the cumulative pavement distress data and to determine the RSL based on the following thresholds: 0.55 inches of rutting, 1,800 square feet of fatigue cracking, 55 transverse cracks per 0.1 mile, and 1,400 linear feet of longitudinal cracking.

Figure 17 and Figure 18 present the calculated and fitted distress data of pavement sections with SMA and Superpave mixtures, respectively. In general, the two mixtures showed comparable performance. SMA pavement sections had a predicted RSL of 17.0 years, which was almost identical to that of Superpave sections (i.e., 17.4 years). In addition, it was observed from the figures that the performance of Superpave sections was mainly governed by transverse cracking, while fatigue cracking, transverse cracking, and longitudinal cracking were found as the controlling distresses for SMA sections.

Table 3. Calculation of Colorado DOT Pavement Distress Data

Mixture Type	Age	Average Distress by Year: Rutting	Average Distress by Year: Fatigue Cracking	Average Distress by Year: Transverse Cracking	Average Distress by Year: Longitudinal Cracking	Change in Average Distress: Rutting	Change in Average Distress: Fatigue Cracking	Change in Average Distress: Transverse Cracking	Change in Average Distress: Longitudinal Cracking	Cumulative Change in Average Distress: Rutting	Cumulative Change in Average Distress: Fatigue Cracking	Cumulative Change in Average Distress: Transverse Cracking	Cumulative Change in Average Distress: Longitudinal Cracking
SMA (52 projects & 321 data points)	0	0.110	0.0	0.0	0.0	0.000	0.0	0.0	0.0	0.000	0.0	0.0	0.0
	1	0.124	5.6	0.6	23.0	0.014	5.6	0.6	23.0	0.014	5.6	0.6	23.0
	2	0.123	9.6	0.9	40.4	0.000	4.0	0.3	17.4	0.014	9.6	0.9	40.4
	3	0.131	7.1	1.5	74.7	0.008	0.0	0.6	34.3	0.022	9.6	1.5	74.7
	4	0.129	55.3	2.7	156.2	0.000	48.3	1.2	81.5	0.022	57.9	2.7	156.2
	5	0.149	93.2	2.5	187.7	0.020	37.9	0.0	31.4	0.042	95.8	2.7	187.7
	6	0.154	67.1	5.4	279.2	0.005	0.0	2.9	91.5	0.047	95.8	5.6	279.2
	7	0.182	143.7	6.2	296.8	0.028	76.6	0.8	17.6	0.075	172.3	6.4	296.8
	8	0.202	109.3	6.3	399.6	0.020	0.0	0.1	102.8	0.095	172.3	6.5	399.6
	9	0.226	246.8	9.0	280.7	0.024	137.5	2.7	0.0	0.119	309.9	9.2	399.6
Superpave (111 projects & 775 data points)	0	0.110	0.0	0.0	0.0	0.000	0.0	0.0	0.0	0.000	0.0	0.0	0.0
	1	0.124	18.7	1.5	50.3	0.014	18.7	1.5	50.3	0.014	18.7	1.5	50.3
	2	0.135	43.3	3.9	112.0	0.011	24.6	2.4	61.7	0.025	43.3	3.9	112.0
	3	0.142	68.6	5.9	185.8	0.007	25.3	2.0	73.9	0.032	68.6	5.9	185.8
	4	0.136	116.5	6.2	243.9	0.000	47.9	0.3	58.1	0.032	116.5	6.2	243.9
	5	0.143	167.4	8.7	286.1	0.006	50.9	2.6	42.2	0.038	167.4	8.7	286.1
	6	0.157	193.4	10.2	333.0	0.015	26.1	1.4	46.9	0.053	193.4	10.2	333.0
	7	0.170	262.9	13.3	274.7	0.013	69.4	3.2	0.0	0.066	262.9	13.3	333.0
	8	0.198	315.3	15.3	285.7	0.027	52.4	2.0	11.0	0.093	315.3	15.3	344.0
	9	0.192	335.8	17.2	260.9	0.000	20.5	1.9	0.0	0.093	335.8	17.2	344.0

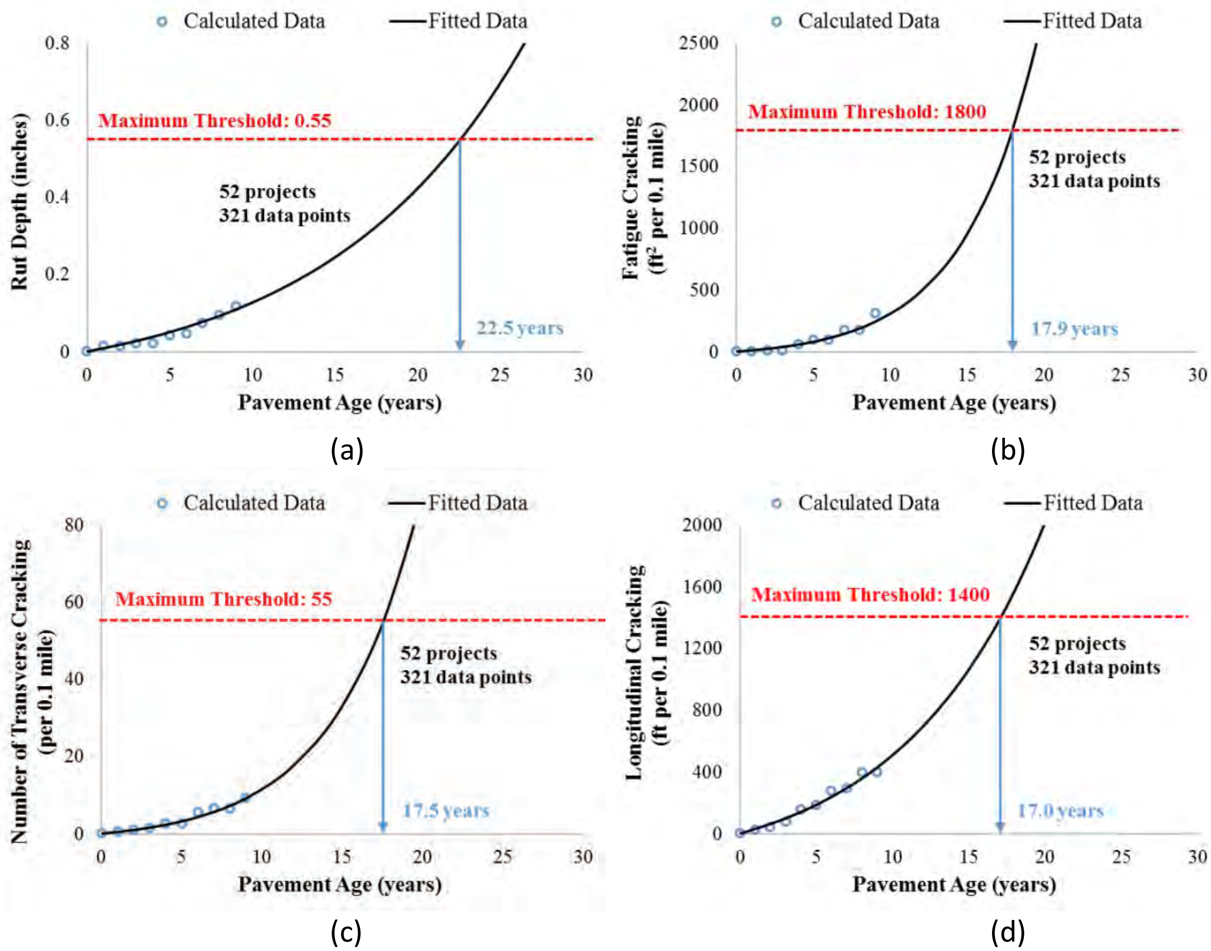


Figure 17. Colorado DOT SMA Pavement Distress Data; (a) Rutting, (b) Fatigue Cracking, (c) Transverse Cracking, (d) Longitudinal Cracking

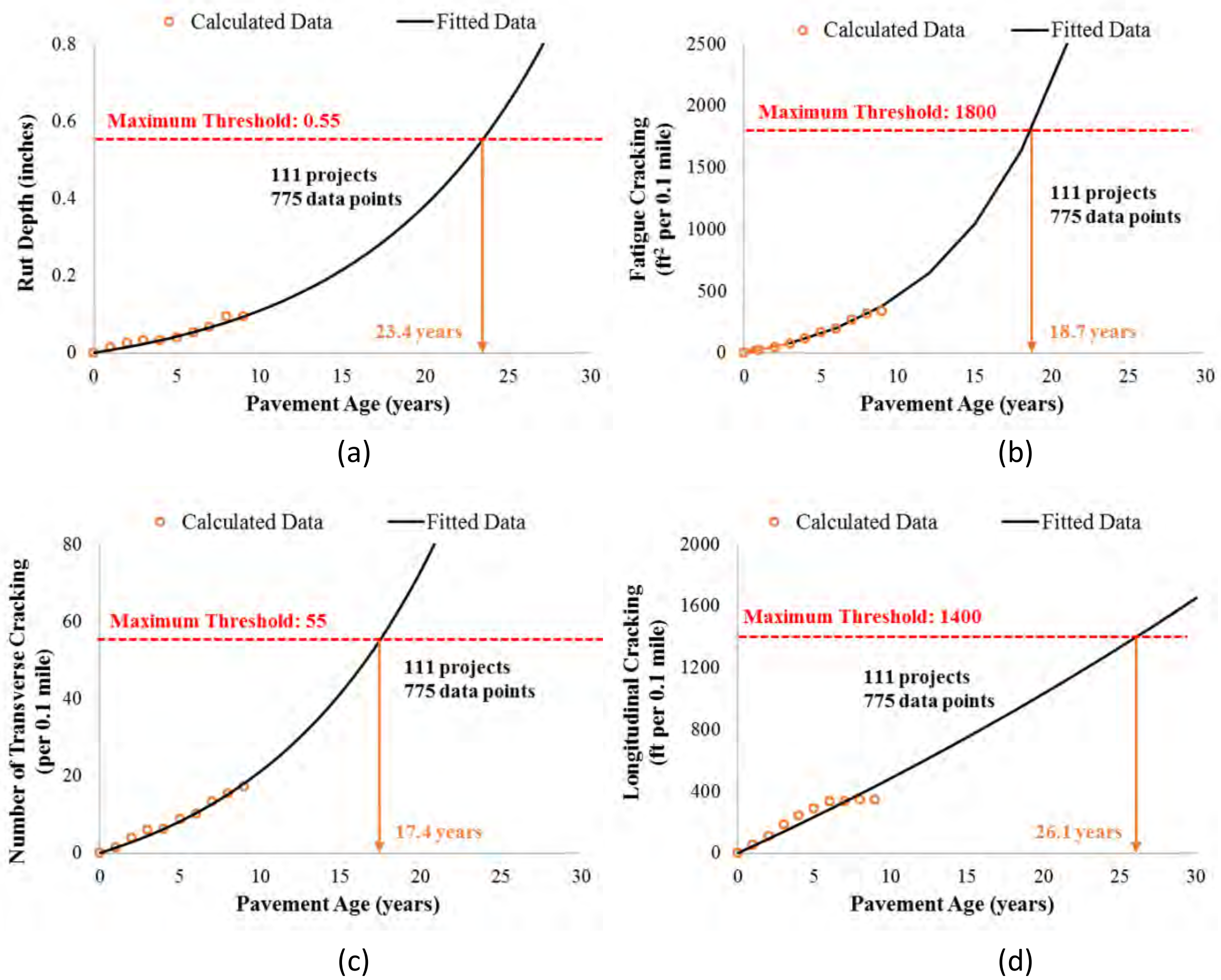


Figure 18. Colorado DOT Superpave Pavement Distress Data; (a) Rutting, (b) Fatigue Cracking, (c) Transverse Cracking, (d) Longitudinal Cracking

3.2.2 Maryland SHA

The Maryland SHA uses ARAN vans to collect pavement condition data. The vans are equipped with high-resolution pavement imaging system as well as transverse and longitudinal profiling systems that videotape pavement surfaces and collect roughness and rutting measurement. The collected data are then processed in the Pavement Management Base system to determine the extent and severity of rutting, structural cracking, and functional cracking. The cracking data are utilized to compute the structural cracking index (SCI) and functional cracking index (FCI). Pavement distresses that comprise FCI include bleeding, block cracking, bumps and sags, corrugation, joint reflective cracking, lane/shoulder drop-off, polished aggregate, slippage cracking, transverse cracking, and weathering and raveling. Distresses that comprise SCI are alligator cracking, depression, longitudinal and edge cracking, and patching/potholes. Both SCI and FCI have a scale of 0 to 100, with 100 indicating a "no cracks" pavement section and zero for a completely cracked section. For data analysis, a linear function was used to fit the rut depth data, and an s-shaped logistic model (Equation 2) was used for the SCI and FCI data. Finally, the service lives of SMA and Superpave mixtures were predicted based on the following thresholds:

- Rural and urban interstate: rut depth of 0.30 inches, SCI of 65, and FCI of 50;
- Rural and urban principal arterial: rut depth of 0.35 inches, SCI of 50, and FCI of 40.

Figure 19 and Figure 20 present the rut depth and FCI data of 103 SMA and 31 Superpave flexible pavement sections on interstate highways, respectively. The SCI data showed no deterioration with time, and thus, the results are not presented here. In these figures, the dots represent the average rut depth and FCI of pavements sections with the same age, and the error bars denote one standard deviation from the average values. Both SMA and Superpave sections had an approximately 2 inches of asphalt surface layer and a design 20-year traffic level of over 6.5 million cumulative ESALs. As shown in Figure 19 and Figure 20, SMA and polymer-modified Superpave dense-graded mixtures showed similar performance; both mixtures were predicted to last for approximately 25 to 27 years until the FCI reached a minimum threshold of 50.

Figure 21 and Figure 22 present the rut depth and FCI data of 60 SMA and 158 Superpave flexible pavement sections on principal arterials, respectively. As shown in Figure 21, both SMA and Superpave pavement sections exhibited outstanding rutting resistance and were predicted to last for at least 45 years until the rut depth reached the maximum threshold of 0.35 inches. Based on the FCI data shown in Figure 22, SMA had a predicted service life of 32.2 years, which was approximately eight years longer than that of comparable Superpave dense-graded mixtures (i.e., 24.0 years).

Figure 23 and Figure 24 present the rut depth and FCI data of 43 SMA and 56 Superpave composite pavement sections on principal arterials, respectively. Once again, the service lives of both SMA and Superpave mixtures were controlled by the FCI data. With a minimum FCI threshold of 40, SMA was predicted to last for 21.8 years, which was slightly longer than that of comparable Superpave dense-graded mixtures (i.e., 19.6 years).

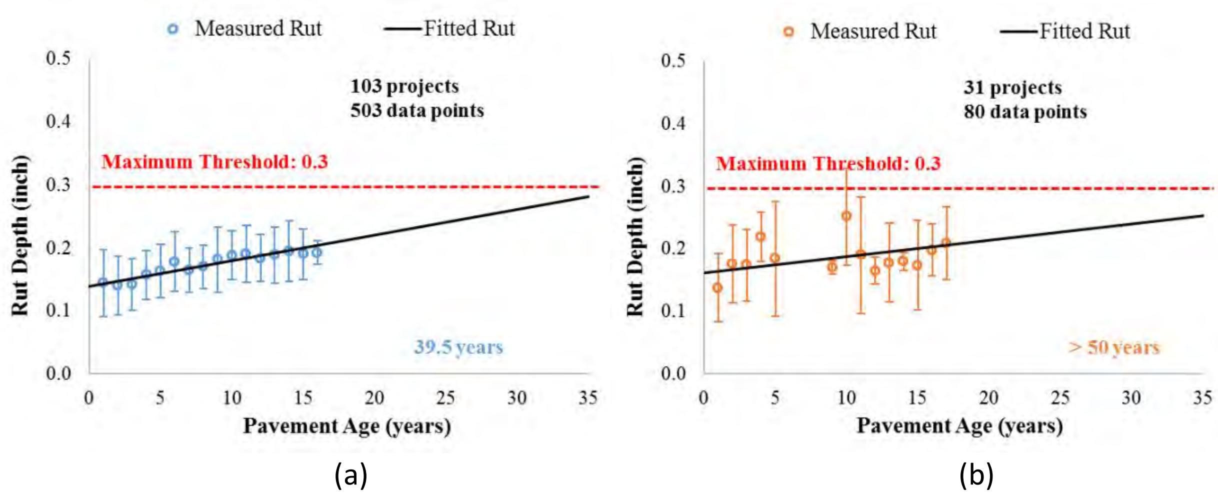
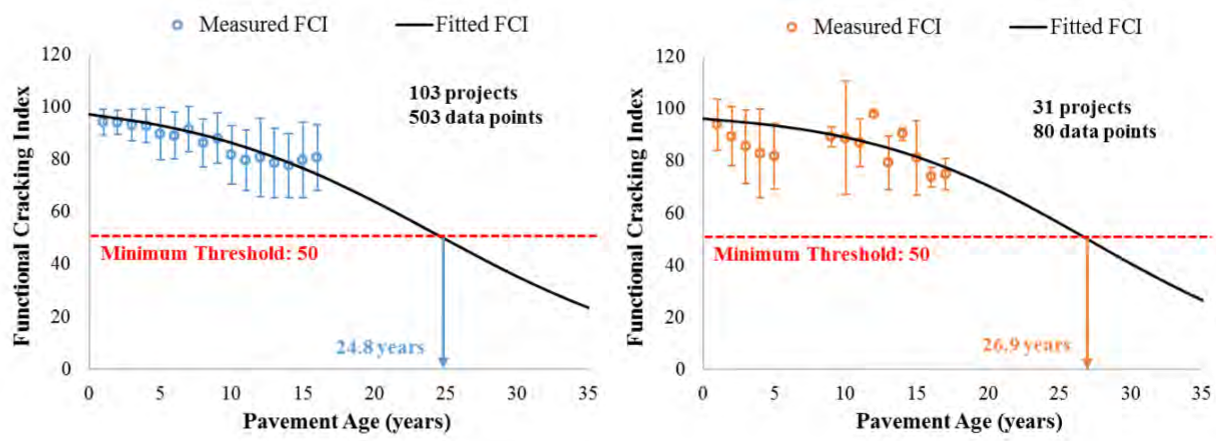
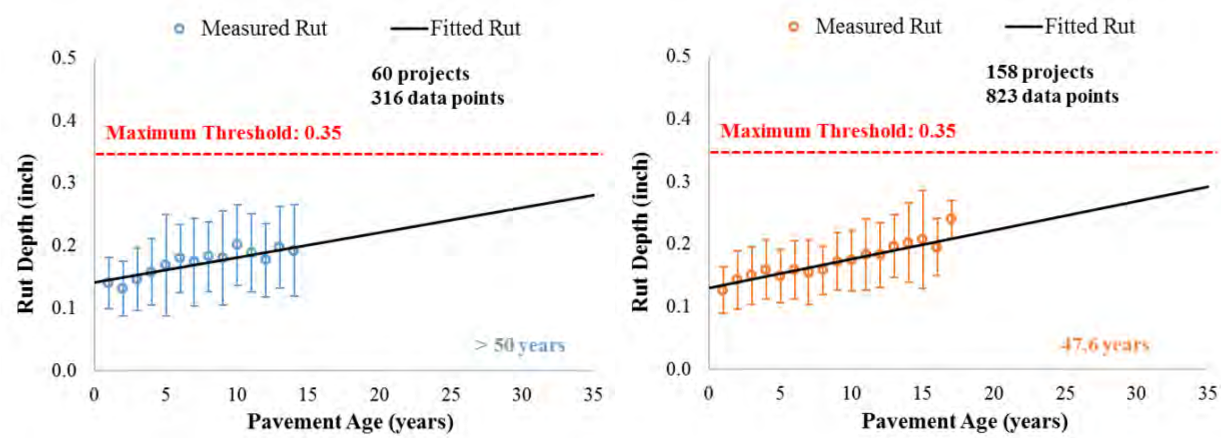


Figure 19. Maryland SHA Rut Depth Data of Flexible Pavement Sections on Interstate Highways; (a) SMA, (b) Polymer-Modified Superpave Mixtures



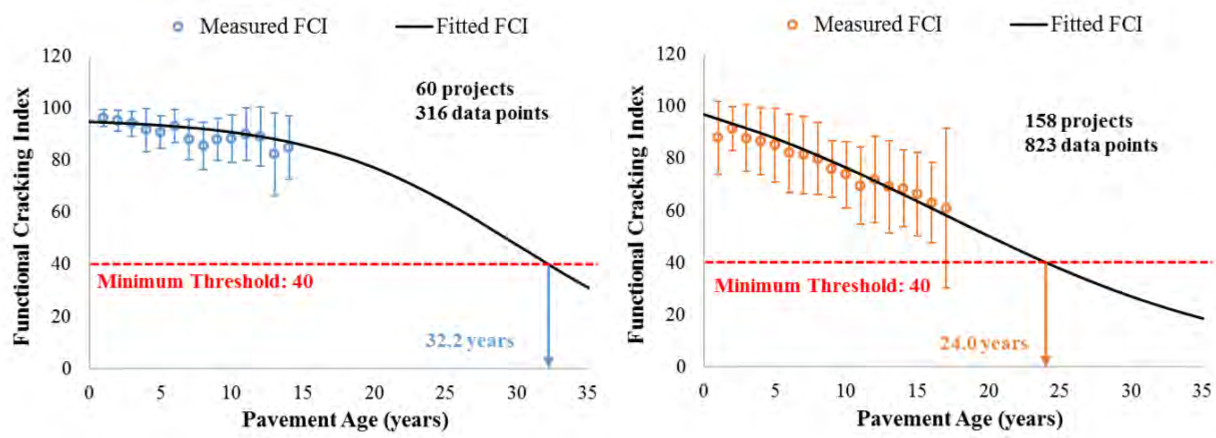
(a) (b)

Figure 20. Maryland SHA FCI Data of Flexible Pavement Sections on Interstate Highways; (a) SMA, (b) Polymer-Modified Superpave Mixtures



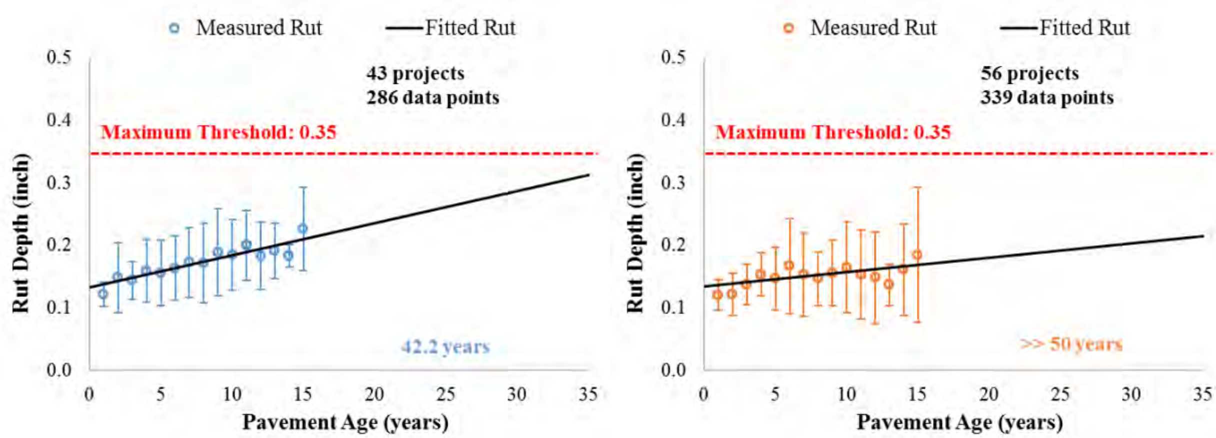
(a) (b)

Figure 21. Maryland SHA Rut Depth Data of Flexible Pavement Sections on Principal Arterial; (a) SMA, (b) Polymer-Modified Superpave Mixtures



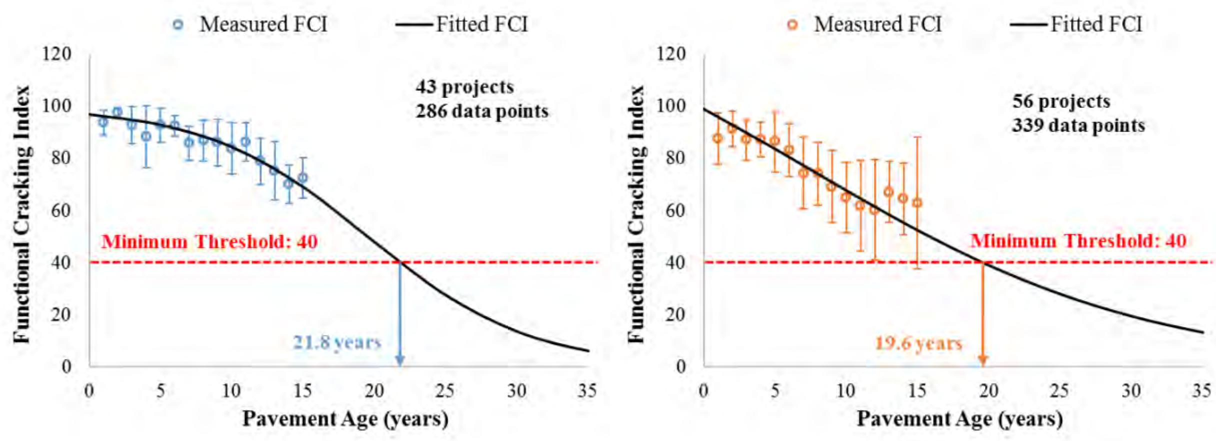
(a) (b)

Figure 22. Maryland SHA FCI Data of Flexible Pavement Sections on Principal Arterial; (a) SMA, (b) Polymer-Modified Superpave Mixtures



(a) (b)

Figure 23. Maryland SHA Rut Depth Data of Composite Pavement Sections on Principal Arterial; (a) SMA, (b) Polymer-Modified Superpave Mixtures



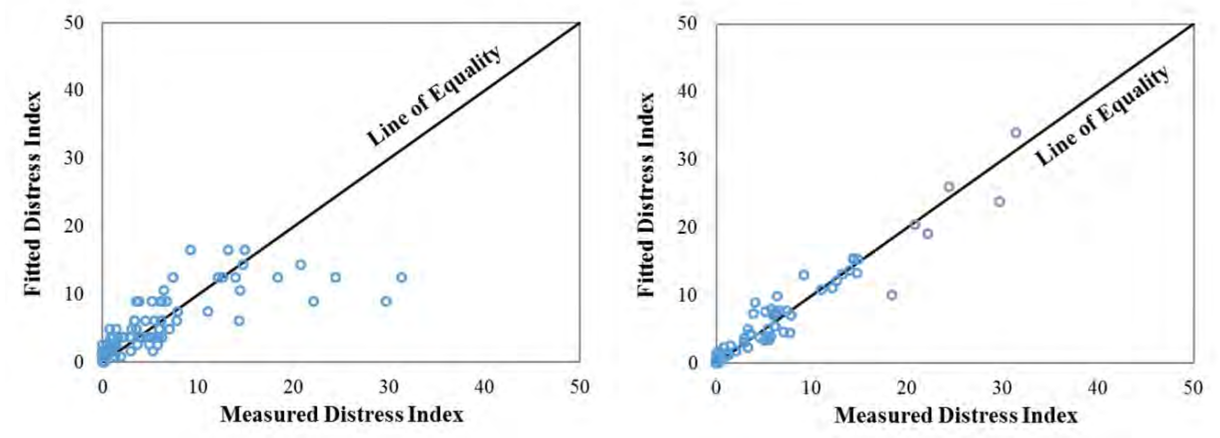
(a) (b)

Figure 24. Maryland SHA FCI Data of Composite Pavement Sections on Principal Arterial; (a) SMA, (b) Polymer-Modified Superpave Mixtures

3.3 Network-Level versus Project-Level Analysis Approaches

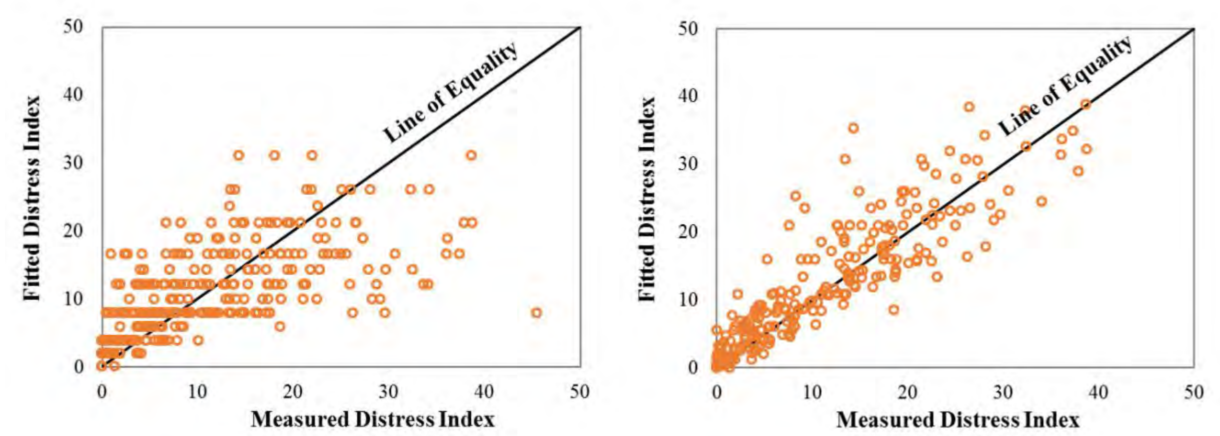
In the previous sections, performance analyses were conducted using the network-level analysis approach. Considering the large number of pavement sections included in the analyses, the data tended to be more aggregated and less specific, and consequently, the results had a relatively high variability. Similar issues were also reported by others (CDOT 2005; Elkins et al. 2013). In this section, the project-level analysis approach was used to compare the long-term field performance of SMA and Superpave dense-graded mixtures for the Michigan DOT data.

For the project-level analysis approach, the s-shaped performance model described in Equation 6 was used to fit the DI data of each individual pavement section. Because the model has three coefficients (m, γ, and c), pavement sections with less than three performance data points were excluded from the analysis. Figure 25 and Figure 26 present the correlation of measured versus fitted DI data for SMA and Superpave mixtures, respectively. For both mixtures, the project-level approach showed a better correlation than the network-level approach. Figure 27 presents the percentage distribution of predicted service lives for SMA and Superpave mixtures. Pavement sections with SMA had an average predicted service life of 21.1 years, which was slightly longer than that of Superpave sections (i.e., 19.6 years). The difference, however, was found not statistically significant in the two-sample t-test (Table 4).



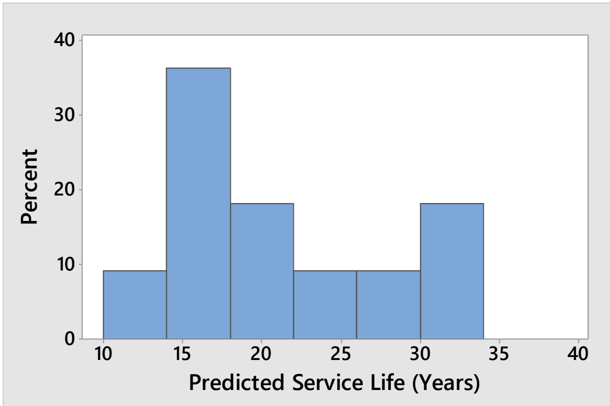
(a) (b)

Figure 25. Michigan DOT Measured versus Fitted DI Data for SMA; (a) Network-Level Approach, (b) Project-Level Approach

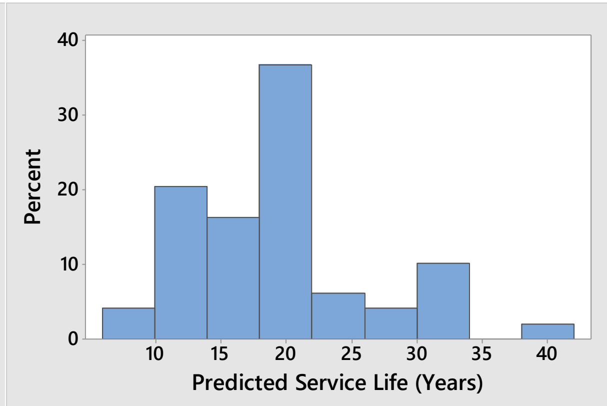


(a) (b)

Figure 26. Michigan DOT Measured versus Fitted DI Data for Superpave Mixtures; (a) Network-Level Approach, (b) Project-Level Approach



(a)



(b)

Figure 27. Michigan DOT Histogram of Predicted Pavement Service Life from Project-Level Analysis Approach; (a) SMA, (b) Polymer-Modified Superpave Mixture

Table 4. Michigan DOT Pavement Service Life Results from Project-Level Analysis Approach

Mixture Type	Number of Pavement Sections	Number of Data Points	Pavement Service Life	
			Mean	Standard Deviation
SMA	11	61	21.1	6.7
Superpave	49	242	19.6	6.9

Two-Sample t-test Results
Difference = μ (SMA) - μ (Superpave)
Estimate for difference: 1.50
95% CI for difference: (-3.28, 6.27)
T-Test of difference = 0 (vs ≠): T-Value = 0.67 P-Value = 0.514 DF = 15

Figure 28 compares the performance analysis results from network-level versus project-level approaches for the Michigan DOT data. The error bars in the figure represent one standard deviation of the predicted service lives from the project-level approach. In general, the two approaches showed a similar trend where SMA had a slightly longer predicted service life (i.e., less than two years) than polymer-modified Superpave dense-graded mixtures.

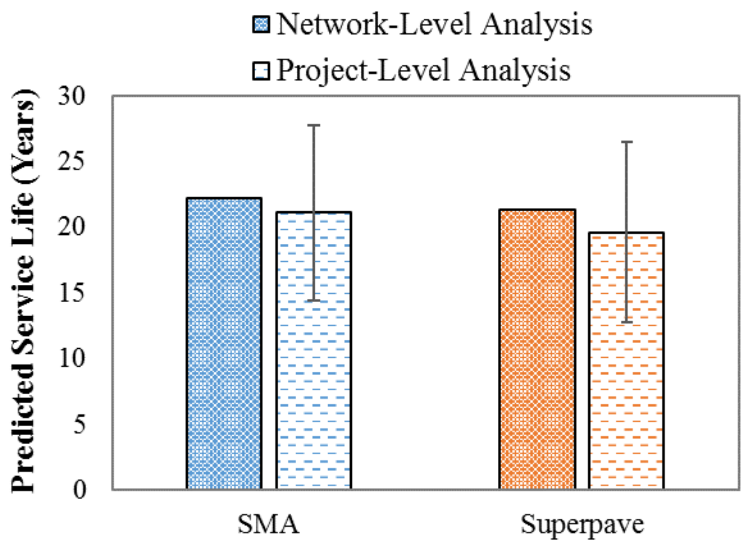


Figure 28. Comparison of Michigan DOT Performance Analysis Results from Network-Level versus Project-Level Approaches

3.4 Summary

Table 5 and Table 6 compare the performance analysis results of SMA versus polymer-modified Superpave dense-graded mixtures for flexible and composite pavements, respectively. The Predicted Service Life was determined based on the agency's PMS data for pavement performance (either individual distresses or composite condition indexes) to reach a specific threshold. Performance comparisons for SMA versus Superpave mixtures were not available for Illinois DOT and South Dakota DOT due to data incompleteness.

In most cases, SMA showed better performance and had a longer predicted service life than comparable Superpave dense-graded mixtures used on similar trafficked highways. The life extension of SMA compared to Superpave mixtures varied from five to eight years for flexible pavements and varied from 1 to 13 years for composite pavements. For the four exceptional cases where Superpave mixtures showed better performance than SMA, the difference in life expectancy between these two mixtures was less than two years. It should be noted that performance analyses for several highway agencies were based on a limited number of pavement sections (i.e., less than 5); thus, those results should be interpreted with caution as different conclusions can be obtained as additional data become available. In addition, most pavement sections included in the analyses only have performance data available for ten years or less, but their predicted service lives to failure fall into a longer time period of at least 15 years. Therefore, the predicted life expectancy of SMA and comparable Superpave mixtures based on extrapolation of a performance model may not necessarily represent the observed service lives in the field. There is a need to continue monitoring the long-term performance of these mixtures in order to validate the performance benefits of SMA.

Table 5. Summary of Performance Analysis Results for Flexible Pavements

Highway Agency	Performance Measure	Number and Max. Field Life of Pavement Sections		Predicted Service Life (Years)		SMA Life Extension	
		SMA	Superpave	SMA	Superpave	Years	Percentage
Alabama DOT	Pavement Condition Rating (PCR)	33 (12 years)	146 (11 years)	16.2	16.6	-	-
Colorado DOT	Rutting Fatigue Cracking Transverse Cracking Longitudinal Cracking	52 (9 years)	111 (9 years)	17.0	17.4	-	-
Georgia	PACES Rating	4 (16 years)	4 (13 years)	16.0	11.0	5.0	45%
Maryland SHA (Interstate)	Rutting Cracking Index (CI)	103 (16 years)	31 (17 years)	24.8	26.9	-	-
Maryland SHA (Principal Arterial)	Rutting Cracking Index (CI)	60 (14 years)	158 (17 years)	32.2	24.0	8.2	34%
Minnesota DOT	Ride Quality Index (RQI) Surface Rating (SR)	5 (11 years)	4 (6 years)	16.6	11.3	5.3	47%
Virginia DOT	Critical Condition Index (CCI)	44 (11 years)	56 (10 years)	19.0	14.4	4.6	32%

Table 6. Summary of Performance Analysis Results for Composite Pavements

Highway Agency	Performance Measure	Number and Max. Field Life of Pavement Sections		Predicted Service Life (Years)		SMA Life Extension	
		SMA	Superpave	SMA	Superpave	Years	Percentage
Illinois Tollway	Overall Condition Rating Survey (CRS)	2 (5 years)	2 (10 years)	13.5	9	4.5	50%
Maryland SHA (Principal Arterial)	Rutting Cracking Index	43 (15 years)	56 (15 years)	21.8	19.6	2.2	11%
Michigan DOT	Overall Distress Index (DI)	23 (12 years)	90 (14 years)	22.2	21.3	0.9	4%
Pennsylvania DOT (Interstate)	Overall Pavement Index (OPI)	5 (12 years)	17 (13 years)	21.1	22.2	-	-
Pennsylvania DOT (Non-Interstate)	Overall Pavement Index (OPI)	5 (14 years)	108 (13 years)	24.5	11.0	13.5	123%
Virginia DOT	Critical Condition Index (CCI)	26 (11 years)	21 (9 years)	23.1	12.8	10.3	80%

4. LIFE-CYCLE COST ANALYSIS

Case studies on deterministic life-cycle cost analysis (LCCA) were conducted for three selected SHAs (i.e., Maryland DOT, Michigan DOT, and Virginia DOT). For each case study, information gathered from the market analysis and performance analysis of that specific SHA was used as inputs to determine and compare the net present value (NPV) and equivalent uniform annual cost (EUAC) of SMA versus polymer-modified Superpave dense-graded mixtures on similar trafficked highways. The overall objective of LCCA was to determine if the higher cost of SMA could be justified by the improved pavement performance (i.e., extended life expectance). The assumption made in the LCCA was to construct a two-inch thick asphalt overlay with these two alternative mixtures using the most recent five-year (i.e., 2011 to 2015) weighted bid prices and predicted service lives for the respective state. In addition, discount rates were selected by following the agency's current practice. Table 7 summarizes the inputs in the LCCA case studies. As shown in Equation 9 and Equation 10, the NPV and EUAC were determined based on the present value of the first overlay cost, future value of the replacement overlay cost, and salvage value at the end of the analysis period.

Table 7. LCCA Input Summary

LCCA Case Study	Pavement Type	Discount Rate	Analysis Period (Years)	Service Life (Years)		Unit Cost ($/ton)	
				SMA	Superpave	SMA	Superpave
Maryland SHA	Flexible Pavement (principal arterials)	2.9%	32	32	24	$98	$88
Michigan DOT	Composite Pavement	1.5%	22	22	21	$92	$76
Virginia DOT	Composite Pavement	4.0%	23	23	13	$114	$89

$$NPV = PV_0 + \Sigma FV_i * \left[\frac{1}{(1+r)^{n_i}}\right] + SV * \left[\frac{1}{(1+r)^{n_s}}\right] \tag{9}$$

where
NPV = net present value;
PV_0 = present value of the first overlay cost;
FV_i = future value of the ith overlay cost;
SV = salvage value at the end of analysis period;
r = discount rate;
n_i = time to apply the ith overlay; and
n_s = analysis period.

$$EUAC = NPV * \left[\frac{r(1+r)^{n_s}}{(1+r)^{n_s}-1}\right] \tag{10}$$

Although traditional LCCA requires an analysis period (35 to 40 years) that includes a minimum of one pavement rehabilitation activity, a shorter analysis period was used in the study to compare the life-cycle cost benefits of SMA versus polymer-modified Superpave mixtures for the same pavement types. For each LCCA case study, the analysis period was selected using the predicted service life of SMA determined from the performance analysis (Table 5 and Table 6). Considering that SMA and comparable Superpave mixtures were used on roadways with equivalent pavement types and similar traffic levels, user costs associated with these two mixtures were likely comparable, and thus, were not included in the analysis. In addition, costs of routine maintenance and traffic control were not considered because these costs would have limited effect on the EUAC when discounted to the present value. The detailed analysis on each case study is presented as follows.

4.1 Case Study 1: Maryland SHA

The recent five-year average weighted bid prices of SMA and polymer-modified Superpave mixtures were \$98 and \$88 per ton, respectively. According to the performance analysis, flexible pavements with SMA on principal arterials had a predicted service life of 32 years, which was eight years longer than that of Superpave mixtures (i.e., 24 years). Thus, an analysis period of 32 years was used in the LCCA. Figure 29 presents the LCCA models and the corresponding cost expenditure streams for SMA and Superpave mixtures.

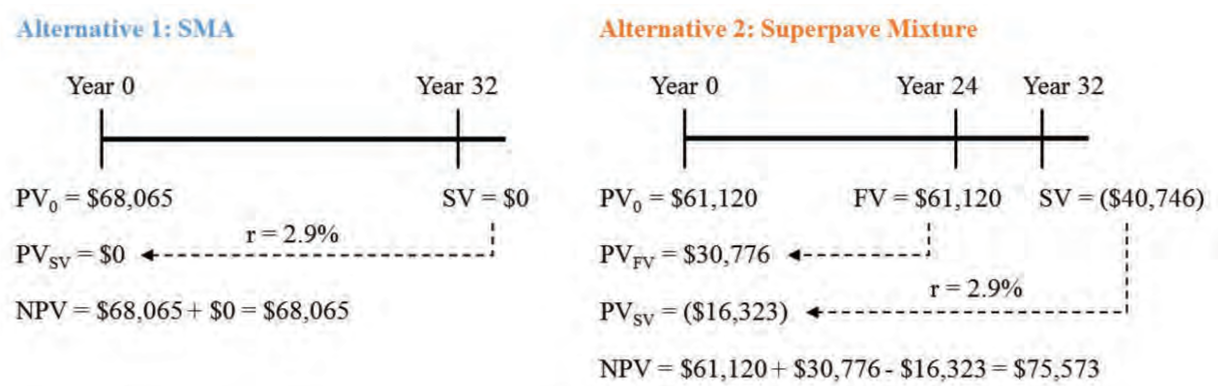


Figure 29. LCCA Models and Cost Expenditure Streams for Maryland SHA

In Alternative 1, the SMA overlay was expected to last 32 years. The agency cost for the initial construction (i.e., present value at year 0) was \$68,065 per lane mile. At year 32, the overlay would be replaced; thus, the salvage value at the end of analysis period (i.e., year 32) would be \$0. The NPV for Alternative 1 was \$68,065 per lane mile.

In Alternative 2, the Superpave overlay was expected to last 24 years with a cost of \$61,120 per lane mile. At year 24, the overlay would be replaced with a new one. The future value of the new overlay was assumed identical to the cost of the first overlay (i.e., \$61,120). The new overlay was also expected to last 24 years. At the end of the analysis period (i.e., year 32), the overlay would have a remaining life of 16 years with a salvage value of \$-40,746. The salvage value of the new overlay was calculated as a prorated portion of its cost. Using an agency specified discount rate of 2.9%, the new overlay cost (at year 24) and its salvage value (at year 32) were then discounted back to year 0 as \$30,776 and \$-16,323, respectively. The NPV for Alternative 2 was \$75,573 per lane mile.

The LCCA results showed that SMA was more cost-effective than comparable Superpave dense-graded mixtures with polymer-modified asphalt binders, with an approximately 10% savings in NPV over a 32-year analysis period. Therefore, the higher cost of SMA in Maryland was justified by the improved pavement performance and extended life expectance.

4.2 Case Study 2: Michigan DOT

The recent five-year average weighted bid price of SMA was $92 per ton, which was approximately 21% higher than that of comparable Superpave dense-graded mixtures (i.e., $76 per ton). The performance analysis results showed that SMA and Superpave mixtures had predicted service lives of 22 years and 21 years, respectively. Thus, an analysis period of 22 years was used in this LCCA case study. Figure 30 presents the LCCA models and the corresponding cost expenditure streams for SMA and Superpave mixtures.

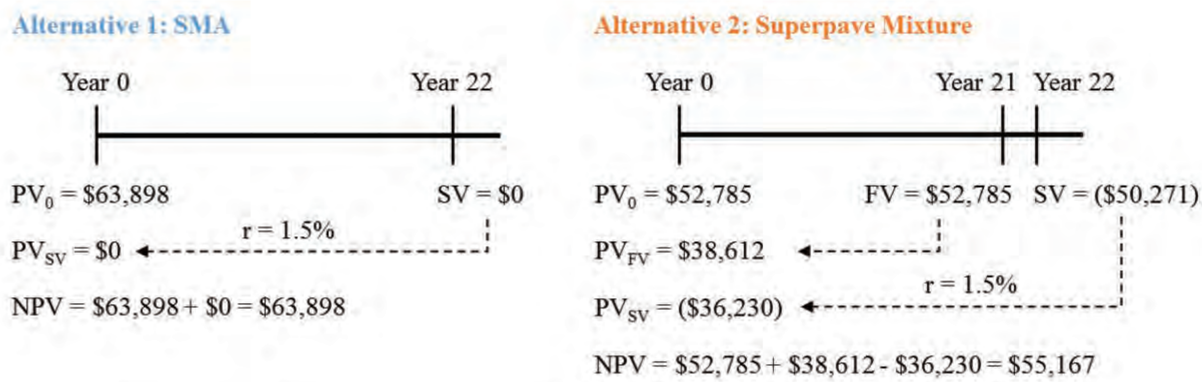


Figure 30. LCCA Models and Cost Expenditure Streams for Michigan DOT

In Alternative 1, the SMA overlay was expected to last 22 years. The agency cost for the initial construction (i.e., present value at year 0) was $63,898 per lane mile. At year 22, the overlay would be replaced; thus, the salvage value at the end of the analysis period (i.e., year 22) would be $0. The NPV for Alternative 1 was $63,898 per lane mile.

In Alternative 2, the Superpave overlay was expected to last 21 years with a cost of $52,785 per lane mile. At year 21, the overlay would be replaced with a new one. The future value of the new overlay was assumed identical to the cost of the first overlay (i.e., $52,785). The new overlay was also expected to last 21 years. At the end of the analysis period (i.e., year 22), the overlay would have a remaining life of 20 years with a salvage value of $-50,271. The salvage value of the new overlay was calculated as a prorated portion of its cost. Using the 2016 real discount rate of 1.5% (MDOT 2017), the new overlay cost (at year 21) and its salvage value (at year 22) were then discounted back to year 0 as $38,612 and $-36,230, respectively. The NPV for Alternative 2 was $55,167 per lane mile.

As indicated by a higher NPV over a 22-year analysis period, SMA was not as cost-effective as Superpave dense-graded mixtures with polymer-modified asphalt binders. Therefore, the higher cost of SMA in Michigan was not justified by the extended life expectance. Additional analysis showed that a minimum service life of approximately 26 years was needed for SMA to be more cost-effective than Superpave mixtures with a predicted life of 21 years (Figure 31).

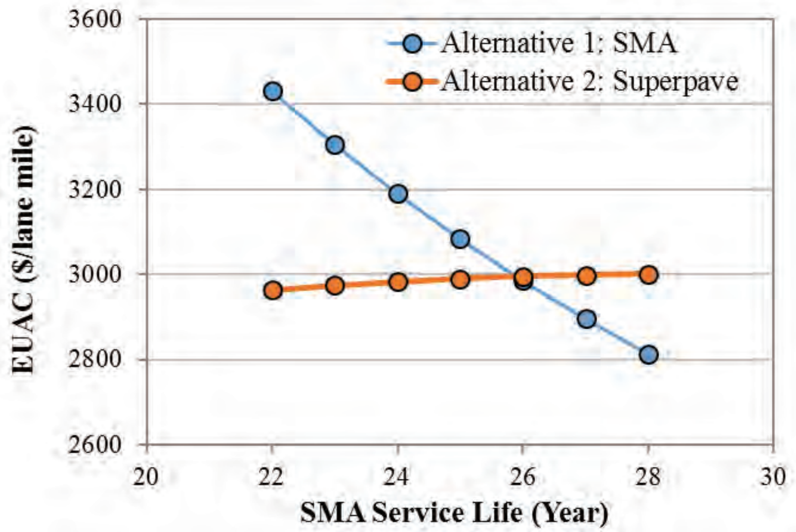


Figure 31. Additional LCCA Results for Michigan DOT

4.3 Case Study 3: Virginia DOT

Cost information gathered in the market analysis showed that the recent five-year average weighted bid prices of SMA and comparable Superpave dense-graded mixtures were $114 and $89 per ton, respectively. According to the performance analysis results, composite pavements with SMA had a predicted service life of 23 years, which was ten years longer than that of Superpave mixtures (i.e., 13 years). As discussed previously, the predicted service lives of these two mixtures were determined based on extrapolation using an s-shaped performance model, which might not necessarily represent the observed service lives in the field. An analysis period of 23 years was used in the LCCA. Figure 32 presents the LCCA models and the corresponding cost expenditure streams for SMA and Superpave mixtures.

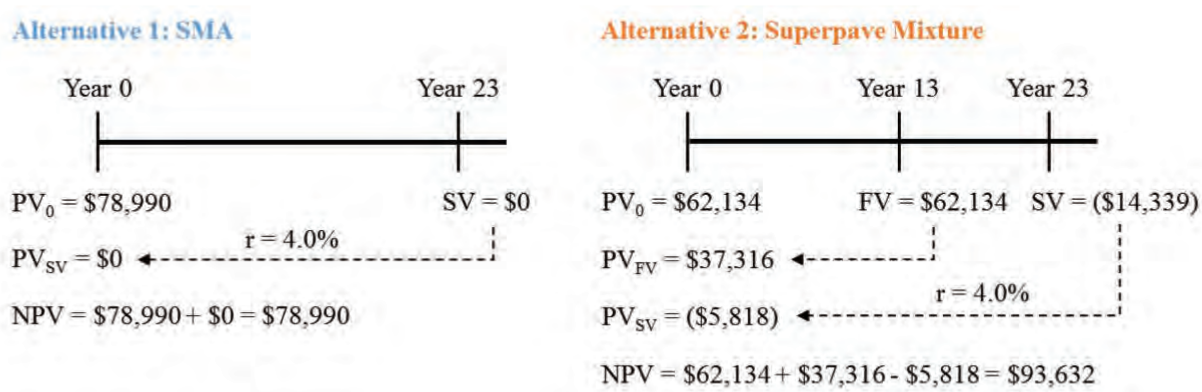


Figure 32. LCCA Models and Cost Expenditure Streams for Virginia DOT

In Alternative 1, the SMA overlay was expected to last 23 years. The agency cost for the initial construction (i.e., present value at year 0) was $78,990 per lane mile. At year 23, the overlay would be replaced; thus, the salvage value at the end of analysis period (i.e., year 23) would be $0. The NPV for Alternative 1 was $78,990 per lane mile.

In Alternative 2, the Superpave overlay was expected to last 13 years with a cost of $62,134 per lane mile. At year 13, the overlay would be replaced with a new one. The future value of the new overlay was assumed identical to the cost of the first overlay (i.e., $62,134). The new overlay was also expected to last 13 years. At the end of the analysis period (i.e., year 23), the overlay would have a remaining life of three years with a salvage value of $-14,339. The salvage value of the new overlay was calculated as a prorated portion of its cost. Using an agency specified discount rate of 4.0%, the new overlay cost (at year 13) and its salvage value (at year 23) were then discounted back to year 0 as $37,316 and $-5,818, respectively. The NPV for Alternative 2 was $93,632 per lane mile.

The LCCA results showed that SMA was more cost-effective than comparable Superpave dense-graded mixtures with polymer-modified asphalt binders, with an approximately 16% savings in NPV over a 23-year analysis period. Therefore, the higher cost of SMA in Virginia was justified by the improved pavement performance and extended life expectance.

4.4 Summary

Figure 33 summarizes the EUAC results for comparing the life-cycle cost of SMA versus comparable Superpave dense-graded mixtures with polymer-modified asphalt binders. For the Michigan DOT results, SMA had higher EUAC than Superpave dense-graded mixtures, which indicated that SMA was not as cost-effective as comparable Superpave mixtures and that a greater extension in pavement life was needed for SMA to justify its higher cost. However, the Virginia DOT and Maryland SHA data showed a different trend; where SMA was more cost-effective than polymer-modified Superpave dense-graded mixtures as indicated by lower EUAC. Overall, there was no consistent conclusion among the states for comparing the life-cycle cost of SMA versus polymer-modified Superpave dense-graded mixtures. Similar findings were also reported by Smith et al. (2006). Whether or not SMA is more cost-effective depends on the relative level of significance from increased cost versus extended life expectance. Therefore, SHAs should conduct their own analyses to determine the cost-effectiveness of SMA within their states.

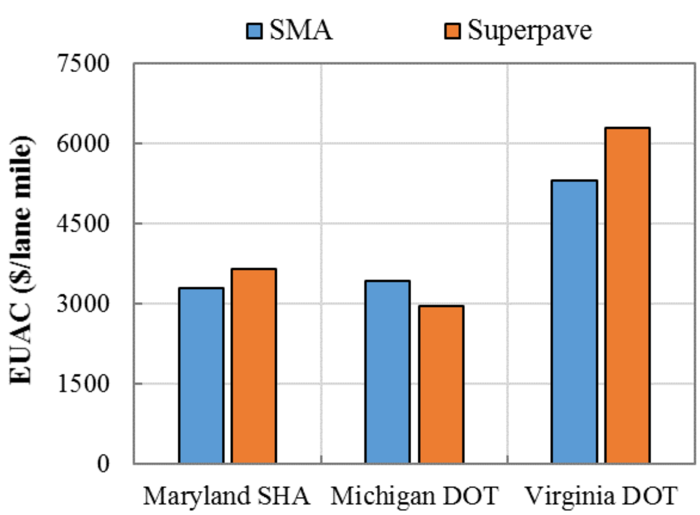


Figure 33. Summary of LCCA EUAC Results

5. ENGINEERING PROPERTY AND FIELD PERFORMANCE OF SMA

5.1 Laboratory Engineering Property

A comprehensive review of literature was performed to collect information on laboratory performance testing of SMA versus conventional Superpave dense-graded mixtures, and the results are briefly summarized in Table 8. It should be noted that although considerable research efforts had been devoted to investigate the effects of asphalt additives, fibers, aggregate types and sizes, WMA technology, and recycled asphalt materials on the engineering property of SMA, performance comparisons versus Superpave dense-graded mixtures were not available. Thus, these efforts are outside the scope of this study and are not discussed here.

In general, the literature indicated that SMA had better resistance to rutting and moisture damage than conventional dense-graded mixtures, which was likely attributed to the stone-on-stone aggregate structure and thicker asphalt films, respectively. However, no consistent trend was reported for the comparisons on mixture stiffness and cracking resistance results. Some studies indicated that SMA had lower dynamic modulus or resilient modulus than Superpave mixtures, and oftentimes, these studies reported better resistance to fatigue cracking or low-temperature cracking for SMA due to greater flexibility. For example, a study by Saboo and Kumar (2016) concluded that the fatigue life of SMA in the four-point bending beam fatigue (BBF) test was almost five times higher than the Superpave dense-graded mixture. However, other studies showed the opposite trend that SMA was more brittle and more susceptible to cracking and fatigue damage when compared to conventional dense-graded mixtures. Three studies assessed the aging characteristics of SMA and they consistently found that SMA experienced a slower rate of field and laboratory aging as compared to the dense-graded mixtures. It was hypothesized that the reduced aging sensitivity of SMA was due to thicker asphalt films. Finally, most of the field studies in Table 8 reported that SMA outperformed comparable Superpave dense-graded mixtures in terms of individual pavement distresses and overall pavement conditions.

Table 8. Literature Review Summary

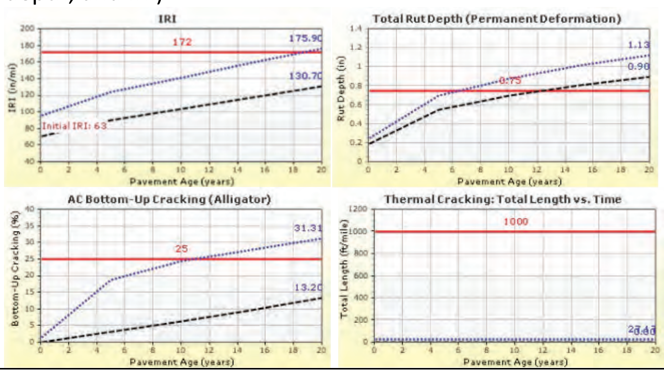
Authors	Asphalt Binders	Laboratory Tests	Research Findings
Brown and Manglorkar, 1993	AC-20	Marshall stability, IDT strength, M_R, Dynamic creep	• Lower stability, strength, and stiffness (SMA) • Slightly worse rutting resistance (SMA)
Mogawer and Stuart, 1994	AC-20	French rutting tester, Loaded wheel tester, Compressive repeated load, IDT E*, IDT strength, TSR	• Similar rutting resistance • Better resistance to moisture damage (SMA) • Better resistance to low-temp. cracking (SMA) • Less aging in the laboratory (SMA)
Brown et al., 1997	Multiple binders	Pavement distress survey	• Better field cracking performance (SMA)
Brown and Cooley, 1999	PG 64-22, PG 70-22, PG 70-28	Dynamic creep, Loaded wheel tester, IDT strength, Permeability	• No consistent trend in rutting resistance • Higher permeability (SMA)
Asi, 2005	60/70 penetration grade	M_R, TSR, IDT fatigue	• Higher stiffness (SMA) • Better resistance to moisture damage (SMA) • Lower fatigue life (SMA)
Haghshenas et al., 2015	SMA: polymer-modified; HMA: AC60/70	TSR	• Better resistance to moisture damage (SMA)
Johnson et al., 2005	PG 70-31, PG 67-37	APA	• Better rutting resistance (SMA)
Qiu and Lum, 2006	Polymer-modified	HWTT, Uniaxial creep	• Better rutting resistance (SMA)
Asfaw, 2008	PG 76-28	HWTT	• Better rutting resistance (SMA)
Lane et al., 2008	85/100 penetration grade	PMS data	• Similar field performance
Nejad et al., 2010	60/70 penetration grade	IDT E*, IDT fatigue	• Higher stiffness (SMA) • Higher fatigue life (SMA)
Prowell et al., 2010	PG 76-22	Repeated load deformation, TSR, OT	• Similar rutting resistance • Better resistance to moisture damage (SMA) • Better cracking resistance (SMA)
Han et al., 2015	PG 64-22	GPC	• Less aging in the field and laboratory (SMA)
Saboo and Kumar, 2016	PG 70-xx PG 76-xx	IDT strength, BBF	• Higher strength (SMA) • Higher fatigue life (SMA)
Son et al., 2016	PG 70-22	IDT strength, HWTT, Low-temperature SCB	• Higher strength (SMA) • Similar rutting resistance • Similar cracking resistance
NCAT, 2017	SMA: PG 67-22 (25% RAP) HMA: PG 67-22 (20% RAP)	APA, FN, Energy Ratio	• Better rutting resistance (SMA) • Slightly worse resistance to top-down cracking (SMA)
West et al., 2017	SMA: PG 70-28 (13% RAP, 5% RAS, 0.4% Evotherm)	IFIT	• Better cracking resistance (SMA)
Wu et al., 2017	SMA: PG 76-28 HMA: PG 64-28	PMS Data, E*, IDT fracture, PG, DSR MSCR	• Better field pavement performance (SMA) • Lower stiffness (SMA) • Better cracking resistance (SMA) • Less aging in the field (SMA)

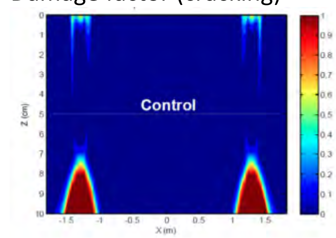
5.2 Pavement Performance Prediction

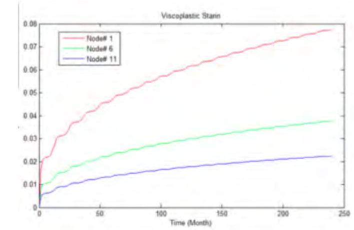
Laboratory test results obtained from literature (Table 8) could be used in advanced pavement analysis and modeling programs as inputs to predict the performance benefits of SMA. Programs considered in this study were AASHTOWare Pavement M-E and the FlexPAVE™ program [formerly the Layered Viscoelastic Pavement Analysis for Critical Distress (LVECD) program]. The Pavement M-E is a mechanistic-empirical pavement design procedure based on multilayer elastic analysis. The program is capable of predicting pavement performance under given traffic, structure, and environmental conditions. The FlexPAVE™ program employs three-dimensional finite element analysis to predict the amount of damage and rutting in a pavement structure under moving loads and changing temperature. In the FlexPAVE™ program, pavement cracking is characterized using a simplified viscoelastic continuum damage (S-VECD) model, and the rutting performance is evaluated using a permanent deformation model (i.e., shift model) developed by Choi et al. (2012).

Table 9 compares the inputs and outputs of Pavement M-E versus FlexPAVE™ programs. Both programs use the enhanced integrated climate model (EICM) to account for the environmental effect. FlexPAVE™ allows for user-defined traffic options, such as wheels, axles, and vehicles, but more comprehensive traffic information is considered in Pavement M-E. Dynamic modulus (AASHTO T 378-17) and indirect tensile (IDT) strength and creep compliance (AASHTO T 322-07) test results are required to perform the Level-1 analysis in Pavement M-E. Additional mechanistic tests such as Flow Number (AASHTO T 378-17) and bending beam fatigue (AASHTO T 321-17) are also needed to adjust material-specific correction factors in the distress transfer functions. For the FlexPAVE™ program, dynamic modulus (AASHTO T 378-17), AMPT cyclic fatigue test (AASHTO TP 107-14), and simplified triaxial stress sweep test [known as the stress sweep rutting (SSR) test] are needed to determine the time-temperature shift factor, damage characteristic curve, energy-based failure criterion, and shift model coefficients. Outputs from Pavement M-E are individual pavement distresses including fatigue cracking, thermal cracking, rutting, and IRI. The damage factor and rut depth are the outcomes from the FlexPAVE™ program. The damage factor is defined as ratio of the current number of load cycles to the number of load cycles that causes failure; a particular element is considered completely cracked when the damage factor reaches a value of 1.0 (Kim 2016).

Table 9. Comparison of Pavement M-E versus FlexPAVE™ Programs

<table>
<tr><th>Program</th><th>Pavement M-E</th><th>FlexPAVE™</th></tr>
<tr><td>Environment</td><td>EICM</td><td>EICM (one-year data)</td></tr>
<tr><td>Traffic</td><td>Base year truck-traffic volume
Vehicle operational speed
Truck-traffic directional and lane distribution factors
Vehicle class distribution
Axle and wheel base configurations
Tire characteristics and inflation pressure
Truck lateral distribution factor
Truck growth factors</td><td>Number of passes of user-defined traffic options (wheel/axle/vehicle)</td></tr>
<tr><td>Laboratory Tests</td><td>Dynamic modulus (AASHTO T 378-17)
IDT strength and creep compliance (AASHTO T 322-07)</td><td>Dynamic modulus (AASHTO T 378-17)
AMPT cyclic fatigue test (AASHTO TP 107-14)
Simplified triaxial stress sweep test</td></tr>
<tr><td>Outputs</td><td>Pavement distresses (fatigue cracking, thermal cracking, rut depth, and IRI)


</td><td>Damage factor (cracking)


(Kim, 2016)
Rut depth


(Kim, 2016)</td></tr>
</table>

This section provides an example of using the Pavement M-E to predict the performance benefits of SMA. Note that the FlexPAVE™ analysis was not conducted because the AMPT cyclic fatigue and SSR test results were not available. Figure 34 presents the hypothetical pavement structures with SMA and conventional Superpave dense-graded surface mixtures. Both sections are designed with a 6-inch asphalt layer, 8-inch non-stabilized base, and semi-infinite subgrade. For the SMA section, the asphalt layer has a 2-inch wearing course of SMA and 4-inch binder course of Superpave dense-graded mixtures [Figure 34(a)]. The same dense-graded mixture is also used as the surface layer of the Superpave section [Figure 34(b)]. In Pavement M-E, the mechanical properties of SMA and Superpave mixtures were input using laboratory test results of two similar mixtures placed on the NCAT Test Track in 2012 (NCAT 2017). It should be noted that the performance prediction of Pavement M-E is primarily driven by the stiffness of asphalt mixtures without considering additional engineering properties such as rutting resistance and cracking resistance. To overcome this shortcoming, mixture correction factors were introduced to the distress transfer functions as local calibration factors.

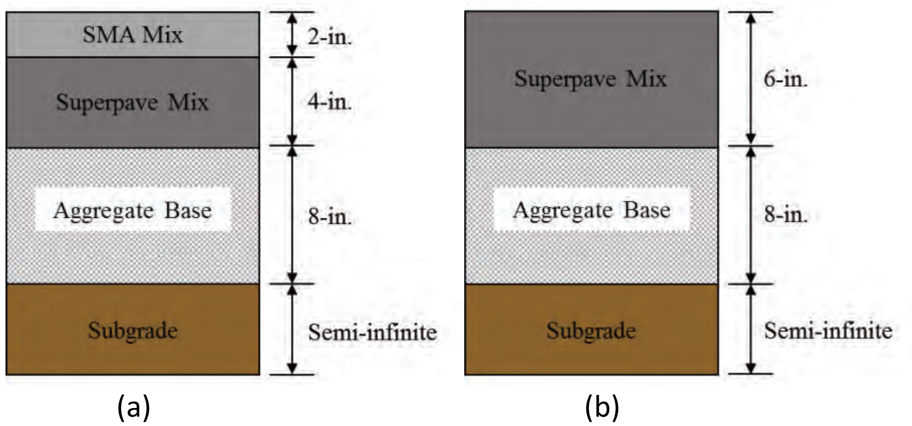


Figure 34. Hypothetical Pavement Structures in Pavement M-E; (a) SMA Section, (b) Polymer-Modified Superpave Mixture Section

Figure 35 presents the Asphalt Pavement Analyzer (APA) results of SMA and Superpave dense-graded mixtures mentioned above. As shown, SMA had approximately 20% less rutting than the Superpave mixture after 8,000 passes of loading cycles, indicating better resistance to permanent deformation. To determine the rutting correction factor $C_{r\text{-}mix}$ of SMA, Equation 11 was first used to fit the rut depth results based on non-linear regression analysis. Once $C_{r\text{-}mix}$ was determined, it was introduced in the permanent deformation transfer function (Equation 12) as a local calibration factor (β_{r1}). The same methodology could also be applied to bending beam fatigue (BBF) test results (if available) to determine the fatigue cracking correction factor $C_{f\text{-}mix}$ using Equation 13 and Equation 14. Table 10 summarizes the key inputs used in Pavement M-E for this example analysis.

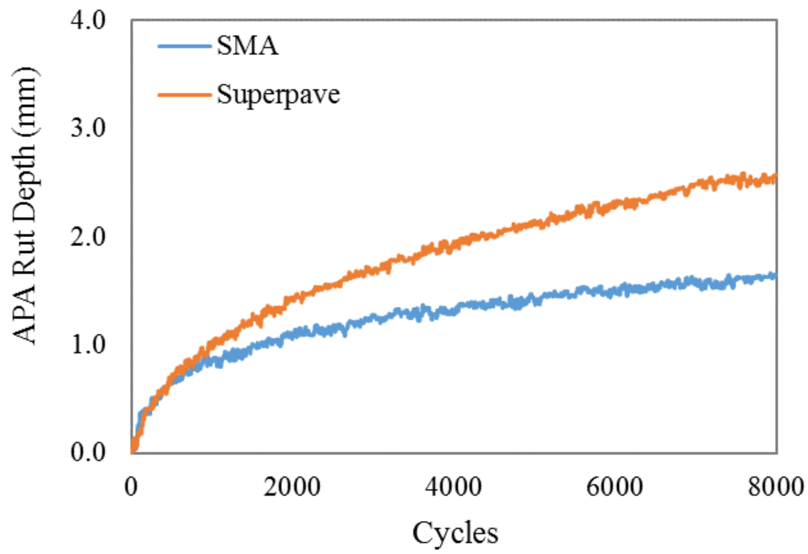


Figure 35. APA Test Results of SMA and Superpave Dense-Graded Mixtures (NCAT 2017)

$$\frac{\varepsilon_p}{\varepsilon_r} = a_1 N^{a_2} C_{r-mix}$$
$$\varepsilon_p = \frac{\Delta}{H} \tag{11}$$
$$\varepsilon_r = \frac{\sigma_0}{E}$$

where

ε_p = accumulated plastic strain at *N* repetitions of loading cycles;
ε_r = resilient strain;
N = number of loading cycles;
a_1 and a_2 = model coefficients;
$C_{r\text{-}mix}$ = SMA rutting correction factor;
Δ = rut depth at *N* repetitions of loading cycles;
H = specimen thickness;
σ_0 = APA hose pressure; and
E = modulus.

$$\frac{\varepsilon_p}{\varepsilon_r} = k_z \beta_{r1} 10^{-3.35412} T^{1.5606\beta_{r2}} N^{0.4791\beta_{r3}} \tag{12}$$

where

k_z = depth correction parameter;
T = temperature; and
β_{r1}, β_{r2}, and β_{r3} = local calibration factors.

$$N_f = b_1 \left(\frac{1}{\varepsilon_t}\right)^{b_2} \left(\frac{1}{E}\right)^{b_3} C_{f-mix} \tag{13}$$

where
N_f = number of repetitions to fatigue cracking;
ε_t = tensile strain;
b_1, b_2, and b_3 = model coefficients; and
C_{f-mix} = SMA fatigue cracking correction factor.

$$N_f = 0.00432\, C\beta_{f1} k_1 \left(\frac{1}{\varepsilon_t}\right)^{3.9492\beta_{f2}} \left(\frac{1}{E}\right)^{1.281\beta_{f3}} \tag{14}$$

where
k_1 = thickness correction parameter; and
β_{f1}, β_{f2}, and β_{f3} = local calibration factors.

Table 10. Summary of Key Inputs in Pavement M-E

Inputs		SMA Section	Superpave Section
Asphalt Concrete	Mixture E*	Figure 36	
	Binder G*-δ	Figure 37	
	Effective P_b (%)	6.3	5.1
	VMA (%)	18.4	15.8
	C_{r-mix}	0.6	1.0
	C_{f-mix}	1.0	
	Poisson's Ratio	0.35	
	Thermal Conductivity (BTU/hr-ft-ºF)	0.67	
	Heat Capacity (BTU/lb-ºF)	0.23	
Aggregate Base	Material Name	A-1-a	
	Resilient Modulus (psi)	40,000	
	Poisson's Ratio	0.35	
Subgrade	Material Name	A-2-4	
	Resilient Modulus (psi)	16,000	
	Poisson's Ratio	0.35	
Climate Station		Montgomery, AL	
Two-way AADTT		2,000	

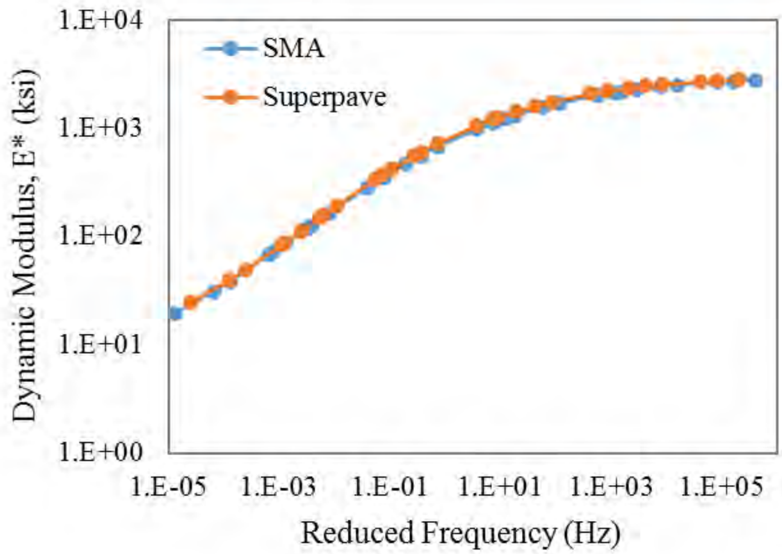


Figure 36. E* Results of SMA and the Superpave Dense-Graded Mixture (NCAT 2017)

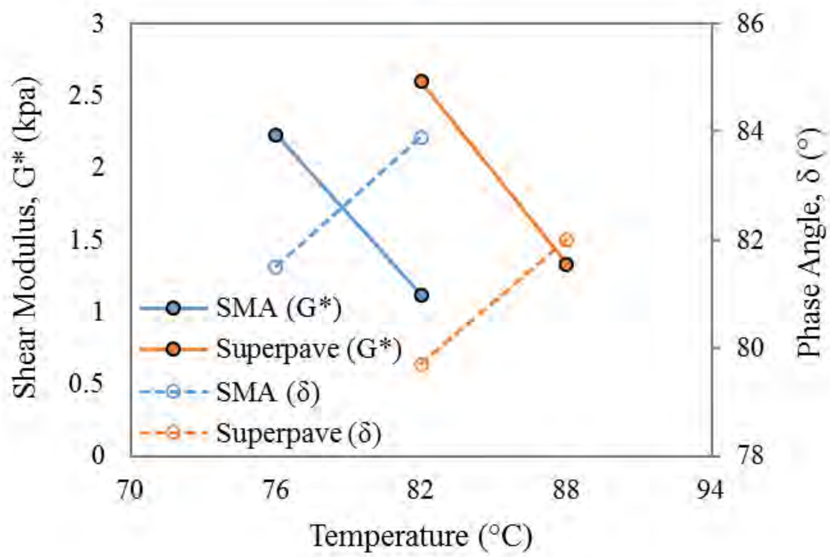
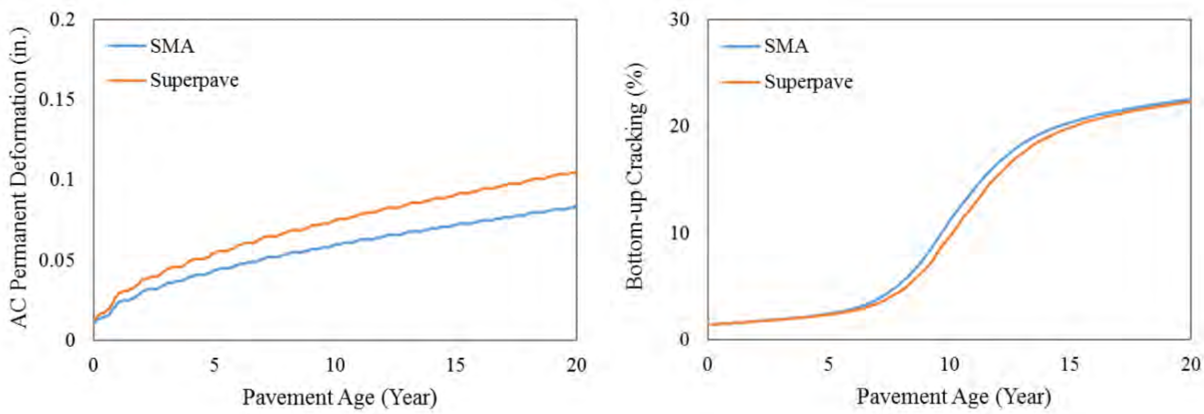


Figure 37. DSR G*-δ Results (at 10 Radians per Second) of SMA and the Superpave Dense-Graded Mixture (NCAT 2017)

Figure 38 presents the Pavement M-E results. The SMA section is predicted with better rutting resistance. At the end of the analysis period, the total rut depth in asphalt concrete layer of the SMA section is approximately 15% less than that in the Superpave section. However, no significant difference in the bottom-up fatigue cracking performance is observed between the two sections, which is due to the fact that SMA and Superpave dense-graded mixtures have similar E* stiffness (Figure 36) and thus, the tensile strains at the bottom of the asphalt layer are comparable between these two pavement sections. It is worthwhile to note that this example provides a conceptual illustration of using an advanced pavement design and modeling program to predict the performance benefits of SMA; different conclusions can be obtained if using different test results as inputs in the program.



(a) (b)

Figure 38. Pavement M-E Results; (a) AC Permanent Deformation, (b) AC Bottom-up Fatigue Cracking

5.3 Pavement Surface Characteristics

Two test sections with SMA and Superpave dense-graded mixtures were constructed on the NCAT test track in 2000 (Figure 39) (Brown et al. 2002). Both mixtures were designed with the same granite aggregates and the same PG 76-22 SBS modified asphalt binder. Surface texture of these two sections was measured weekly using an ARAN inertial profiler. In addition, quarterly measurements of pavement friction and tire-pavement noise were conducted using a skid trailer and on-board sound intensity (OBSI) device, respectively. The results are discussed as follows.

(a) (b)

Figure 39. NCAT Test Track Pavement Sections; (a) SMA, (b) Polymer-Modified Superpave Dense-Graded Mixture (Photos Taken in June 2017)

To measure surface texture, the ARAN inertial profiler sampled the right wheel path of the pavement section at a relatively high frequency of 64 kHz. The data was then analyzed to determine the mean texture depth (MTD), a parameter that characterizes pavement surface macrotexture. Figure 40 presents the MTD comparison between the SMA and Superpave test sections. The MTD of the SMA section showed a reduction from 1.3 mm to 0.9 mm between September 2000 and January 2004 but exhibited a steady increase with time afterwards. The paired t-test showed that the SMA section had consistently and statistically higher MTD than the Superpave section and that the average difference between these two sections was 0.24 mm. The higher surface texture of SMA could provide safety benefits through increased visibility of pavement markings, reduced glare from light reflections, and reduced splash and spray (Hughes 1999).

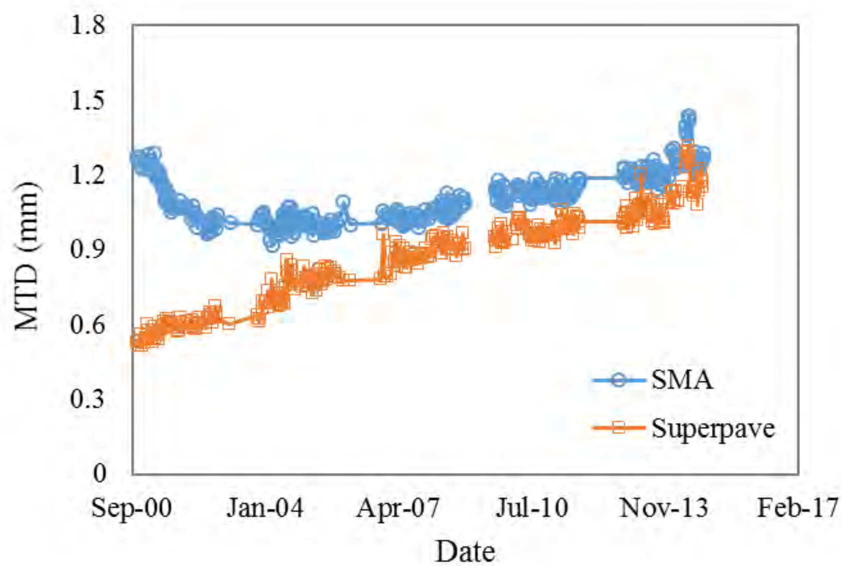


Figure 40. Macrotexture Comparison of NCAT Test Track SMA and Superpave Sections

Surface friction was measured using a full-scale locked-wheel skid trailer in accordance with ASTM E274-11 *Skid Resistance of Paved Surfaces Using a Full-Scale Tire*. The trailer used a specified ribbed test tire and travelled at a speed of 40 mph for testing. Figure 41 presents the surface friction (SN40R) results of the SMA and Superpave sections. In general, the SMA section had higher SN40R values than the Superpave section, which was likely due to the higher surface texture. The difference in the SN40R results was also verified in the paired t-test. The average SN40R of the SMA and Superpave sections was approximately 35.3 and 30.4, respectively. The higher frictional resistance of SMA could provide improved safety to motoring public when traveling on wet pavements (Hughes 1999).

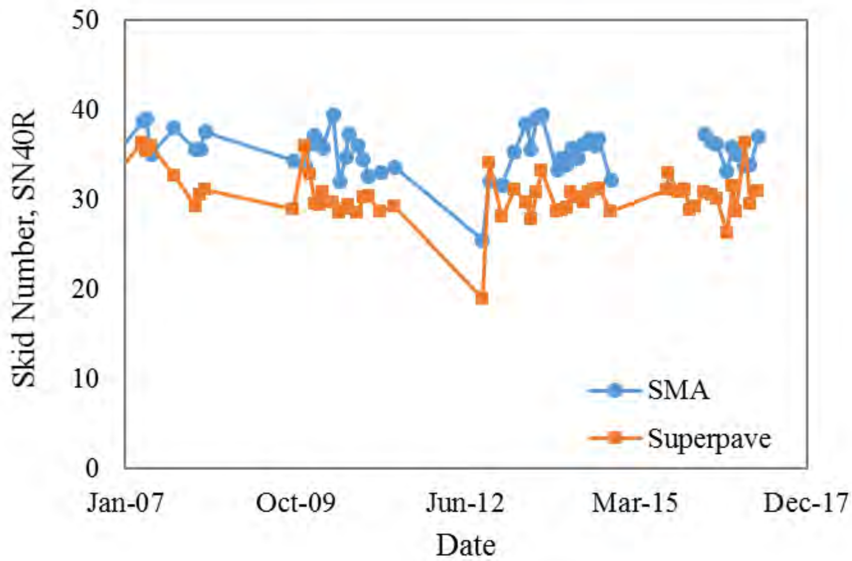


Figure 41. Surface Friction Comparison of NCAT Test Track SMA and Superpave Sections

Tire-pavement noise was measured with an OBSI device, which included two sound intensity probes, one at the leading edge and the other at the trailing edge of the tire-pavement contact patch. The measurement was conducted at a constant speed of 45 mph. The results were reported in sound intensity levels in one-third octave bands from 315 Hz through 4000 Hz, from which a global average OBSI value was computed as an overall indicator of the tire-pavement noise. Figure 42 presents the OBSI results of the two sections with SMA and Superpave dense-graded mixtures. It should be noted that the OBSI measurement started in July 2009, and thus, prior noise data was not available. For both sections, the global average OBSI fluctuated between 97 dB(A) and 102 dB(A), but in most cases, the SMA section was quieter than the Superpave section, as shown in Figure 42(b). Based on the paired t-test, the overall OBSI data of the SMA section was statistically lower than that of the Superpave section with an average difference of 0.46 dB(A). These results are in agreement with findings from other studies (Hoppe 1991; Polcak 1994; Rockliff 1996; Bellin 1998; EAPA 1998). The two largest differences in the global average OBSI between the two test sections corresponded to measurements conducted in August 2013 and September 2016.

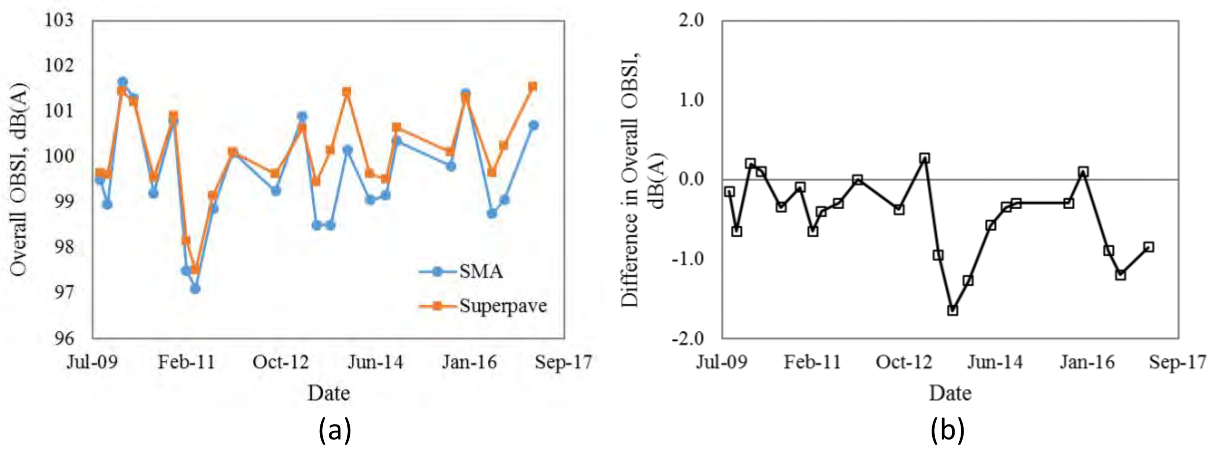


Figure 42. Tire-Pavement Noise Comparison of NCAT Test Track SMA and Superpave Sections; (a) OBSI Results, (b) Difference in OBSI (SMA - Superpave)

5.4 Summary

Previous studies have consistently indicated that SMA had better resistance to rutting and moisture damage than conventional Superpave dense-graded mixtures. These superior properties of SMA were likely attributed to the stone-on-stone aggregate structure and thicker asphalt films. However, different results were reported for the comparisons on mixture stiffness and cracking resistance between the two mixtures. Laboratory test results obtained from literature could be used in advanced pavement design and modeling programs as inputs to predict the performance benefits of SMA. An example of using the AASHTOWare Pavement M-E was provided. In addition to performance benefits, SMA pavements demonstrated functional benefits such as improved visibility, increased frictional resistance, and noise reduction.

6. CONCLUSIONS

The objective of this study was to quantify and compare the performance and life-cycle cost benefits of SMA versus those of conventional Superpave dense-graded mixtures. Market analysis was first conducted to determine the usage of SMA through surveys of SHAs and SAPAs. In addition, field performance data was collected from nine SHAs to determine if SMA outperformed polymer-modified Superpave dense-graded mixtures used for equivalent roadway categories and pavement types. Information gathered from the market analysis and performance analysis was then used to compare the life-cycle cost between these two mixtures. Finally, a comprehensive review of literature was performed to summarize the engineering property and field performance of SMA. The following conclusions were made based on this study:

- Currently, SMA is used on a routine basis by at least 18 SHAs on state and interstate routes with high traffic volumes and on projects where frequent maintenance is costly and disruptive to high traffic volumes.
- The most recent five-year average weighted bid price of SMA was 7% to 43% higher than that of Superpave dense-graded mixtures with polymer-modified asphalt binders. The difference ranged from $6 to $31 per ton among the 16 agencies that responded to the survey.

- SMA generally had equivalent or better field performance than conventional Superpave dense-graded mixtures used on similar trafficked highways. For cases where SMA had better performance, the life extension of SMA varied from 1 to 13 years among the states and varied for different pavement types. It is worth noting that the predicted service lives of SMA and Superpave mixtures were based on extrapolation of limited field performance data; thus, longer-term performance data is needed to verify the performance benefits of SMA.
- There was no consistent conclusion for comparing the life-cycle cost of SMA versus conventional Superpave dense-graded mixtures. Whether or not SMA is more cost-effective depends on the relative level of significance from increased cost versus extended life expectance. SHAs should conduct their own analyses to determine the cost-effectiveness of SMA within their states.
- Laboratory test results from literature consistently showed SMA had equivalent or better resistance to rutting and moisture damage than conventional Superpave dense-graded mixtures, but no consistent results were reported for the comparisons on mixture stiffness and cracking resistance results.
- In addition to performance benefits, SMA pavements demonstrated functional benefits such as improved visibility, reduced splash and spray, increased frictional resistance, and noise reduction.

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APPENDIX A. HIGHWAY AGENCY SURVEY RESPONSES

Alabama DOT

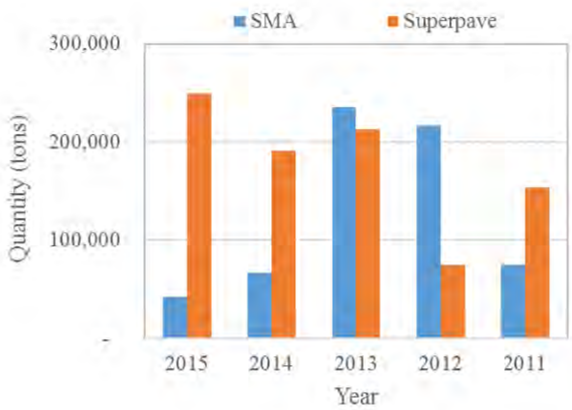
According to ALDOT Guidelines for Operations, SMA wearing surface layer shall be used on projects wherein the number of 20-year equivalent single axle loads (ESALs) is equal to or greater than 30 million, as well as on projects where rutting is a significant concern. ALDOT's procedure for designing SMA (ALDOT-395-1999) is based on the volumetric properties including air voids, voids in the mineral aggregate, stone on stone contact, and mortar properties. The design procedure can be performed using either the Superpave gyratory compactor (N_{des} of 65) or Marshall hammer (50 blows). **Figure A-1** presents the quantity and weighted mix bid price of SMA and Superpave dense-graded mixtures used on similar trafficked highways from 2011 to 2015. The weighted bid price of SMA was 6% to 22% ($5 to $18 per ton) higher than that of Superpave dense-graded mixtures with polymer-modified asphalt binders.

(a) (b)

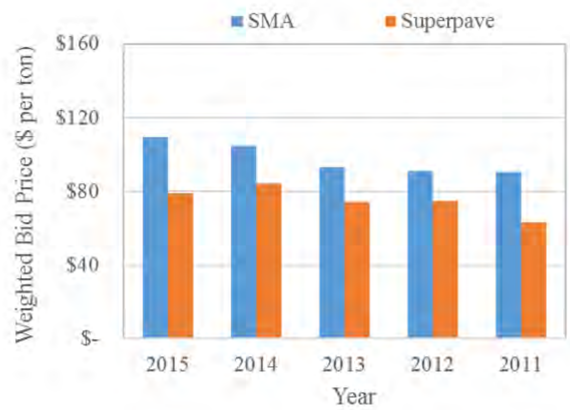
Figure A-1. Alabama DOT Information of SMA versus Polymer-Modified Superpave Dense-Graded Mixtures; (a) Quantity, (b) Weighted Bid Price

Colorado DOT

The Colorado DOT does not have a published selection guideline for SMA. Typically, the Region Materials Engineers decide when to use SMA surface mixture on high volume roadways. On projects where SMA is used, most contractors perform mix design in accordance with AASHTO Specification R 46-08. **Figure A-2** presents the quantity and weighted mix bid price of SMA and Superpave dense-graded mixtures used on similar trafficked highways from 2011 to 2015. As illustrated in **Figure A-2**(a), more Superpave mixtures were produced in 2011, 2014, and 2015 than SMA, while the opposite trend was shown for 2012 and 2013. Results in **Figure A-2**(b) showed that the weighted bid price of SMA was 22% to 43% (i.e., $16 to $31 per ton) higher than that of comparable Superpave dense-graded mixtures. It was noted by the DOT representative that recycled materials were not permitted in SMA but were allowed in Superpave mixtures; thus, this was one of the reasons for causing SMA to be more expensive.



(a)



(b)

Figure A-2. Colorado DOT Information of SMA versus Polymer-Modified Superpave Dense-Graded Mixture; (a) Quantity, (b) Weighted Bid Price

Georgia DOT

The Georgia DOT's mixture selection guideline specifies the use of SMA on state and interstate routes with average daily traffic (ADT) greater than 50,000. It is worth mentioning that the majority of SMA on interstates are covered with an open-graded friction course (OGFC). Previous experience has shown that SMA is able to provide a consistent micro-milled surface for OGFC; thus, the use of a SMA/OGFC combination allows the micro-milling of the OGFC without replacing SMA for the first maintenance cycle. The department's procedure for designing SMA (GDT 123) follows the Marshall mix design method and determines the proper proportions of coarse and fine aggregate, mineral filler, and asphalt binder for SMA that satisfy both volumetric requirements and performance specifications in terms of moisture susceptibility, rutting resistance, permeability, and asphalt draindown. Up to 15% RAP is allowed in SMA. From 2011 to 2015, approximately 783,000 tons of SMA were produced, which accounted for about 40% of the total tonnage of polymer-modified Superpave dense-graded mixtures (i.e., 1,972,000 tons). **Figure A-3** presents the quantity and weighted mix bid price of these two mixtures. As illustrated in **Figure A-3**(b), the weighted bid price of SMA increased from 2011 to 2013 but decreased in 2014 and 2015. The reduction in the cost of SMA was possibly due to a change in the DOT specification in 2015, which allowed the use of aggregates with a maximum of 5:1 flat and elongated (F&E) particles ratio instead of 3:1 F&E ratio. In general, the weighted bid price of SMA was 29% to 61% (i.e., $21 to $46 per ton) higher than of Superpave dense-graded mixtures used on similar trafficked highways.

Illinois DOT

According to the mixture selection policy used by the Illinois DOT, SMA shall be used as the pavement surface course on projects with ADT greater than 35,000. SMA is designed following AASHTO R 46-08 with several modifications in terms of mixing and compaction temperature, specimen conditioning and compaction, and moisture susceptibility evaluation. **Figure A-4** presents the quantity and weighted mix bid price of SMA and Superpave dense-graded mixtures used on similar trafficked highways from 2011 to 2015. As shown in **Figure A-4**(a), over 726,000 tons of SMA were produced in 2011, 2014, and 2015, while only approximately 4,000 tons were produced in 2012 and 2013. The comparison in weighted mix bid price shown in **Figure A-4**(b) showed that SMA was 2% to 11% ($2 to $9 per ton) more expensive than Superpave dense-graded mixtures with polymer-modified asphalt binders.

(a) (b)

Figure A-3. Georgia DOT Information of SMA versus Polymer-Modified Superpave Dense-Graded Mixture; (a) Quantity, (b) Weighted Bid Price

(a) (b)

Figure A-4. Illinois DOT Information of SMA versus Polymer-Modified Superpave Dense-Graded Mixture; (a) Quantity, (b) Weighted Bid Price

<u>Illinois Tollway</u>

The Illinois Tollway has recognized that SMA is the long-term solution to asphalt pavement performance by reducing pavement distresses and long-term maintenance requirements. The Tollway specifies SMA surface and binder mixtures for all mainline asphalt pavements. The Tollway has a special provision that governs the design of SMA, including materials selection, volumetric design, and performance testing. **Figure A-5** presents the quantity and weighted mix bid price of SMA from 2011 to 2015. As shown, over 514,000 tons of SMA were produced in 2011 and 2012, but after that, the quantity reduced significantly. The five-year average weighted bid price of SMA was $102 per ton.

(a) (b)

Figure A-5. Illinois Tollway Information of SMA; (a) Quantity, (b) Weighted Bid Price

<u>Indiana DOT</u>

The Indiana DOT typically uses SMA on projects with more than three million ESALs over 20 years of design life. SMA shall be designed by following AASHTO M 325 and R 46-08. (a) (b)

Figure A-6 presents the quantity and weighted mix bid price of SMA and Superpave dense-graded mixtures used on similar traffic highways. As shown, over 591,000 tons of SMA and 4,953,000 tons of Superpave mixtures were produced from 2011 to 2015, respectively. The tonnage of SMA increased significantly from 22,000 tons in 2011 to 210,000 tons in 2015. The bid price comparison in (a) (b)

Figure A-6(b) showed that SMA was 21% to 65% more expensive than comparable Superpave dense-graded mixtures, and the difference in weighted mix bid price varied from $12 to $38 per ton from 2011 to 2015.

(a) (b)

Figure A-6. Indiana DOT Information of SMA versus Polymer-Modified Superpave Dense-Graded Mixture; (a) Quantity, (b) Weighted Bid Price

<u>Kansas DOT</u>

The Kansas DOT does not routinely use SMA and the mixture selection is made on a project-by-project basis. The DOT does not have a SMA mix design specification in its 2015 specifications manual, but there was a special provision in the 2007 specifications manual that governed the design and construction of SMA. **Figure A-7** shows the quantity and weighted mix bid price of SMA and Superpave dense-graded mixtures used on similar trafficked highways from 2011 to 2015. As shown, only 10,000 and 57,000 tons of SMA were produced in 2013 and 2011, respectively, while approximately 2,354,000 tons of comparable Superpave mixtures were produced from 2011 to 2015. The average weighed mix bid price of SMA was $91 per ton, which was approximately 41% (i.e., $27 per ton) higher than that of Superpave mixtures with polymer-modified asphalt binders. It was noted by the DOT representative that recycled materials were not permitted in SMA but were allowed in Superpave mixtures; thus, this was one of the reasons for causing SMA to be more expensive.

(a) (b)

Figure A-7. Kansas DOT Information of SMA versus Polymer-Modified Superpave Dense-Graded Mixture; (a) Quantity, (b) Weighted Bid Price

<u>Maryland SHA</u>

The Maryland SHA typically uses SMA as the wearing course on projects with a 20-year design traffic level of greater than 30 million ESALs and on projects with a functional class of Principal Arterial or greater. The SMA mix design follows AASHTO R 35. **Figure A-8** shows the quantity and weighted mix bid price of SMA and Superpave dense-graded mixtures used on similar trafficked highways from 2011 to 2015. A total of approximately 1,872,000 and 892,000 tons of SMA and Superpave mixtures were produced in the past five years, respectively. As shown in **Figure A-8**(b), the five-year average weighed mix bid price of SMA was $98 per ton, which was approximately 12% (i.e., $10 per ton) higher than that of Superpave dense-graded mixtures with polymer-modified asphalt binders.

(a) (b)

Figure A-8. Maryland SHA Information of SMA versus Polymer-Modified Superpave Dense-Graded Mixture; (a) Quantity, (b) Weighted Bid Price

<u>Michigan DOT</u>

The Michigan DOT specifies the use of SMA as the surface course on projects with 20-year design ESALs between 10 and 100 million. The SMA mix design procedure follows AASHTO R 46-08. **Figure A-9** presents the quantity and weighted mix bid price of SMA and Superpave dense-graded mixtures used on similar trafficked highways. In the past five years except 2014, more Superpave mixtures were produced than SMA. The comparison in weighted mix bid price of these two mixtures showed that SMA was 12% to 29% more expensive than Superpave dense-graded mixtures and the difference varied from $9 to $21 per ton.

(a) (b)

Figure A-9. Michigan DOT Information of SMA versus Polymer-Modified Superpave Dense-Graded Mixture; (a) Quantity, (b) Weighted Bid Price

<u>Minnesota DOT</u>

The Minnesota DOT does not have a published mixture selection policy, but the State Materials Engineer typically specifies the use of SMA on pavements with high traffic volumes. SMA mix design follows AASHTO R 46-08. **Figure A-10** presents the comparison in quantity and weighted mix bid price of SMA and Superpave dense-graded mixtures used on similar trafficked highways from 2011 to 2015. Approximately 50,000 and 95,000 tons of SMA were produced in 2011 and 2013, respectively, but no SMA was produced in the other three years. The weighted mix bid price comparison in **Figure A-10**(b) showed that SMA was 32% to 60% more expensive than Superpave dense-graded mixtures with polymer-modified asphalt binders. The average difference in the weighted bid price of these two mixtures was approximately $29 per ton. It was noted by the DOT representative that recycled materials were not permitted in SMA but were allowed in Superpave mixtures; thus, this was one of the reasons for causing SMA to be more expensive.

(a) (b)

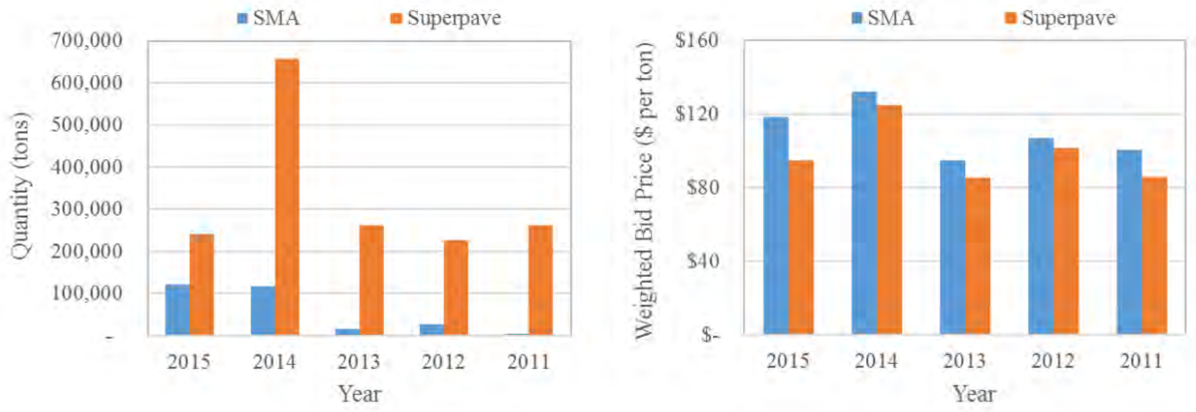
Figure A-10. Minnesota DOT Information of SMA versus Polymer-Modified Superpave Dense-Graded Mixture; (a) Quantity, (b) Weighted Bid Price

Missouri DOT

The Missouri DOT mixture selection guide requires SMA on interstates and other freeways with greater than 3,000 total average 24-hour commercial truck traffic. SMA mix design follows AASHTO R 46-08. Since SMA and Superpave dense-graded mixtures are not used for the same traffic volume, the comparisons in quantity and weighted mix bid price between these two mixtures are not available.

Pennsylvania DOT

According to the Pennsylvania DOT's Pavement Policy Manual, SMA is recommended for interstates, interstate look-alike highways, high-speed freeways, and as the wearing course on current roadways with greater than 30 million ESALs. The SMA mix design procedure follows AASHTO R 46-08 with few modifications in terms of mix design criteria and moisture susceptibility test method. **Figure A-11** presents the quantity and weighted mix bid price of SMA and Superpave dense-graded mixtures used on similar trafficked highways from 2011 to 2015. Approximately 286,000 and 1,573,000 tons of SMA and Superpave mixtures were produced from 2011 to 2015. The comparison in **Figure A-11**(b) showed that the weighted bid price of SMA was 5% to 25% (i.e., $5 to $23 per ton) higher than that of Superpave dense-graded mixtures with polymer-modified asphalt binders. It was noted by the DOT representative that recycled materials were not permitted in SMA but were allowed in Superpave mixtures; thus, this was one of the reasons for causing SMA to be more expensive.



(a) (b)

Figure A-11. Pennsylvania DOT Information of SMA versus Polymer-Modified Superpave Dense-Graded Mixture; (a) Quantity, (b) Weighted Bid Price

South Dakota DOT

The South Dakota DOT does not have a published mixture selection guideline for SMA, but SMA is typically used as the surface course on most four-lane roads and all interstates. SMA mix design follows AASHTO R 46-08. From 2011 to 2015, a total of approximately 145,000 and 185,000 tons of SMA and Superpave dense-graded mixtures were produced, respectively. The weighted bid price of SMA was 7% to 23% higher than that of Superpave mixtures. It was noted by the DOT representative that the average binder content of SMA was approximately 0.8% higher than that of Superpave mixtures. In addition, recycled materials were not permitted in SMA but up to 30% RAP were allowed in Superpave mixtures. These were two of the reasons for causing SMA to be more expensive.

Utah DOT

The Utah DOT does not have a published mixture selection guideline for SMA, but SMA is typically used as the surface course on interstate routes. SMA mix design follows AASHTO R 46-08. The comparisons in quantity and weighted mix bid price of SMA versus Superpave dense-graded mixtures are not available for the Utah DOT.

Virginia DOT

The Virginia DOT specifies the use of SMA on heavy to extreme heavy traffic volume routes where the expected higher cost can be justified with improved performance over other mixtures. Typically, SMA is used on routes with greater than three million cumulative ESALs. The DOT has its own specification (i.e., Virgin Test Method – 99) for designing SMA. **Figure A-12** presents the quantity and weighted mix bid price of SMA versus comparable Superpave dense-graded mixtures used on similar trafficked highways from 2011 to 2015. Approximately 740,000 tons of SMA were produced from 2011 to 2015, which was lower than the tonnage of comparable Superpave mixtures with polymer-modified asphalt binders (i.e., 4,654,000 tons). The weighted mix bid price of SMA was consistently higher than that of Superpave mixtures; the difference varied from $17 to $30 per ton during 2011 to 2015.

<u>Wisconsin DOT</u>

The Wisconsin DOT considers the use of SMA as the surface course for pavements with greater than five million ESALs over 20 years of design life. Currently, the Wisconsin DOT designs SMA by following AASHTO R 35 and M 323. **Figure A-13** presents the quantity and weighted mix bid price of SMA from 2011 to 2015. Since SMA and Superpave dense-graded mixtures are not used for the same traffic volume, the parallel comparison between these two mixtures is not available. Approximately 391,000 tons of SMA were produced from 2011 to 2015. The weighted bid price of SMA showed a consistent increase from $64 per ton in 2011 to $100 per ton in 2015, but then reduced to $85 and $76 per ton in 2016 and 2017, respectively.

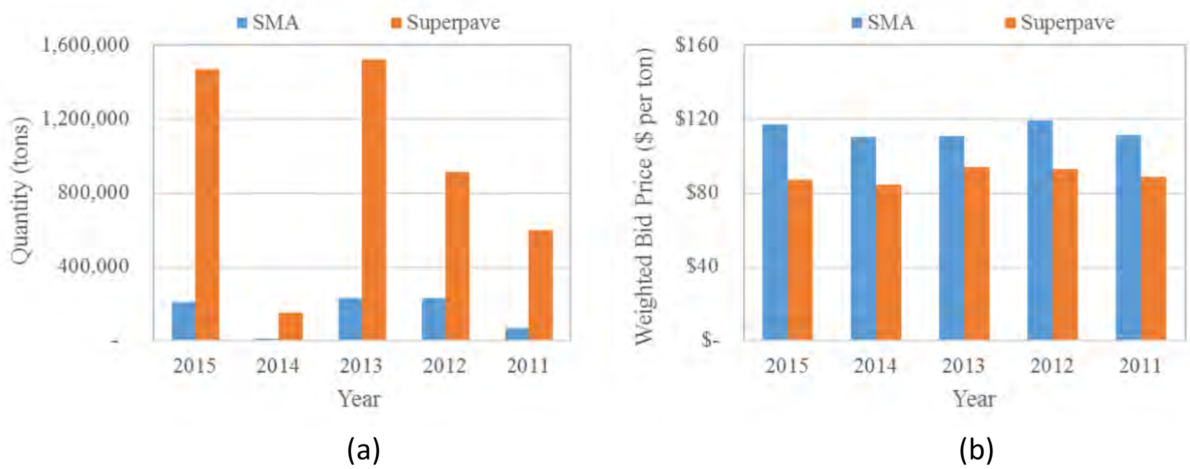


Figure A-12. Virginia DOT Information of SMA versus Polymer-Modified Superpave Dense-Graded Mixture; (a) Quantity, (b) Weighted Bid Price

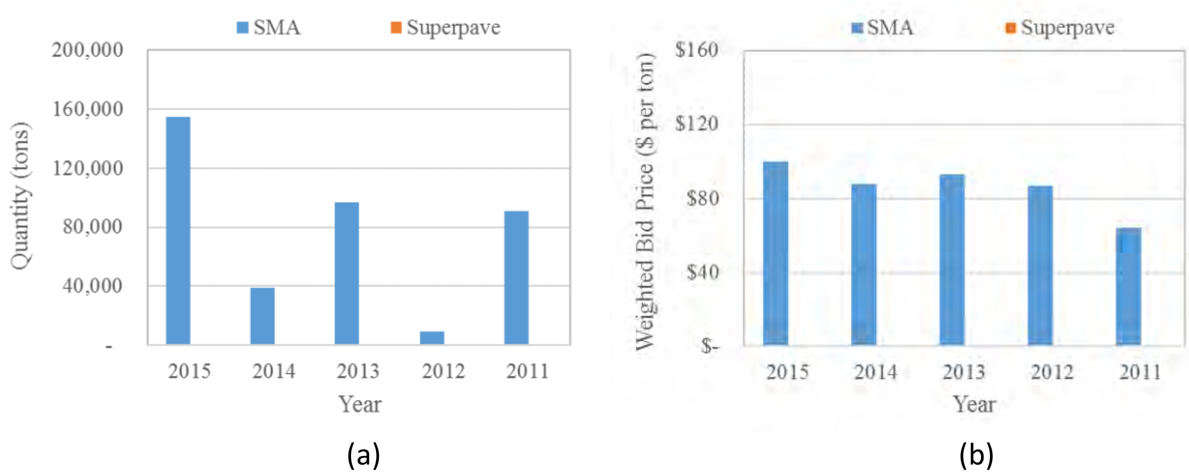


Figure A-13. Wisconsin DOT Information of SMA; (a) Quantity, (b) Weighted Bid Price