TechBrief

The Asphalt Pavement Technology Program is an integrated national effort to improve the long-term performance and cost effectiveness of asphalt pavements. Managed by the Federal Highway Administration through partnerships with State highway agencies, industry and academia, the program's primary goals are to reduce congestion, improve safety, and foster technology innovation. The program was established to develop and implement guidelines, methods, procedures and other tools for use in asphalt pavement materials selection, mixture design, testing, construction and quality control.

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Advances in the Design, Production, and Construction of Stone Matrix Asphalt (SMA)

This Technical Brief provides an overview of some advances that have been made in design and construction of Stone Matrix Asphalt (SMA) technology to improve flexible pavement and asphalt overlay performance.

Introduction

Stone matrix asphalt (SMA), also called stone mastic asphalt, is a tough and rut-resistant dense, gap-graded asphalt mixture with a stable stone-on-stone skeleton. The stone-on-stone skeleton can increase mixture strength while a rich mortar binder, coupled with stabilizing agents such as fibers and/or asphalt modifiers provides durability.

SMA was introduced into the U.S. in the mid-1980s and gained momentum following the European asphalt study tour by Federal Highway Administration (FHWA), American Association of State Highway and Transportation Officials (AASHTO), and National Asphalt Pavement Association (NAPA) in 1990 (Brown et al., 1997; Brown and Cooley, 1999; NAPA, 2002). A survey conducted by state asphalt pavement associations (SAPAs) shows that SMA is routinely used by 18 States (highlighted in solid green in Figure 1), mostly on State and Interstate routes with high traffic volumes (Yin and West, 2018).

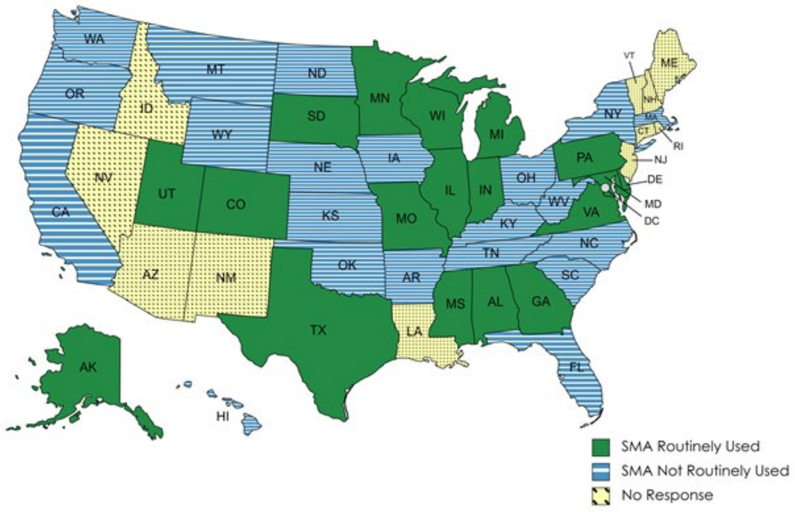

**Figure 1: SMA usage in the U.S.
(Source: Yin and West, 2018)**

Figure 2 shows the differences between SMA and conventional dense-graded mixtures. SMA is comprised of 70 to 80 percent coarse aggregate, 8 to 12 percent filler, and 6 to 7 percent asphalt binder. SMA has a higher asphalt binder content compared to dense-graded mixtures, so there is a higher tendency for asphalt draindown during silo storage and transportation. To prevent or reduce draindown sensitivity, a small amount of cellulose or mineral fibers (about 0.3 percent for cellulose and 0.3–0.4 percent for mineral fiber) are added to the mixture.

There has been some use of polymers in SMA as a stabilizing agent. Studies have shown the use of polymer-modified asphalt binder in conjunction with fiber increases durability and resistance to both rutting and cracking (Emery et al., 1993; Brown et al., 1997; NAPA, 2002).

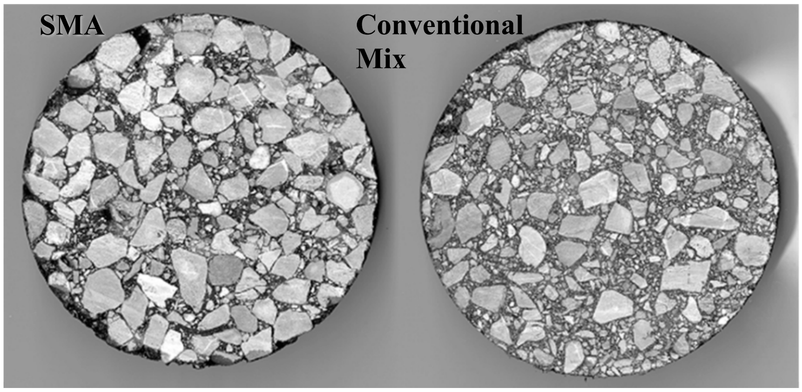

Figure 2: Coarse Stone Skeleton and Rich Mortar of SMA Compared to Conventional Mix. (Source: FHWA)

Historically, SMA mixtures have been successfully placed on routes that necessitate the ability to withstand heavy traffic such as State and Interstate routes, high-stress pavement areas (e.g., intersections, bus stops, and toll booths), thin overlays, airfields, and racetracks. NAPA suggests SMA should be used in extreme loading and high-stress conditions because of past performance observations in reducing distress (Von Quintus and Hughes, 2019). Other reported advantages of SMA are noise reduction and improved frictional resistance (Emery et al., 1993; NAPA, 2002).

In terms of initial cost, SMA mixture typically is more expensive than conventional mixtures, mainly because it requires higher asphalt contents, more durable aggregates, and inclusion of fibers and a modified asphalt binder. There has been no consistent conclusion on comparing the cost-effectiveness of SMA versus conventional dense-graded mixtures. Thus, selection criteria and policies to identify when SMA should be used are not consistent among agencies. Table 1 summarizes the SMA selection policy used by some State Departments of Transportation (DOTs) (Yin and West, 2018).

SMA Performance

Since the first SMA mixture was placed in the U.S. (in Wisconsin followed by Michigan, Georgia, and Missouri during the same year) in 1991, many research studies have been conducted to characterize the engineering properties and performance of SMA through laboratory testing and field evaluations (West et al., 2018; Yin and West, 2018). Most of these studies compared SMA to a counterpart conventional dense-graded mixture and reported that SMA showed better rutting resistance due to stone-on-stone contact and lower moisture susceptibility due to a better aggregate coating and asphalt film thickness. Regarding cracking resistance, most studies reported greater flexibility and cracking resistance (West et al., 2018; Yin and West, 2018).

Table 1. State's Policy for SMA Mixture Selection (Yin and West, 2018; Hajj et al., 2021).

Highway Agency	Application
Alabama DOT	Projects with 20-year design traffic greater than 30 million equivalent single axle loads (MESALs); 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 average daily traffic (ADT) greater than 50,000; State routes with ADT between 10,000–50,000 only when recommended by Office of Materials and Testing.
Illinois DOT	Projects with both less and greater than 10 MESALs.
Illinois Tollway	All mainline pavements.
Indiana DOT	Decision by the Pavement Designer.
Kansas DOT	Project-by-project decision, but rarely used.
Louisiana DOT & Development	Required on all Interstate wearing courses with traffic volumes greater than 35,000 ADT.
Maryland State Highway Administration	Projects with 20-year design traffic greater than 30 MESALs; projects with a functional class of Principal Arterial or greater.
Michigan DOT	Projects with 20-year design traffic between 10 and 100 MESALs.
Minnesota DOT	No criteria, but typically used on projects with high traffic volumes.[1]
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 MESALs.
South Dakota DOT	Most four-lane roads and Interstate routes.
Texas DOT	Intermediate or surface layer on high volume (or high demand) roadways.
Utah DOT	No criteria, but typically used on Interstate routes.
Virginia DOT	Projects with greater than 3 MESALs; 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 MESALs; Projects where low maintenance is beneficial (such as high-traffic areas); Projects where SMA is economically feasible.

One of the first comprehensive studies to develop and validate mix design procedure for SMA was conducted under the National Cooperative Highway Research Program (NCHRP) project D9-8, "Designing Stone Matrix Asphalt Mixtures." This study defined material and mix properties to ensure rut-resistant and durable SMA. Material specifications, a mix design method, supporting performance tests, and construction guidelines were developed and validated through the construction of 11 SMA pavement projects (Brown and Cooley, 1999).

Currently, AASHTO R 46-08[1], Standard Practice for Designing Stone Matrix Asphalt (SMA), AASHTO M 325-08, Standard Specification for Stone Matrix Asphalt (SMA), and AASHTO T 305-14[1], Standard Method of Test for Determination of Draindown Characteristics in Uncompacted Asphalt Mixtures, are the commonly used standards for the design of SMA. As presented in Table 2, nine agencies follow AASHTO R 46-08[1] or a modified version (Yin and West, 2018).

Table 3 and Table 4 present the predicted service life of SMA versus polymer-modified Superpave dense-graded mixtures for flexible and composite pavements, respectively (Yin and West, 2018). The predicted service lives listed in Table 3 and Table 4 are normalized to the same traffic level and they are based on the agency's pavement management database. As listed, SMA exhibited a longer service life for four of the seven flexible pavements, while SMA exhibited longer service life for three of the six composite pavements. It should be noted that the predicted service lives are longer than the measured performance data which are limited to ten years or less. As such, caution should be exercised by monitoring and validating the long-term performance of SMA sections.

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[1] A voluntary standard not required under Federal law.

Table 2. State's SMA Mix Design Procedures[1] (Yin and West, 2018; Hajj et al., 2021).

Highway Agency	Standard(s) Used
Alabama DOT	ALDOT-395-1999
Colorado DOT	AASHTO R 46-08, with 50-blow Marshall design
Georgia DOT	GDT-123
Illinois DOT	AASHTO R 46-08, with modifications
Illinois Tollway	Illinois Tollway SMA special provision
Indiana DOT	AASHTO M 325-08 and AASHTO R 46-08
Kansas DOT	KDOT special provision
Louisiana DOT & Development	AASHTO M 325-08
Maryland SHA	AASHTO R 35-17
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
Texas DOT	Tex-204-F
Utah DOT	AASHTO R 46-08
Virginia DOT	Virginia Test Method 99
Wisconsin DOT	AASHTO R 35-17 and AASHTO M 323-17

Table 3. Predicted Service Life for Flexible Pavement (Yin and West, 2018).

Highway Agency	Performance Measure	Predicted Service Life (Years)	
		SMA	Superpave
Alabama DOT	Pavement Condition Rating (PCR)	16.2	16.6
Colorado DOT	Rutting Fatigue Cracking Transverse Cracking Longitudinal Cracking	17.0	17.4
Georgia DOT	PACES Rating	16.0	11.0
Maryland SHA (Interstate)	Rutting Cracking Index (CI)	24.8	26.9
Maryland SHA (Principal Arterial)	Rutting Cracking Index (CI)	32.2	24.0
Minnesota DOT	Ride Quality Index (RQI) Surface Rating (SR)	16.6	11.3
Virginia DOT	Critical Condition Index (CCI)	19.0	14.4

Table 4. Predicted Service Life for Composite Pavement (Yin and West, 2018).

Highway Agency	Performance Measure	Predicted Service Life (Years)	
		SMA	Superpave
Illinois Tollway	Overall Condition Rating Survey (CRS)	13.5	9.0
Maryland SHA (Principal Arterial)	Rutting Cracking Index	21.8	19.6
Michigan DOT	Overall Distress Index (DI)	22.2	21.3
Pennsylvania DOT (Interstate)	Overall Pavement Index (OPI)	21.1	22.2
Pennsylvania DOT (Non-Interstate)	Overall Pavement Index (OPI)	24.5	11.0
Virginia DOT	Critical Condition Index (CCI)	23.1	12.8

The performance of 86 SMA pavement projects in various States was monitored in a research study led by the National Center for Asphalt Technology (NCAT) (Brown et al., 1997). Field performance data showed that SMA outperformed standard dense-graded asphalt mixtures in terms of both rutting and cracking resistance after being in service life for two to six years. Over 90 percent of the SMA projects had rutting measurements less than 4 mm. There was no evidence of raveling on the SMA projects. However, fat spots due to segregation, low voids in mineral aggregate (VMA), draindown, high asphalt content, and/or improper type or amount of stabilizer were reported as the biggest performance problems (Figure 3). To the authors' knowledge, an updated performance study on these 86 SMA pavement projects was not completed.

The SMA pavement section at the intersection of Williams and Margaret in Thornton, Illinois, has proven a successful use of SMA. This intersection serves as the main gateway to the Thornton Quarry with 1,800 fully-loaded trucks per day (approximately one million equivalent single axle loads (ESALs) annually). The pavement section was subjected to high stress and substantial traffic loading, and has been in service for over two decades with minimal maintenance, until recently resurfaced in 2017. It was found that the use of steel slag aggregate for the 2-inch wearing course and sound dolomitic stone for the asphalt binder course along with polymer modified asphalt binder and cellulose fiber were key factors for the long-life performance (Miller and Dahhan, 2018).

Figure 3. Localized fat spot in an SMA section (Source: Brown et al., 1997).

Performance data collected from 19 SMA sections at the NCAT Test Track showed excellent performance of these sections that prompted several States to adopt SMA for heavy traffic highways (West et al., 2012; West et al., 2018). Agency-sponsored (Mississippi, Missouri, and Georgia) SMA test sections at the Test Track exhibited clear evidence that many different aggregate sources can be used, which in turn reduce overall mixture costs. A notable example of these studies is a section paved with a 12.5 mm nominal maximum aggregate size (NMAS) SMA mixture with granite aggregate and 28% flat and elongated (F&E) particles at a 3:1 ratio. After more than 10 million ESALs, less than 5 mm of total rutting was measured that was more attributed to the initial consolidation at the onset of trafficking. There was no cracking evident within the test section and, as shown in Figure 4, the roughness measurements showed that the surface characteristics were unchanged throughout the two-year testing cycle (West et al., 2012; West et al., 2018).

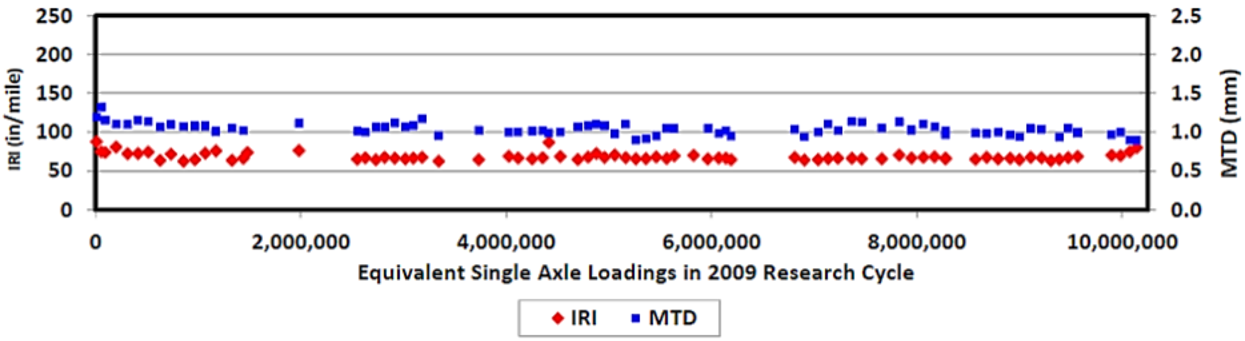

Figure 4. International roughness index (IRI) and mean texture depth (MRD) performance. (Source: West et al., 2012)

Similar findings were also reported in a follow-up study in which the engineering properties and laboratory performance of SMA designed with different percentages of F&E aggregate were evaluated (Watson and Julian, 2018). The Asphalt Pavement Analyzer (APA) rutting test results are represented in Figure 5. Watson and Julian (2018) concluded that SMA aggregate properties, i.e., Los Angeles (LA) abrasion loss and F&E particles, established based on European specifications can be restrictive, eliminating aggregate sources that may exhibit low to no distress over their design life. If aggregate has low abrasion loss values, the adverse effect of using high F&E aggregate would be negligible. As such, the maximum F&E limit (≤ 20 percent F&E at 3:1 ratio) that is a standard threshold in the AASHTO M 325-08[1] and is being used by most agencies for SMA aggregate can be reevaluated through performance testing and field projects.

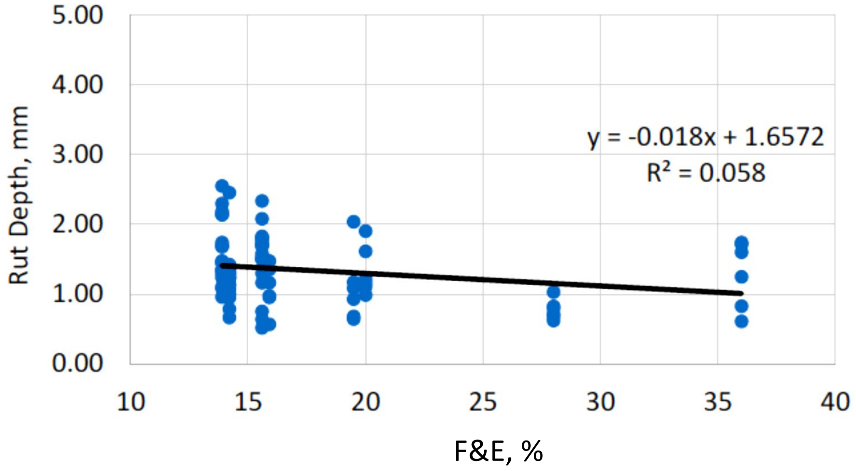

Figure 5. APA rut depth for SMA mixtures with different percentages of F&E particles (Source: Watson and Julian, 2018).

The Georgia DOT (GDOT) began to evaluate the viability of using SMA on the Georgia road system since 1990 (Jared, 1997). The first GDOT's SMA research project in 1991 consisted of different combinations of SMA and standard mixes on 2.5 miles of high traffic volume test section on Interstate 85 (I-85) (Jared, 1997; Wu and Tsai, 2016). The test section had average daily traffic (ADT) of 35,000, including 40 percent trucks (about 2 million ESALs per year). Since then, GDOT has implemented SMA on a more routine basis and has expanded the use of SMA as a surface mixture on Interstate pavements. GDOT's experience with SMA shows 30 to 40 percent less rutting and 3 to 5 times greater fatigue life, compared to standard mixtures.

Based upon the findings from many research studies, GDOT has made several revisions to the SMA specifications, including the use of longer fiber length to enhance mortar network and polymer-modified PG 76-22 asphalt binder to improve stiffness and durability (GDOT, 2003; Wu and Tsai, 2016). In addition, GDOT implemented the use of aggregates with up to 45 percent abrasion loss while restricting F&E particles (measured at the 3:1 ratio) to 20 percent. Corresponding LA abrasion values and F&E particles for SMA are shown in Table 5. It can be seen that as the abrasion value decreases, the corresponding flatness/elongation ratio may increase (Barksdale, 1995; GDOT, 2003). The most recent GDOT Standard Specifications Construction of Transportation Systems specifies (GDOT, 2021):

- F&E particles at 5:1 ratio (instead of 3:1 ratio) less than 10 percent.
- Maximum LA abrasion of 45 percent based on the B grading of AASHTO T 96-02[1].

Table 5. Relationship of L.A. Abrasion Value to F&E (GDOT, 2003).

LA Abrasion Loss (percent)	F&E Particles (percent)
≤ 45	≤ 20
≤ 40	21 – 25
≤ 35	26 – 35
≤ 30	36 – 40
≤ 25	41 – 45

A study by Celaya and Haddock (2006) reported that the widespread use of SMA in Indiana has been limited by coarse aggregate requirements. The findings from this study indicated that LA Abrasion value alone is not a sufficient indicator of acceptability of a coarse aggregate for SMA mixtures as some aggregates may degrade during compaction while meeting the 30 percent LA abrasion limit. The compaction degradation was defined as the change in percent passing the 2.36-mm (No.8) sieve during compaction. In addition, as many aggregates are more susceptible to abrasion in the presence of water (i.e., wet condition), the Micro-Deval test was regarded as an alternative for the LA Abrasion test for establishing the acceptability of a coarse aggregate for use in SMA. Based on the findings from this study, the Micro-Deval test and compaction degradation in the Superpave gyratory compactor were implemented in the Indiana Test Method (ITM) 220 to evaluate "Class AS" coarse aggregates for use in SMA. The ITM 220 specifies the following acceptance criteria (INDOT, 2020):

- The total Micro-Deval Abrasion loss value for an acceptable coarse aggregate or blend of coarse aggregates needs to be 18.0 percent or less.
- The Aggregate Degradation loss value for an acceptable coarse aggregate or blend of coarse aggregates needs to be 3.0 percent or less.

It should be mentioned that the Indiana DOT (INDOT) Standard Specifications allows for the use of steel furnace slag, sandstone, crushed dolomite, and polish-resistant aggregates for SMA surfaces. A later study demonstrated that local, polish susceptible aggregates can be used to replace up to 20 percent of premium materials (i.e., high-quality aggregates) in SMA surface mixtures without detrimental effect on performance and surface friction (McDaniel and Shah, 2012).

The total tonnage of SMA and polymer-modified Superpave dense-graded surface mixtures for the same traffic level from 2011 to 2015 is shown in Figure 6 for fifteen agencies (Yin and West, 2018). Of those fifteen agencies, the Maryland State Highway Administration (SHA) produced and placed the highest tonnage of SMA between 2011 and 2015 (see Figure 6). In 2017, Maryland SHA conducted a pilot project in which warm mix SMA with Evotherm® on I-195 was incorporated. The purpose of this pilot study was to evaluate the application of warm mix asphalt (WMA) technology to eliminate the need for stabilizing fiber (fiberless SMA). It was argued that the potential of draindown due to the elimination of fibers can be coupled with the mixture temperature reduction and using WMA additive that does not influence the asphalt binder viscosity (Bennert, 2018).

Fiberless SMA was also paved on two pilot projects in the U.S. Route 1 in New Jersey (Steger, 2018; Bennert, 2018). It was found that reduction in production temperature (275 to 285°F) successfully reduced draindown when fibers were eliminated. The difference in field densities of SMA with and without fibers were statistically insignificant. It is anticipated that the reduction in temperature reduces the amount of oxidation aging during production, thus reducing the increase in stiffness and brittleness and making SMA more cracking resistance. In addition, cost-saving as a result of removing the extra step of adding fiber to the mixture, lower energy consumption, increase in mixture haul time, as well as lower environmental impacts are the anticipated benefits of utilizing warm mix SMA.

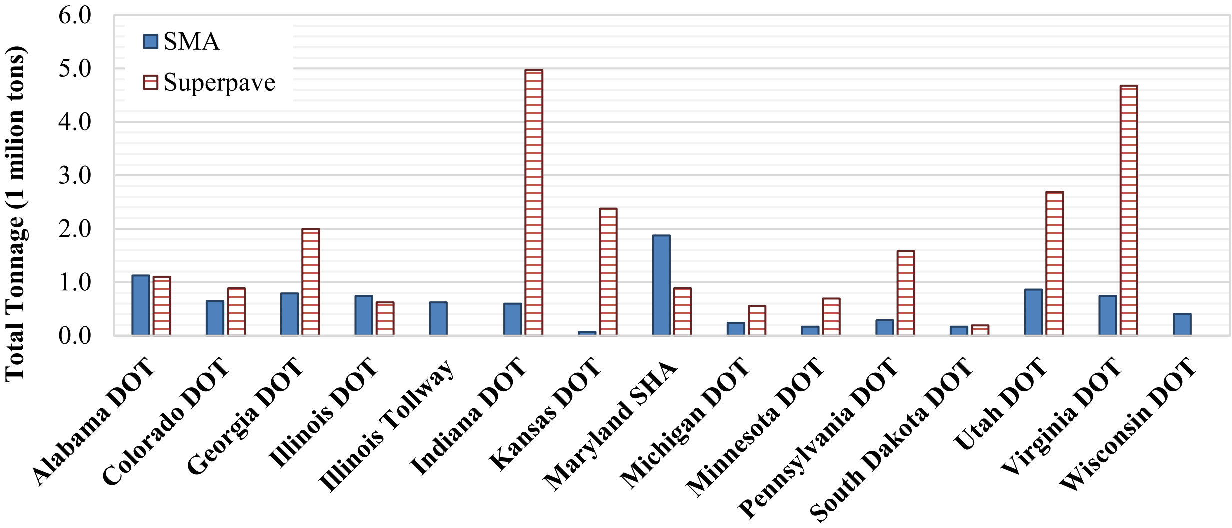

**Figure 6. Total tonnage of SMA and polymer-modified Superpave dense-graded mixtures from 2011-2015.
(Source: Yin and West, 2018)**

Other Advantages of SMA

SMA pavements provide added functional benefits that include: improving frictional resistance, reducing splash and spray (i.e., improve visibility), and reducing noise (Emery et al., 1993; NAPA, 2002). Several research studies conducted in Europe (e.g., Germany, Italy, Poland, Spain, U.K.) and the U.S. (e.g., Colorado, Maryland, Michigan, NCAT, New Jersey, Wisconsin) found SMA was quieter than standard dense-graded asphalt by 2 to 7 dB(A). The average of comparative noise levels of different pavement surface types is shown in Table 6 (Kandhal, 2004; Smit, 2008).

Figure 7 shows the surface texture of an SMA and a fine-graded mixture. The improved frictional resistance of SMA compared to conventional asphalt mixtures is attributed to the higher surface macrotexture. The rough surface texture provides more space for standing water within the SMA rather than the surface, thus reducing hydroplaning, splash and spray, as well as nighttime glare during wet conditions, and enhancing the visibility of pavement markings (Emery et al., 1993; NAPA, 2002).

Table 6. Comparative Noise Levels of Different Pavement Surface (Kandhal, 2004).

Pavement Surface Type	Comparative Noise Level (dB(A))
Open Graded Friction Course (OGFC)	–4
SMA	–2
Dense-graded Asphalt	0 (reference)
Portland Cement Concrete	+3

Figure 7. Surface texture of SMA (left) and fine-graded asphalt mixture (right) (NAPA, 2002).

Recent studies found that SMA has performed successfully in airports and heavy-duty roads in Australia (White and Jamieson, 2018; Jamieson and White, 2019). SMA application as airport surface was evaluated in two trial sections on taxiways and aprons. Australian runways are typically surfaced with grooved Marshall-designed dense-graded asphalt. Grooves are commonly sawed into the surface to improve skid resistance during wet weather events and satisfy Australia's regulatory requirements. However, the time-consuming and costly process of grooving, the increased complexity of applying preservation treatments, as well as rubber contamination from landing aircraft are objectionable limitations of grooved asphalt surfaces. As an example, Figure 8 includes a photograph of a recently grooved surface (left photograph), in comparison to the closure of the grooves at a different facility (right photograph).

Figure 8. Runway grooves (left) and groove closure (right); a pen is included in the photograph on the right to show the closure of the grooves (Source: Jamieson and White, 2019).

A research study to validate the potential use of SMA as an alternate runway surface for Australian airports was recently completed. The primary objective of this study was to develop a performance-based specification through the results of laboratory performance testing and field validation. As of late 2019, the preliminary results indicated that SMA met the desired rutting and cracking criteria. In terms of surface texture, initial friction test results showed a marginal non-compliance with the minimum regulatory requirement. However, it was found that after 23 days, the friction requirement was met as the surface asphalt binder film wears down through traffic and weathering (White and Jamieson, 2018; Jamieson and White, 2019). The Unified Facilities Guide Specifications (UFGS) of the U.S. Army Corps of Engineers (USACE) also developed a specification for the design and construction of SMA for airfield pavements (Prowell et al., 2009; USACE, 2019).

Economic Considerations

SMA is more expensive than conventional mixtures, mainly due to higher asphalt binder contents, need for more durable aggregates, and inclusion of fibers and polymers. SMA production often uses special aggregates in the cold feed bins; thus, reducing plant versatility by imposing limitations when switching to other mixture types. In addition, shortened paving windows due to traffic control restrictions on projects is another factor contributing to the higher cost for SMA mixtures. The relative percent differences between five-year average weighted bid price of SMA and polymer-modified conventional dense-graded surface mixtures for the same traffic level from 2011 to 2015 is shown in Figure 9. The weighted bid price is the sum of project bid price times the project tonnage divided by the total tonnage for that mixture for the year. It can be seen that the weighted bid prices for SMA were between 9 to 45 percent higher per ton than polymer-modified dense-graded mixtures.

Another important factor that contributes to the higher cost of SMA is the limited use of recycled materials, including reclaimed asphalt pavements (RAP) and reclaimed asphalt shingles (RAS). Some agencies limit or even prohibit the use of recycled materials in SMA. An example of such States is GDOT that allows only 15 percent RAP for SMA while up to 40 and 25 percent RAP for conventional dense-graded mixtures in continuous and batch plants are allowed, respectively. The difference in weighted bid price between SMA and polymer-modified conventional dense-graded mixtures for States allowing RAP/RAS in SMA is shown in Figure 10 (Yin and West, 2018).

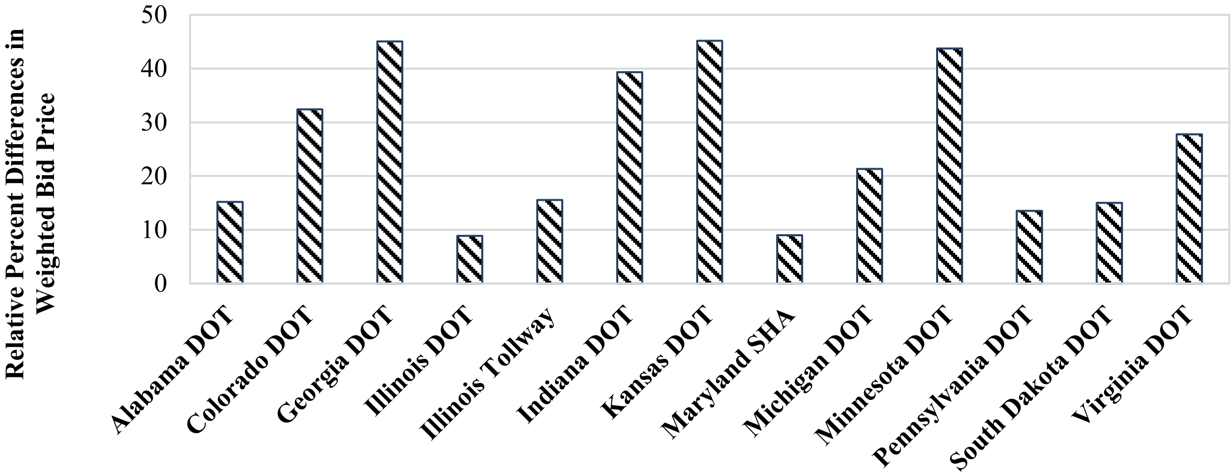

Figure 9. Relative percent differences in weighted bid price of SMA and polymer-modified Superpave dense-graded mixtures from 2011-2015 (Source: Yin and West, 2018).

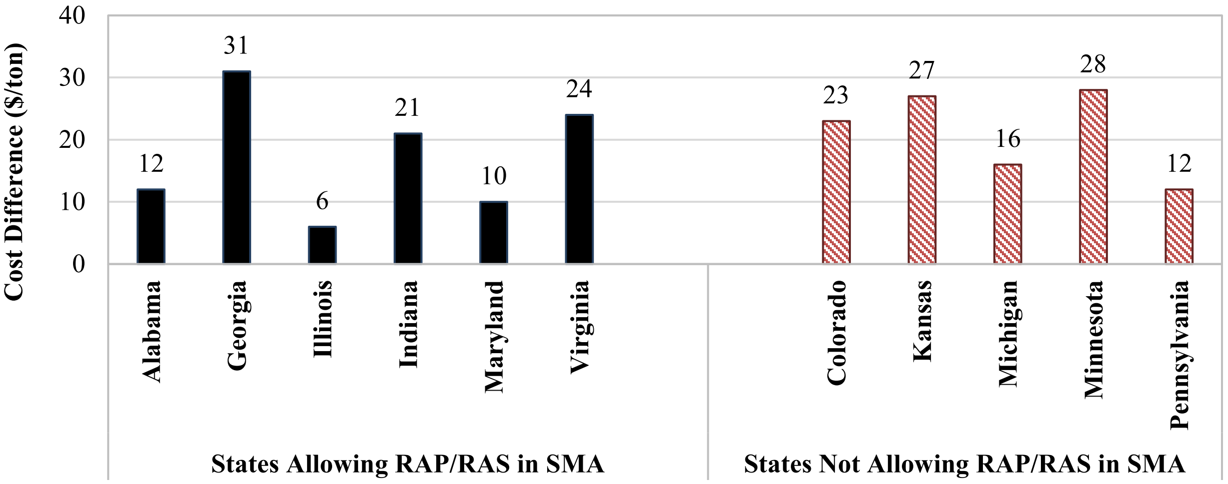

Figure 10. Difference in weighted bid price between SMA and polymer-modified Superpave dense-graded mixtures (Source: Yin and West, 2018).

Studies in which the life-cycle cost (LCC) of SMA was compared to conventional dense-graded mixtures indicated that although SMA had equivalent or better field performance (varied from 1 to 13 years) than conventional dense-graded mixtures, SMA cost-effectiveness should be evaluated on a case-by-case basis. LCC analysis (LCCA) case studies for three agencies were conducted to determine if the higher cost of SMA could be justified by the extended service life (Yin and West, 2018). The assumption for the LCCA was a 2 inch thick asphalt overlay with SMA (Alternative 1) and conventional Superpave mixture (Alternative 2) using the most recent five-year weighted bid prices shown in Figure 9 and predicted service lives presented in Table 3 and Table 4.

The summary of the LCCA presented in Table 7 implies that SMA has a higher net present value (NPV) than Superpave dense-graded mixtures for Michigan DOT meaning that SMA is not a cost-effective alternative. However, for the Virginia DOT and Maryland SHA, the higher cost of SMA is justified by the greater pavement life extension, and therefore it is more cost-effective than the Superpave mixtures for these two agencies. Wisconsin DOT made a similar observation, SMA was cost effective under some conditions or selected pavement structures (Smith, et al., 2006).

Table 7. Summary of LCCA for Three Agencies (Yin and West, 2018).

LCCA Case Study	**Pavement Type**	**Discount Rate***	**Analysis Period (Years)**	**Service Life (Years)**		**Unit Cost ($/ton)**		**Net Present Value ($/milex1000)**	
				SMA	**Superpave**	**SMA**	**Superpave**	**SMA**	**Superpave**
Maryland SHA	Flexible	2.9%	32	32	24	98	88	68	75
Michigan DOT	Composite	1.5%	22	22	21	92	76	64	55
Virginia DOT	Composite	4.0%	23	23	13	114	89	79	94

*In accordance with the State's current practice.

Whether or not SMA is cost-effective depends on the relative level of significance from the increased initial cost versus extended life expectance. Selection criteria and policies to identify when SMA is cost-effective need to consider initial costs, maintenance and rehabilitation frequency, and sources of roadway construction and maintenance funding. Therefore, agencies need to determine the cost-effectiveness of SMA within their States (Smith et al., 2006; McGhee and Clark, 2007; Son and Al-Qadi, 2014; Yin and West, 2018).

Balanced Mix Design

Balanced mix design (BMD) is one of the design procedures that supports the Performance Engineered Pavements (PEP) vision of the FHWA. This vision incorporates the goal of long-term performance into structural pavement design, mix design, construction, and materials acceptance (Duval et al., 2019).

BMD is described as "asphalt mix design using performance tests on appropriately conditioned specimens that address multiple modes of distress taking into consideration mix aging, traffic, climate and location within the pavement structure" per AASHTO PP 105-20, a non-binding standard[1]. Some State DOTs, as an example, Illinois DOT (IDOT), New Jersey DOT (NJDOT), and Texas DOT (TxDOT), have used the BMD process as part of mix design and acceptance on select demonstration projects or have well-developed BMD specifications, performance test methods, and practices in place (Hajj et al., 2021).

While SMA performance has been historically good (refer to "SMA Performance" section), some State DOTs added performance testing to their SMA mixture design as part of their implementation effort for BMD. As an example, Table 8 summarizes the performance tests selected by IDOT, Louisiana DOT and Development (LaDOTD), and TxDOT for their SMA design (Hajj et al., 2021).

Table 8. Example State DOTs for SMA Mix Design Performance Tests.[1]

State DOT	**Rutting**	**Cracking**	**Moisture Damage**
IDOT	Hamburg Wheel Track Test (Illinois Modified AASHTO T 324-19).	Flexibility Index (Illinois Modified AASHTO T 393).	Tensile Strength (Illinois Modified AASTO T 283-14).
LaDOTD	Loaded Wheel Tester (AASHTO T 324-19)	Semi-Circular Bend Test (ASTM D8044-16)	Loaded Wheel Tester (AASHTO T 324-19)
TxDOT	Hamburg Wheel Track Test (Tex-242-F)	Overlay Test (Tex-248-F)	Hamburg Wheel Track Test (Tex-242-F)

Mechanistic-Empirical Pavement Design

Mechanistic-empirical (ME) design methods use laboratory tests to measure different asphalt properties for predicting measures of flexible pavement performance. In support of the use of ME-based design methods, some State DOTs (as an example, Colorado, Pennsylvania, Utah, and Wisconsin) have sponsored test programs to measure the asphalt properties of SMA mixtures (Colorado DOT, 2018; Nabizadeh, et al., 2022 [Wisconsin DOT]; Wilke et al., 2019 [Pennsylvania DOT]; Utah, 2021). The properties measured on SMA mixtures include: dynamic modulus for rutting and fatigue cracking predictions; indirect tensile creep compliance and strength for transverse cracking predictions; repeated load plastic strain for rutting predictions; and bending beam fatigue and/or indirect tensile strain at failure for bottom-up fatigue cracking predictions. It needs to be noted that SMA is mainly placed as a wearing surface, so bottom-up fatigue cracks are not applicable to SMA.

Performance observations are needed to ensure that an ME-based design method is predicting, without bias, distresses for the SMA and other asphalt mixtures. The distress observations made for flexible pavements confirmed that SMA exhibits lower levels of rutting, lower levels of transverse cracks, lower levels of fatigue cracks (top-down fatigue cracks), and lower International Roughness Index (IRI) values. As an example, the performance data collected by the Pennsylvania DOT showed the following observations between dense-graded Superpave and SMA mixtures (Von Quintus, 2020):

- The average rut depth of SMA was 0.37 inches, compared to 0.40 inches for Superpave mixtures.
- The average alligator cracking of SMA was 2.4 percent, compared to 7.0 percent for Superpave mixtures.
- The average length of transverse cracks of SMA was 581 ft./mi., compared to 1,144 ft./mi. for Superpave mixtures.

In other words, ME-based methods use performance properties measured in the laboratory to predict the performance of SMA and other dense-graded asphalt mixtures. The measured and predicted distresses for SMA mixtures exhibited better performance than the dense-graded Superpave mixtures based on laboratory-derived performance properties.

Summary

In summary, SMA has exhibited very good performance and longer service lives in comparison to standard dense-graded asphalt mixtures but is more costly. Whether the longer service life and/or lower amounts of distress are sufficiently different to offset the higher material costs has yet to be confirmed across the industry. SMA is cost effective for selected high stress conditions. It is important to recognize that the aggregate specifications for SMA could be too restrictive based on past studies and performance observations. If the aggregate properties become less restrictive, more local materials can be used; thus, reducing the materials cost and making SMA more cost competitive in terms of lower LCCs.

References

Alabama Department of Transportation (2008). ALDOT-395-1999, Stone Matrix Asphalt Mix Design, ALDOT, Montgomery, AL.

American Association of State Highway and Transportation Officials (2017). AASHTO R 46-08, Standard Practice for Designing Stone Matrix Asphalt (SMA), AASHTO, Washington, DC.

American Association of State Highway and Transportation Officials (2017). AASHTO M 323-17, Standard Specification for Superpave Volumetric Mix Design, AASHTO, Washington, DC.

American Association of State Highway and Transportation Officials (2017). AASHTO M 325-08, Standard Specification for Stone Matrix Asphalt (SMA), AASHTO, Washington, DC.

American Association of State Highway and Transportation Officials (2017). AASHTO R 35-17, Standard Practice for Superpave Volumetric Design for Asphalt Mixtures, AASHTO, Washington, DC.

American Association of State Highway and Transportation Officials (2018). AASHTO T 283-14, Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage, AASHTO, Washington, DC.

American Association of State Highway and Transportation Officials (2018). AASHTO T 305-14, Standard Method of Test for Determination of Draindown Characteristics in Uncompacted Asphalt Mixtures, AASHTO, Washington, DC.

American Association of State Highway and Transportation Officials (2019). AASHTO T 96-02, Standard Method of Test for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine, AASHTO, Washington, DC.

American Association of State Highway and Transportation Officials (2019). AASHTO T 324-19, Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA), AASHTO, Washington, DC.

American Association of State Highway and Transportation Officials (2020). AASHTO PP 105-20, Standard Practice for Balanced Design of Asphalt Mixtures, AASHTO, Washington, DC.

American Association of State Highway and Transportation Officials (2021). AASHTO T 393-21, Standard Method of Test for Determining the Fracture Potential of Asphalt Mixtures Using Illinois Flexibility Index Test (I-FIT), AASHTO, Washington, DC.

American Society for Testing and Materials (2019). ASTM D8044-16, Standard Test Method for Evaluation of Asphalt Mixture Cracking Resistance using the Semi-Circular Bend Test (SCB) at Intermediate Temperatures, ASTM International, West Conshohocken, PA.

Barksdale, R. D., Han, J., Miller, S., and Thompson, S. (1995) Optimum Design of Stone Matrix Asphalt Mixes, GDOT Research Project 9217, Georgia Department of Transportation (GDOT), Atlanta, GA.

Bennert, T. (2018). Performance Summary of New Jersey's SMA, Conference presentation, 2018 NAPA Conference on SMA, Atlanta, GA.

Brown, E. R., Haddock, J., Mallick, R. B., and Lynn, T. A. (1997). Development of a Mix Design Procedure for Stone Matrix Asphalt (SMA) Mixtures, Journal of the Association of Asphalt Paving Technologists, Vol. 66, pp. 1-30, Association of Asphalt Paving Technologists, St Paul, MN.

Brown, E. R., Mallick, R. B., Haddock, J., and Bukowski, J. (1997). Performance of Stone Matrix Asphalt (SMA) Mixtures in the United States, Journal of the Association of Asphalt Paving Technologists, Vol. 66, pp. 426-457, Association of Asphalt Paving Technologists, St Paul, MN.

Brown, E.R. and Cooley JR, L.A. (1999). Designing Stone Matrix Asphalt Mixtures for Rut-Resistant Pavements, NCHRP Report 425, Project NCHRP D9-8, Transportation Research Board of the National Academies, Washington, DC.

Celaya, B. J. and Haddock, J. E. (2006). Investigation of Coarse Aggregate Strength for Use in Stone Matrix Asphalt, Report No. FHWA/IN/JTRP-2006/4, Indiana Department of Transportation (INDOT), West Lafayette, IN.

Colorado DOT (2018). Unpublished XML Files. Laboratory testing of asphalt mixtures to support material inputs to the Pavement ME Design software for recalibration, Denver, CO (on file with the FHWA Office of Infrastructure).

Duval, R., Corrigan, M., and Conway, B. (2019). Performance Engineered Pavements, Report No. FHWA-HIF-20-005, Federal Highway administration, Washington D.C.

Emery, J. J., Schenk, W., Carrick, J. J., Davidson, J. K., MacInnis, W. K., and Kennepohl, G. J. (1993). Stone Mastic Asphalt Trials in Ontario, Transportation Research Record, Vol. 1427, pp. 47-53.

Georgia Department of Transportation (2010). GDT-123, Determining the Design Proportions of Stone Matrix Asphalt Mixtures, GDOT, Atlanta, GA.

Georgia Department of Transportation (2003). Summary of Georgia's Experience with Stone Matrix Asphalt Mixes, GDOT, Atlanta, GA.

Georgia Department of Transportation (2021). Standard Specifications Construction of Transportation Systems, GDOT, Atlanta, GA.

Hajj, E. Y., Aschenbrener, T. B., and Nener-Plante, D. (2021). Case Studies on the Implementation of Balanced Mix Design and Performance Tests for Asphalt Mixtures. Available online: https://www.eng.auburn.edu/research/centers/ncat/education/bmd.html, last accessed September 14, 2021.

INDOT. (2020). Standard Specifications, Indiana Department of Transportation (INDOT), IN.

Jamieson, S. and White, G. (2019). Developing a Performance-Based Specification for Stone Mastic Asphalt as an Ungrooved Runway Surface, International Airfield and Highway Pavements Conference 2019, Chicago, IL.

Jared, D. (1997). Evaluation of Stone Matrix Asphalt and Porous European Mix, Report No. FHWA-GA-97-9102, Georgia Department of Transportation (GDOT), Atlanta, GA.

Kandhal, P. (2004). Asphalt Pavements Mitigate Tire/Pavement Noise, Hot Mix Asphalt Technology, Vol. 9(2), pp. 22-31.

McDaniel, R. S. and Shah, A. (2012). Maximizing the Use of Local Materials in HMA Surfaces, Report No. FHWA/IN/JTRPT2012/07, Indiana Department of Transportation (INDOT), West Lafayette, IN.

McGhee, K. K. and Clark, T. M. (2007). A Cost-Comparison Methodology for Selecting Appropriate Hot-Mix Asphalt Materials, Report No. VTRC 07-R31, Virginia Department of Transportation (VDOT), Richmond, VA.

Miller, J. D. and Veeraragavan, A. Z. (2018). Stone Matrix Asphalt (SMA) Case Study, Thornton, Illinois: Analysis of 20-Year Stone MatrixAsphalt Material on Williams Street, Special Report 223 Advances in the Design, Production, and Construction of Stone Matrix (Mastic) Asphalt, National Asphalt Pavement Association (NAPA), Lanham, MD.

Nabizadeh, Hadi., et al. (2022). Expansion of AASHTOWare ME Inputs for Asphalt Layers, Report Number 0092-20-03, Wisconsin Highway Research Program (WHRP), Madison, WI.

NAPA. (2002). Designing and Constructing SMA Mixtures—State-of-the-Practice, Quality Improvement Series 122, National Asphalt Pavement Association (NAPA), Lanham, MD.

Powell, B. D., Watson, D. E., Hurley, G. C., Brown, E. R. (2009). Evaluation of Stone Matrix Asphalt (SMA) for Airfield Pavements, Report No. AAPTP 04-04, Airport Asphalt Pavement Technology Program (AAPTP), Auburn, AL.

Smit, A. (2008). Synthesis of NCAT Low-Noise HMA Studies, NCAT Report 08-01, National Center for Asphalt Technology (NCAT), Auburn, AL.

Smith, K. L., Titus-Glover, L., Rao, S., Von Quintus, H. L., and Stanley M. (2006). Life-Cycle Cost Analysis of SMA Pavements and SMA Application Guidelines, Report No. WHRP 06-11, Wisconsin Department of Transportation (WisDOT), Madison, WI.

Son, S. and Al-Qadi, I. L. (2014). Engineering Cost–Benefit Analysis of Thin, Durable Asphalt Overlays, Transportation Research Record, Vol. 2456(1), pp. 135-145.

Steger, R. (2018). Development and Use of Fiberless SMA in the United States, Conference presentation, 2018 NAPA Conference on SMA, Atlanta, GA.

Texas Department of Transportation (2016). Tex-204-F, Test Procedure for Design of Bituminous Mixtures, TxDOT, Austin, TX.

Texas Department of Transportation (2019). Tex-242-F, Test Procedure for Hamburg Wheel-Tracking Test, TxDOT, Austin, TX.

Texas Department of Transportation (2019). Tex-248-F, Test Procedure for Overlay Test, TxDOT, Austin, TX.

Utah DOT (2021). Unpublished XML Files. Laboratory testing of asphalt mixtures to support material inputs to the Pavement ME Design software, Salt Lake City, UT (on file with the FHWA Office of Infrastructure).

U.S. Army Corps of Engineers (USACE). (2019). Stone Matrix Asphalt (SMA) for Airfield Paving, Unified Facilities Guide Specifications (UFGS) 32 12 15.16, National Institute of Building Sciences, Washington, DC.

Von Quintus, Harold L. and Chuck S. Hughes. (2019). Design and Construction of Heavy Duty Pavements, Second Edition, Quality Improvement Series 123, National Asphalt Pavement Association, Lanham, MD.

Von Quintus, Harold L. (2020). Observations of the distress data used in calibration of the Pavement ME Design software, version 2.6, Pennsylvania DOT (on file with the FHWA Office of Infrastructure).

Wilke, Paul, et al. (2019). Verification and Local Calibration of the MEPDG Transfer Functions in Pennsylvania, Unpublished Report, Pennsylvania DOT, Harrisburg, PA (on file with the FHWA Office of Infrastructure).

Watson, D. E. and Julian, G. (2018). Effect of Flat and Elongated Aggregate on Stone Matrix Asphalt Performance, Special Report 223 Advances in the Design, Production, and Construction of Stone Matrix (Mastic) Asphalt, National Asphalt Pavement Association (NAPA), Lanham, MD.

West et al. (2012). Phase IV NCAT Pavement Test Track Findings, NCAT Report 12-10, National Center for Asphalt Technology (NCAT), Auburn, AL.

West et al. (2018). Phase V (2012-2014) NCAT Test Track Findings, NCAT Report 16-04, National Center for Asphalt Technology (NCAT), Auburn, AL.

White, G. and Jamieson, S. (2018). Introduction of Stone Matrix Asphalt to Australian Runways, Special Report 223 Advances in the Design, Production, and Construction of Stone Matrix (Mastic) Asphalt, National Asphalt Pavement Association (NAPA), Lanham, MD.

Wu, Y. and Tsai, Y. Georgia Long-Term Pavement Performance (GALTPP) Program – Maintaining Georgia's Calibration Sites and Identifying The Potential for Using MEPDG For Characterization of Non-standard Materials and Methods (Phase 1), Report No. FHWA-GA-16-1425, Georgia Department of Transportation (GDOT), Forest Park, GA.

Yin, F. and West, R. (2018). Performance and Life-Cycle Cost Benefits of Stone Matrix Asphalt, NCAT Report 18-03, National Center for Asphalt Technology (NCAT), Auburn, AL.

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