TOPS

Targeted Overlay Pavement Solutions

Stone Matrix Asphalt Georgia Case Study

September 2022

U.S. Department of Transportation
Federal Highway Administration

Every Day Counts
Innovation for a Nation on the Move

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<tr><td colspan="4">**16. Abstract:** Stone Matrix Asphalt (SMA) was developed as a durable, highly rut-resistant asphalt mix that could withstand the abrasive effect of studded tires used in the winter. The mix concept depended on a coarse aggregate skeleton to provide resistance to rutting and wear, and a rich mortar of mineral filler and binder to provide long-term durability. SMA has been used in Europe for nearly 60 years due to its excellent rutting resistance and ability to withstand the wearing effect of studded tire use during winter driving conditions. It was introduced to the United States in 1990. The Georgia Department of Transportation (GDOT) was one of the first agencies to place test sections to evaluate its performance on some of its heaviest traveled interstate routes. GDOT was interested in SMA based on reports that it had greater rutting resistance, longer fatigue life, longer service life, and lower annualized cost than conventional mixes (GDOT, 2002). However, GDOT had concerns over whether SMA would perform in the southeastern United States with its warmer climate, and with aggregates that have higher loss as measured using the Los Angeles Abrasion Test (AASHTO T 96). This report is a case study of GDOT's experience and includes historical background, construction considerations, and performance.</td></tr>
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LIST OF ACRONYMS

ADT	Average daily traffic
ASTM	American Society for Traffic and Medicine
ESAL	Equivalent single axle load
F&E	Flat and elongated
FHWA	Federal Highway Administration
$\mathbf{G_{sb}}$	Bulk specific gravity
$\mathbf{G_{mm}}$	Maximum specific gravity
GDOT	Georgia Department of Transportation
HOV	High-occupancy vehicle
LP	Locking point
MTV	Material transfer vehicle
NCHRP	National Cooperative Highway Research Program
$\mathbf{N_{design}}$	Number of design gyrations
OGFC	Open-graded friction course
PCC	Portland cement concrete
SGC	Superpave^{TM} gyratory compactor
SMA	Stone Matrix Asphalt
TSR	Tensile strength ratio
TWG	Technical working group

STONE MATRIX ASPHALT
Case Study Overview
Georgia Department of Transportation

OVERVIEW

Stone matrix asphalt (SMA) has been used in Europe for nearly 60 years due to its rutting resistance and ability to withstand the wearing effect of studded tire use during winter driving conditions (AASHTO, 1991). It was first introduced to the United States in 1990 through the European Asphalt Study Tour. Federal Highway Administration (FHWA) representatives participated in the tour, assisted with research funding, and developed a technical working group (TWG) to assist agencies with SMA implementation. The TWG provided the first example specifications for materials and construction, mix design suggestions, and trouble-shooting assistance for agencies. The mix concept used a coarse aggregate skeleton to provide resistance to rutting and wear, and a rich mortar of mineral filler and binder to provide long-term durability (Figure 1).

The Georgia Department of Transportation (GDOT) was interested in SMA based on reports that it had greater rutting resistance, longer fatigue life, longer service life, and lower annualized cost than conventional mixes (GDOT, 2002). However, GDOT had concerns over whether SMA would perform in the southeastern United States with its warmer climate, and with aggregates that have higher abrasion loss as measured using the Los Angeles Abrasion Test (AASHTO T 96).[1]

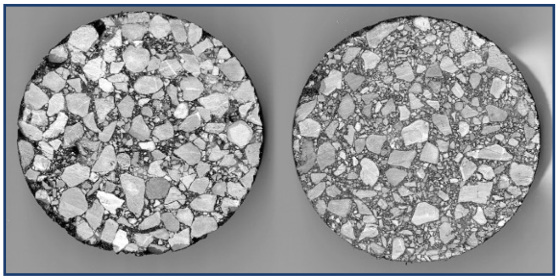
(A) **(B)**

Figure 1: SMA coarse stone skeleton and rich mortar (A) compared to conventional mix (B). (Source: FHWA)

RESEARCH ACTIVITIES

GDOT constructed test sections on two research projects to evaluate SMA effectiveness at reducing rutting potential and increasing asphalt mixture durability. The two test sections were used to determine if SMA could reduce or eliminate reflective cracking when placed over jointed Portland cement concrete (PCC) pavements. The first test SMA and conventional mix test section comparison was on I-85 northeast of Atlanta in Jackson County with 35,000 average daily traffic (ADT) including 40 percent heavy trucks that resulted in about 2 million equivalent single axle loads (ESALs) per year. The SMA overlay on a PCC pavement was on I-75 south of Atlanta in Henry County. This project had 47,000 ADT with 21 percent truck traffic.

One concern for GDOT was the high European SMA aggregate quality requirements. European nations typically required Los Angeles Abrasion Test loss within a maximum of 20-30 percent based on AASHTO T 96, and 20 percent maximum flat and elongated particles (F&E) at a ratio of 3:1 based on American Society for Testing and Materials (ASTM) D4791. This reduces the potential for aggregate breakdown from the use of studded tires. Georgia aggregates generally have a higher abrasion loss value, but performance has been acceptable as GDOT does not allow use of studded tires. For example, the aggregate used on the I-85 test

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[1] The use of SMA is not a Federal requirement. None of the AASHTO or ASTM specifications or standards in this case study are Federal requirements.

section had 35 percent Los Angeles Abrasion Test loss, while the Henry County test section had Los Angeles Abrasion Test loss of 37 percent, along with 29 percent F&E particles at the 3:1 ratio.

To further evaluate higher F&E aggregate properties in SMA mixes, GDOT placed an SMA test section on an Alabama test track that consisted of granite aggregate with 28 percent F&E particles at the 3:1 ratio. The mix had a binder content of 6.5 percent and was compacted in place to 94.7 percent of theoretical maximum specific gravity (G_{mm}) based on AASHTO T 209. The mix had less than 5 mm of rutting after more than 10 million ESAL applications with no apparent cracking within the section. At the end of the three-year test cycle, researchers concluded the higher F&E aggregate provided resistance to rutting, raveling, and cracking (West, et al., 2012). Based on this project, it appeared the earlier European approach to SMA aggregate properties may have been too restrictive and may unnecessarily eliminate local aggregates that perform well under heavy loading. Researchers, therefore, suggested that agencies conduct performance tests with their own available materials when setting specification limits.

IMPLEMENTATION

After two test sections were placed on I-85 and I-75 that validated the improved rutting resistance and durability of SMA mixes, a full-scale widening project on I-95 was contracted to use 195,000 tons of SMA in the dense-graded intermediate and surface layers. After the I-95 project, GDOT was confident in SMA performance benefits and decided to use it for a high-occupancy vehicle (HOV) project on the I-75/I-85 corridor through Atlanta (Figure 2) with more than 300,000 ADT. The HOV construction was a $41 million project consisting of 330 lane miles using 200,000 tons of SMA.

Since then, GDOT has considered SMA the premier asphalt mix and SMA is used as the final dense-graded surface on all interstate resurfacing projects and high-traffic projects with a volume of greater than or equal to 50,000 ADT.

Figure 2: SMA HOV lane construction project in Atlanta.
(Source: GDOT)

MIX DESIGN

Materials

GDOT found that higher abrasive loss aggregates (up to 45 percent) may perform very well since the use of studded tires is not allowed statewide. Further research also confirmed that low F & E values at a 3:1 ratio may also be overly restrictive. As a result, GDOT began requiring the same aggregate quality requirements for SMA mixtures as conventional Superpave mixtures.

Figure 3: Asphalt binder "rich" streaks caused by draindown. (Source: D. Watson)

GDOT requires a polymer modified PG 76-22 be used in SMA production. Hydrated lime is used as an anti-strip agent at a dosage rate of 1 percent by aggregate weight, and a stabilizing fiber is required to prevent binder draindown. Draindown occurs when the intermediate or "sand" fraction is removed from the mix. This "gap grading," inherent to SMA mixtures, increases the binder coating on the larger aggregate particles. Unfortunately, during production and paving while the binder is at an elevated temperature, there are no intermediate particles to prevent the binder from "draining" out of the mixture without a stabilizer. Draindown segregates the asphalt binder and forms puddles in the bottom of the truck bed. These puddles will render asphalt release agents ineffective causing mix to stick to the truck bed resulting in "rich" streaks in the finished mat (Figure 3).

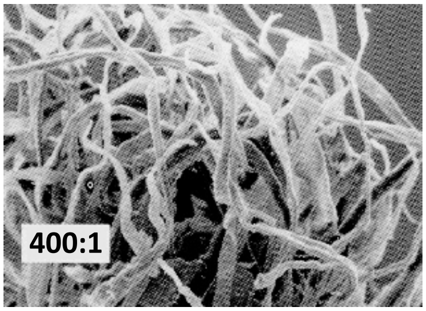

Figure 4: Magnified view of fiber stabilizer. (Source: FHWA)

The fiber (Figure 4) reinforces the binder film to hold it in place. Cellulose fiber is the only type on the GDOT qualified products list (QPL, QP# 77), although GDOT specifications allow either cellulose or mineral fiber. Cellulose is added at a dosage rate between 0.2-0.4 percent and mineral fiber is added at 0.3-0.6 percent based on total mix weight.

GDOT requires cellulose fiber have an ash content based on ASTM D 128 of 23 percent maximum non-volatile content, a pH of 7-12, and a moisture content of no more than 5 percent. Fiber may be added loose or in pellet form. Pellets should have an average diameter no more than 6 mm. If the pellet binder ingredient exceeds 3 percent, GDOT bases the dosage rate on the net fiber content. GDOT does not allow pellets if the binder ingredient exceeds 20 percent of the total pellet weight or if they soften and clump together when stored at temperatures up to 122 degrees Fahrenheit. According to GDOT test procedure 130, mineral fiber should not exceed 25 percent shot content when tested using wet elutriation. More specific requirements for fiber stabilizers are suggested in National Cooperative Highway Research Program (NCHRP) Report 425.

Gradation

GDOT's SMA gradations are primarily based on research in NCHRP Report 425 (Brown and Cooley, 1999). Current gradation specifications (based on total weight of aggregate) are provided in Table 1. GDOT does not blend aggregates based on volume as described in AASHTO R 46.

Table 1: GDOT SMA Gradation Limits and Binder Content Ranges. (GDOT, 2021)

Sieve Size	Percent Passing, 19.0 mm	Percent Passing, 12.5 mm	Percent Passing, 9.5 mm
1 inch (25.0 mm)	100	--	--
¾ inch (19.0 mm)	90 - 100	100	100
½ inch (12.5 mm)	44 - 70	85 - 100	98 - 100
3/8 inch (9.5 mm)	25 - 60	50 - 75	70 - 100
No. 4 (4.75 mm)	20 - 28	20 - 28	28 - 50
No. 8 (2.36 mm)	15 - 22	16 - 24	15 - 30
No. 50 (0.30 mm)	10 - 20	10 - 20	10 - 17
No. 200 (0.075 mm)	8 - 12	8 - 12	8 - 13
Asphalt Content Range, Percent	5.5 - 7.5	5.8 - 7.5	6.0 - 7.5

Controlling SMA gradation is critical since materials and testing variability may make a difference as to whether the mix maintains stone-on-stone contact of the coarse aggregate particles.

Asphalt Content

GDOT asphalt content range is based on nominal maximum aggregate size and was developed through in-house research prior to the first two test sections and experience gained since then. The range used by GDOT is shown in Table 1. This varies from AASHTO R 46, which specifies minimum asphalt content based on bulk specific gravity (G_{sb}) of the combined aggregate blend. G_{sb} for Georgia aggregates generally ranges from 2.58 - 2.78 so the minimum asphalt content would range between 5.9 to 6.4 percent. Absorption of Georgia aggregates is less than 1.0 percent.

Laboratory Compaction Method

GDOT uses the 50-blow Marshall procedure for laboratory compaction of SMA mixtures. While this is consistent with European design methods, many U.S. agencies have used the gyratory compaction since the introduction of the Superpave mix design technology in the 1990s. In the 1990s and 2000s, GDOT allowed either 50-blow Marshall or 50 gyrations with the Superpave gyratory compactor (SGC). In the late 2000s, GDOT conducted a research study to determine the SGC number of design gyrations that would provide equivalent density with the 50-blow Marshall procedure for Georgia materials. The study included five aggregate sources and three gyration levels and found the N_{design} gyration level, on average, should be 35 gyrations to achieve the same density as 50-blow Marshall (West, et al., 2007). This is much lower than the 100 gyrations suggested in AASHTO R 46 or the 75 gyrations suggested when the Los Angeles Abrasion Test loss is greater than 30 percent. When GDOT revised its specifications in 2013, either 50-blow Marshall or 35 gyrations with the SGC were allowed for compaction during laboratory mix design.

Based on these and other studies, GDOT determined that in many instances direct comparisons between the 50-blow Marshall density and the SGC density were frequently inconclusive. Consequently, GDOT suggests that agencies evaluate their own local materials to determine the appropriate SGC compaction level. Parameters such as aggregate locking point (where sample height remains the same for successive gyrations), and slope of the densification curve have been proposed to make that determination (Polaczyk et al. 2018).

Watson and Julian (2017) considered the rate of change in density and the locking point for determining N_{design} compaction levels with the SGC on Georgia SMA mixtures. As an example, the change in percent G_{mm} for the Buford quarry materials (Figure 5), shows 0.0 percent change in density began to occur at 58 gyrations. The aggregate structure began to lock up so that the density changed no more than 0.1 percent of G_{mm} at approximately 37 gyrations. Aggregate locking point 1 (LP1), the gyration level which has the first occurrence of the height remaining the same for two successive gyrations, occurred at 61 gyrations. LP2, the second occurrence of the height remaining the same for two successive gyrations occurred at 67 gyrations. This closely matches the N_{design} level of 65 gyrations that GDOT uses for all Superpave mix designs. The number of gyrations to reach 96 percent G_{mm} was 63 gyrations, which also corresponded closely with the aggregate locking point. The study concluded the N_{design} level of 65 gyrations used for Superpave mixes may also be used for SMA mixes.

A review of two other State specifications shows Alabama allows 50-blow Marshall or 60 gyrations with the SGC. Texas generally designs at 50 gyrations but allows a reduction as low as 35 gyrations at the contractor’s discretion.

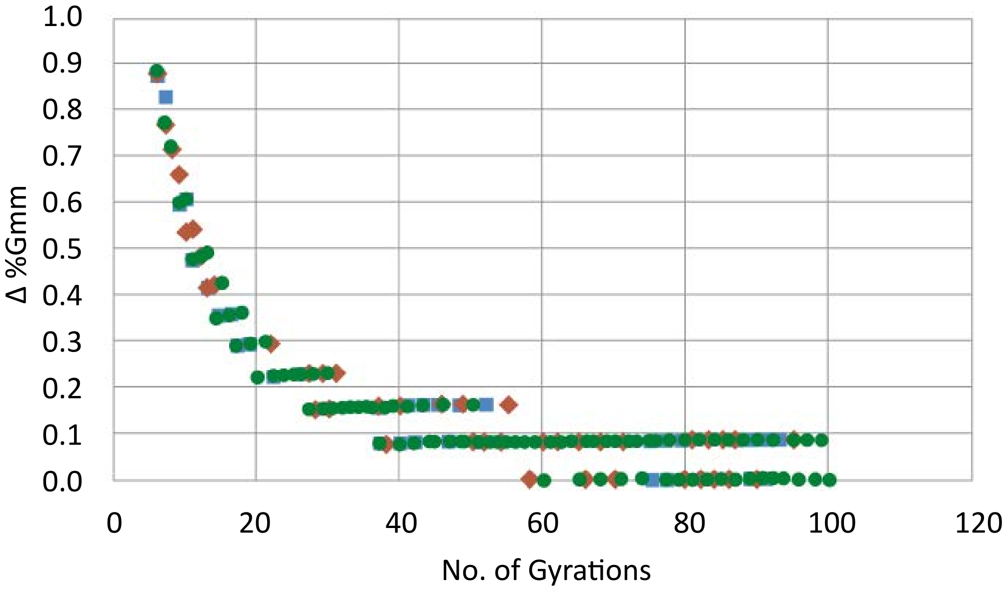

Figure 5: Change in percent G_{mm} based on number of gyrations. (Source: Watson and Julian, 2017)

Mix Design Procedure

The SMA mix design procedure is described in GDT-123, *Determining the Design Proportions of Stone Matrix Asphalt Mixes* (GDOT, 2019). GDT-123 and GDOT require three trial blends with varying gradations. Then the aggregate structure is evaluated using characteristics related to the dry-rodded unit weight of the aggregate blend. This process ensures the final blend will have stone-on-stone contact of coarse aggregate particles to maximize rutting resistance. Once a blend is determined, the mix design is evaluated at varying binder contents. An optimum binder content is determined based on the criteria shown in Table 2.

Table 2: SMA Volumetric Properties.

Mix Property	Criteria
Design Air Voids	3.5 ± 0.5%
Minimum VMA	17.0%
VFA Range	70-90%

Once the optimum binder content is selected, additional tests are performed for moisture susceptibility, permeability, draindown, and rutting resistance. In accordance to GDOT's requirements, rut depth cannot exceed 12.5 mm and the stripping inflection point must be greater than 20,000 passes. If visible signs of stripping are evident, GDOT may require further moisture susceptibility testing.

The moisture susceptibility test used by GDOT is like AASHTO T 283 with three main differences. Samples are prepared at 6 plus or minus 1 percent air voids; a 30-minute vacuum saturation period is used; and a much slower loading rate of 0.065 inches (1.65 mm) per minute is also used. An average tensile strength ratio (TSR) of conditioned specimen strength to unconditioned specimen strength is determined. A ratio of 0.80 is required by GDOT with the exception that if all individual specimens have a tensile strength exceeding 100 psi (690 kPa), a TSR ratio greater than or equal to 0.70 is permitted. GDOT requires that average tensile strengths of both control and conditioned samples must be greater than or equal to 60 psi (415 kPa).

Permeability testing is conducted on laboratory prepared samples during the mix design process. Specimens are compacted to 6.0 plus or minus 1.0 percent air voids and tested according to GDT 1. GDOT requires that results must not exceed 3.6 feet/day (125 x 10-5 cm/sec).

Draindown testing is conducted according to AASHTO T 305. GDOT requires that results must be less than 0.3 percent.

CONSTRUCTION

A batch plant was used on the I-85 project. Modifications were made to include a holding pod for the mineral filler that was mounted on the side of the plant to allow gravity to feed into the weigh hopper. An opening was cut in the rear of the weigh hopper so pre-bagged mineral fiber could be added to each batch. At the time, polymer-modified binders were not readily available at terminals, so a special blending trailer with a shear mill and holding tanks was brought on-site. A high-density polyethylene was sheared into the asphalt binder. The mixture production temperature was 325 degrees Fahrenheit, and the mixing time was set to 15 seconds for the dry cycle (to ensure sufficient time for dispersion of fibers) and 45 seconds for the wet mix cycle. Mix was produced in three-ton batches and discharged directly into the haul trucks (Jared, 1997-A).

GDOT requires a rubber-tire roller in the compaction train when placing conventional mixes. However, on the first SMA test section, it was discovered that the matrix of polymer-modified binder and mineral filler would readily stick to the rubber tires, so this roller was eliminated from the compaction process on SMA mixtures. It is not suggested by GDOT for all mixtures that include a polymer-modified binder. The SMA mix was initially compacted with a vibratory steel wheel roller and finish rolling was with an 8-12 ton static steel wheel roller. The average in-place air voids were 6.7 percent for the 12.5 mm SMA surface mix and 5 percent for the 19 mm intermediate layer. Some agencies have been reluctant to vibrate SMA mixes because of concerns aggregate particles will break down. However, GDOT has used a vibratory roller successfully in the breakdown position for all SMA placement.

For production of the I-75 test section in Henry County, GDOT used a double-barrel drum plant. Plant modifications were made to add cellulose fibers, mineral filler, and modified asphalt. A separate cellulose fiber feed system allowed fibers to be added in large bales. The bales were broken down into individual fibers within a dispersion chamber in the machine. The dispersion chamber was mounted on load cells and had a rate controller (Figure 6) connected to the plant controls to ensure that the feed rate of the fibers was proportional to plant production. Mineral filler was stored in a silo and augured into the mix at a rate proportional to plant production. The fiber, mineral filler, and hydrated lime anti-strip agent (required in Georgia) were added to the outer drum at the same location as the returned baghouse dust (Figure 7). Polymer-modified binder was supplied from a terminal and was pumped directly from the tanker transport.

Figure 6: Rate controller for accurately proportioning fiber. (Source: Krendl Machine Co.)

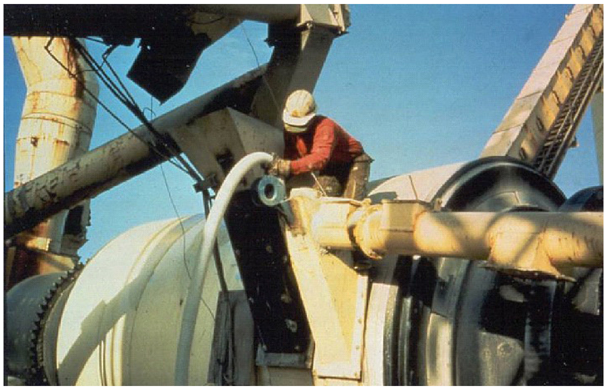

Figure 7: Fiber injection point in a double-barrel asphalt plant. (Source: Krendl Machine Co)

GDOT requires a material transfer vehicle (MTV) be used in the paving operation for State route and interstate projects when the two-way ADT is at least 6,000, the project is at least 3,000 linear feet, and total tonnage is greater than 2,000 tons. The MTV helps maintain a continuous paving operation so there is no need for the paver to stop. It also remixes material to a homogeneous mixture and consistent temperature to aid in the placement and compaction process.

The compaction process and equipment used is the same as for any conventional mix that uses polymer modified binder. Rollers should be kept close to the paver so compaction can be achieved while the mix is hot.

GDOT applies SMA in layer thicknesses shown in Table 3. The 9.5mm and 19 mm mixes are seldom used. The 19 mm SMA has been used in 2-inch layers as an intermediate course placed directly on jointed PCC pavement. A 12.5 mm SMA is the primary dense-graded surface mix and is generally placed in a 2-inch layer when OGFC is placed as the final wearing course; otherwise, it is placed in a 1.5-inch layer.

Table 3: GDOT SMA Layer Thickness.

Mix Type	Minimum Layer Thickness	Maximum Layer Thickness	Maximum Total Thickness
9.5 mm	1 1/8 in. (29 mm)	1 1/2 in. (38mm)	4 in. (100 mm)
12.5 mm	1 3/8 in. (35mm)	3 in. (75 mm)	6 in. (150 mm)
19.0 mm	1 3/4 in. (44mm)	3 in. (75 mm)	—

GDOT Lessons Learned

GDOT lessons learned include the feed of materials into the plant. Coarse aggregate accounts for about 70 to 80 percent of the total aggregate and according to GDOT, separating it into two bins may provide the contractor better control of the gradation. If SMA aggregate is required to have different quality standards than aggregate for conventional mix, GDOT recommends that it be stockpiled separately, and the stockpile be clearly marked to avoid having truck drivers or loader operators delivering material to or from the wrong pile and contaminating the stockpiled materials.

According to GDOT, mineral filler should not be fed through a cold feed bin. Keep the mineral filler dry and avoid wind exposure. For a batch plant, mineral filler fed through cold feed bins will tend to accumulate on the side of the hot bin walls due to static electricity and will release in surges. According to GDOT, it is best to feed mineral filler through a silo directly into batch plant aggregate weigh hoppers and just prior to the addition of asphalt binder in drum plants. Fly ash has typically been used for mineral filler. However, due to supply shortages, a marble dust product has been approved by GDOT as well.

If the paver or asphalt plant must stop for any reason, GDOT recommends the conveyors are stopped as well. Slat conveyors that transfer mix from the drum discharge to the silo, MTV conveyors that transfer mix to the paver, and paver slat conveyors and augers will sling off any build-up of binder-filler mortar and will result in “rich” spots just as those caused by draindown. If a paver stops and this results in cold mixture, irregular texture may be evident. Figure 8 shows a transverse “rich” spot on the roadway caused by a paver stop where material dripped from augers and conveyors.

Figure 8: Transverse “rich” spot caused by a paver stop. (Source: D. Watson)

GDOT recommends that truck beds be sprayed with an approved asphalt release agent (not diesel or fuel products) to prevent the mix from sticking to the bottom of the bed. Some release agents perform better than others, so a contractor may need to experiment to find the agent that works best for the material being produced.

PERFORMANCE AND EVALUATIONS

On the first SMA test section constructed in 1991, the improved rutting resistance of SMA compared to conventional dense-graded mix was evident. Within four years, the conventional mix had rutted more than twice the amount of rutting on the SMA sections as shown in Table 4.

Table 4: Rutting in SMA Surface versus Conventional Mix Surface on I-85.

Year	SMA (mm)	Conventional (mm)
1993	0	3
1994	2.3	5.3
1995	2.5	6.8

Friction numbers were monitored for 5 years because there was some initial concern the SMA thick binder film may cause safety issues (Jared, 1997-A). GDOT conducted friction tests according to ASTM E274 using a locked-wheel skid trailer with ribbed tires. Although values were lower immediately after construction, the thick film on the surface quickly wore off and friction values increased (Table 5).

Table 5: Friction Values for SMA Surface on I-85.

Date	Friction Number
11/1991	45
2/1992	50
7/1992	51
4/1993	52
6/1994	52
1/1996	52

One of the first full-scale SMA projects constructed in 1994 on I-95 in Chatham County near Georgia’s coastline is an example of SMA durability. The project had approximately 72,000 vehicles per day, 28.5 percent was truck traffic. The OGFC surface, typically placed on interstate routes, was removed and replaced after 15 years, but the SMA layer underneath is still performing well after more than 25 years of service.

Average bid price for 12.5 mm SMA mixtures over the past 3 years is $107.85 per ton, while a comparable 12.5 mm polymer modified Superpave mix average price is 28 percent less at $84.13 per ton. SMA is primarily used on heavily trafficked routes that often require nighttime paving with restrictive working hours, which is part of the reason for the higher costs. However, in general, researchers have determined the higher initial costs for SMA are offset by an increase in service life that reduces costs associated with maintenance and future rehabilitation (Al-Qadi, 2021).

In addition to performance benefits, SMA mixtures also show improved visibility due to reduced splash and spray, increased friction resistance, and improved noise reduction (Yin and West, 2018). SMA’s long-term performance and environmental benefits may contribute to sustainable asphalt pavements.

After several years of research, early project performance evaluation, and review of European experiences, GDOT found that SMA mixtures are more rut resistant with longer fatigue lives and longer service lives than conventional dense-graded mixtures.

Georgia has placed 4.4 million tons of SMA on 133 projects since its first test section in 1991.

At least 40 State DOTs have used SMA, and it is routinely used in 18 States (Aschenbrener, 2021).

CONCLUSIONS

GDOT research has led to enhanced use of local materials, reduced mixture costs, and the following conclusions:

- When considering SMA implementation, solicit input from other experienced paving professionals.
- Quarry producers, paving contractors, and agency construction personnel should be kept informed of what to expect and providing trouble-shooting tips for problems that might develop.
- Original aggregate quality requirements from Europe that are included in AASHTO M 325 can be relaxed for granite aggregate sources without adverse impact on performance.
- Agencies should conduct SMA research with locally available materials to determine the appropriate N_{design} gyration level. Use a locking point where the gyrated sample height remains the same for two consecutive gyrations. The value is selected for N_{design}.
- Vibratory rollers may be successfully used to compact SMA, but rubber-tired rollers are not advised.
- Some of GDOT's SMA mixes are still performing well after more than 25 years of service.
- SMA can be used for interstates and projects with high-traffic volume (greater than or equal to 50,000 ADT) or heavy-vehicle loading.

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