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STONE MASTIC ASPHALT IN COLORADO

Donna Harmelink, P.E. CDOT Research

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16. Abstract
This report documents the construction and performance of CDOT's first two SMA projects. The first project, located on SH 119 from SH 52 to Longmont, contained three SMA mixes, two polymer- stabilized mixes and one fiber mix. This project successfully demonstrated the design, production and placement of SMA.

The second project located on the Colfax Viaduct in Denver was CDOT's first attempt to use SMA on a bridge deck. This project used a polymer-stabilized mix. This project successfully demonstrated the placement of SMA on a bridge deck.

Implementatioc
SMA is currently being used as a wearing surface in Colorado. Guidelines and a best practice guide have been developed and have been adopted for
statewide use. In addition, CDOT's Bridge Branch has developed a specification for using SMA as part of the overlay system.

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by

Donna Harmelink

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Colorado Department of Transportation
Research Branch
4201 E. Arkansas Ave.
Denver, CO 80222
(303) 757-9506

EXECUTIVE SUMMARY

Stone mastic asphalt (SMA) is a hot mix asphalt consisting of two parts, a coarse aggregate skeleton and a binder rich mortar. It is made up of a mixture of crushed coarse and fine aggregates, mineral filler, asphalt cement, and a stabilizer for the binder such as polymer or fibers. The philosophy of SMA is that the coarse aggregate skeleton will provide a stone on stone contact (the stone portion) to prevent rutting and provide skid resistance and that the mix will be held together with sufficient specialized mortar (the mastic portion) to prevent draindown of the binder and provide the mix with durability.

This report documents the Colorado Department of Transportation's (CDOT) first two SMA pavements. The first project is located in Boulder County on State Highway 119 and is documented in Section 2 of this report. The second project is located in Denver on Colfax Viaduct. This project was the first project placed on a bridge deck. This project is detailed in Section 3 of this report.

The SMA project on State Highway 119 successfully demonstrated design, production and placement of the SMA. The Colfax Viaduct project was Colorado's second SMA project but their first attempt to use it on a bridge deck. The Colfax Viaduct project was different than the project placed on SH 119 in that it was constructed on a bridge deck requiring a different paving technique. This project successfully demonstrated the placement of the SMA on a bridge deck. Since these projects were placed, five additional projects have been placed through June 2000.

CDOT will continue to use SMA as a wearing surface. CDOT's SMA specification can be found in Appendix C. Guidelines and a best practice guide were also developed and can be found in Appendix G.

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1.0 BACKGROUND

In 1990, a team of pavement specialists from the United States took part in a tour of six European nations. The team included representation from the American Association of State Highway and Transportation Officials (AASHTO), the Federal Highway Administration (FHWA), the National Asphalt Pavement Association (NAPA), the Strategic Highway Research Program (SHRP), the Asphalt Institute and the Transportation Research Board (TRB).[1] One of the European technologies that the team felt had potential in the United States was a surface mix, stone mastic asphalt (SMA). SMA is a technology that has been used in Europe since the 1960's.[2] It was not until after this European Asphalt Study Tour that this technology was introduced in the United States. This technology showed promise as a tough, stable, rut-resistant surface mixture.

Stone mastic asphalt is hot mix asphalt consisting of two parts, a coarse aggregate skeleton and a binder rich mortar. It is made up of mixture of crushed coarse and fine aggregates, mineral filler, asphalt cement, and a stabilizer for the binder such as polymer or fibers. The philosophy of SMA is that the coarse aggregate skeleton will provide a stone on stone contact (the stone portion) to prevent rutting and provide skid resistance and that the mix will be held together with sufficient specialized mortar (the mastic portion) to prevent draindown of the binder and provide the mix with durability.

In 1992, the Colorado Department of Transportation (CDOT) and the asphalt contracting industry created oversight groups to study problems that faced the asphalt industry. The groups consisted of CDOT, FHWA, contractor and consulting firm personnel. One of the committees of this group was the New Materials and Technology Oversight Group. This committee focused on SMA, developed a specification, prepared a research proposal, and identified a project to place the SMA.

Since SMA was a new technology to Colorado many contractors did not have a high level of comfort with this new technology. The first time the initial SMA project, located on US-85 near Ault, was advertised the low bid exceeded the engineer's estimate by 28%. This project was readvertised without SMA.

In 1994, an SMA trial mixture was placed in plans for a project located on SH119 near Niwot. Again the bids were significantly over the engineer's estimate. Adjustments were made to the plans and project budget, and the project was readvertised. In May 1994, the 2.45 million-dollar contract was awarded with SMA.

This project was constructed in August and September 1994. Following construction a report titled "Demonstration of the Placement of Stone Matrix Asphalt in Colorado" No. CDOT-DTD-R-95-1 was published.[3] Report No. CDOT-DTD-R-95-1 documented the process used to construct the trial mixture, including the mix designs, field construction, and field verification.

Since 1994, CDOT has constructed six other SMA projects. This report documents the performance of the first two SMA projects constructed in Colorado. The first project, Project No. NH 1191-005 is located in Boulder County on State Highway 119 and is documented in Section 2. The second project, Project No. C0404-030 is located in Denver on Colfax Viaduct. This project was the first SMA mix placed on a bridge deck. Report No. CDOT-DTD-R-96-7 "SMA (Stone Matrix Asphalt) Colfax Avenue Viaduct" documents the design and construction of this SMA project.[4] In this report this project is detailed in Section 3.0.

2.0 SMA - LONGMONT, STATE HIGHWAY 119

Project No. NH 1191-005 located in Boulder County on State Highway 119 (Figure 1). The project extends approximately 5 miles between State Highway 52 on the southwest end to Hover Road in Longmont on the northeast end. The 1993 ADT was 23,500. The 1999 ADT was 26,300. The 10-year design (2003) ADT was 442,000 with 3% trucks. The designed traffic loading for 10 years was 807,000 18-kips ESALs.

2.1 Project Development

2.1.2 Evaluation Sections On this project 5 mix designs were incorporated for evaluation purposes. A description of the different additives that were used can be found in Section 2.2.3. Below are the 5 mix designs that were used on this project.

1. Standard dense graded HBP (Grading C).*
2. Stone Mastic Asphalt (SMA) with Vestoplast S, and AC-20
3. SMA with polymer modified asphalt PM-1D, 150 softening point, (AASHTO Task Force 31, Type 1D polymer)[5] PM-1D had a high polymer content, which was a special blend for SMA. The PM-1D tested to the current performance grade 76-28.
4. SMA with cellulose fiber pellets, and AC-20
5. Grading C with AC-20R (AASHTO Task Force 31, Type II-B polymer)[5]. AC-20R tested to the current performance grade 64-22.

* CDOT's specification for Grading C can be found in Appendix A

Nine evaluation sections were established on this project. The evaluation sections are as follows:

<u>Northbound Lanes</u>		
Section 1	Grading C	one 2" (50 mm) lift
Section 2	SMA with Vestoplast S	one 2" (50 mm) lift
Section 3	SMA with PM-1D	one 2" (50 mm) lift
Section 4	SMA with PM-1D	Bottom 2" (50 mm) lift (Grading C) Top 2" (50 mm) Sma with PM-1D
Section 5	SMA with Fiber Pellets	Bottom 2" (50 mm) lift (Grading C) Top 2" (50 mm) SMA with Fiber Pellets
Section 6	Grading C	Bottom 2" (50 mm) lift (Grading C) Top 2" (50 mm) Grading C with AC-20R
<u>Southbound Lanes</u>		
Section 7	Grading C	Bottom 2-1/2" (64 mm) lift (Grading C) Top 2" (50 mm) lift Grading C with AC20R
Section 8	SMA with PM-1D	Bottom 2-1/2" (64 mm) lift (Grading C) Top 2" (50 mm) lift SMA with PM-1D

Section 9	SMA with Vestoplast S	Bottom 2-1/2" (64 mm) lift (Grading C) Top 2" lift SMA with Vestoplast

Each of the evaluation sections was approximately 1000 feet in length. A location map of the evaluation sections is shown in Figure 2.

2.1.3 Existing Distress A preconstruction evaluation was performed on the project to note the existing distresses on the pavement. This evaluation included measuring the ruts and documenting the cracking.

Rut depths were measured every 15 meters (50 feet) throughout the evaluation sections in both the right and left wheel paths of lane 2 (first lane on right side). The ruts were measured with a two-meter (six foot) straight edge and were measured to the nearest 2 mm (0.1 in). Rutting in the evaluation sections was fairly low. The average of the sections ranged from 15 mm (0.06 in) in the northbound Grading C section (section 1) to approximately 3 mm (0.1 in) in the southbound Vestoplast S section (section 9). The magnitude of the majority of the rut measured approximately 8 mm (0.3 in). In accordance with CDOT's standard this measurement is considered low.

Crack maps, depicting longitudinal, transverse, alligator and block cracking, were prepared for each of the evaluation sections. Cracking in the sections was fairly uniform. On the average, transverse cracks could be found every 5 m (15 ft) throughout the sections. Load associated longitudinal cracking was found in the wheel paths of the driving lane. In some areas the longitudinal cracking had deteriorated into block cracking or alligator cracking. The cracks were wide (up to 25 mm, 1 inch) and many had begun to deteriorate on the edges. Although the pavement in the southbound lanes on the north end of the project had been covered by a thin maintenance blade patch, the severity and amount of distress in all the evaluation sections prior to construction were considered to be equal for evaluation purposes. Typical distress found in the existing pavement is shown in Figures 3 and 4.

2.1.4 Bids Prior to the advertisement of this project a pre-bid conference was held. All the contractors that planned on bidding on this project were required to attend. In Table A, the CDOT's estimate and the contractor's bid (one that was awarded the project) for each of the different designs is shown.

Table A. Estimated and bid costs of the SMA and HMA.

	Engineer's Estimate	Contractor's Bid	Difference (%)
SMA Vestoplast S	$47.00	$54.00	+15
SMA Fiber Pellets	$43.00	$59.00	+37
SMA PM-1D	$47.00	$63.00	+34
Grading C	$28.00	$24.50	-13
Grading C (AC-20R)	$33.00	$30.00	-9

The item for each ton of HMA included the asphalt cement, the modifier, haul and placement. All the estimates on the contractor's SMA designs exceeded the engineer's estimate.

2.1.5 CDOT's Preparation Several steps were taken in preparation for CDOT's first SMA. Several CDOT and contractor's personnel had the opportunity to attend a one-day technical session and demonstration of an SMA project in Amarillo, Texas. This demonstration provided CDOT and the contractor an insight into what to expect during construction.

A partnering workshop was held prior to construction. This workshop helped to point out the conflicts that could arise during construction and offered methods to resolve them.

In addition, during construction of this project a demonstration workshop to view the production and placement of the SMA pavement was held. Included in the demonstration was a four-hour seminar. The seminar covered the FHWA, state and contractor/industry perspective. In addition the perspective of suppliers of the specialty items was addressed. The variety of presentations provided a wide range of perspectives. Following the technical session participants were transported to the plant and construction site. Project and construction personnel were on hand to answer questions during the tour. In addition the participants were able to view placement of SMA.

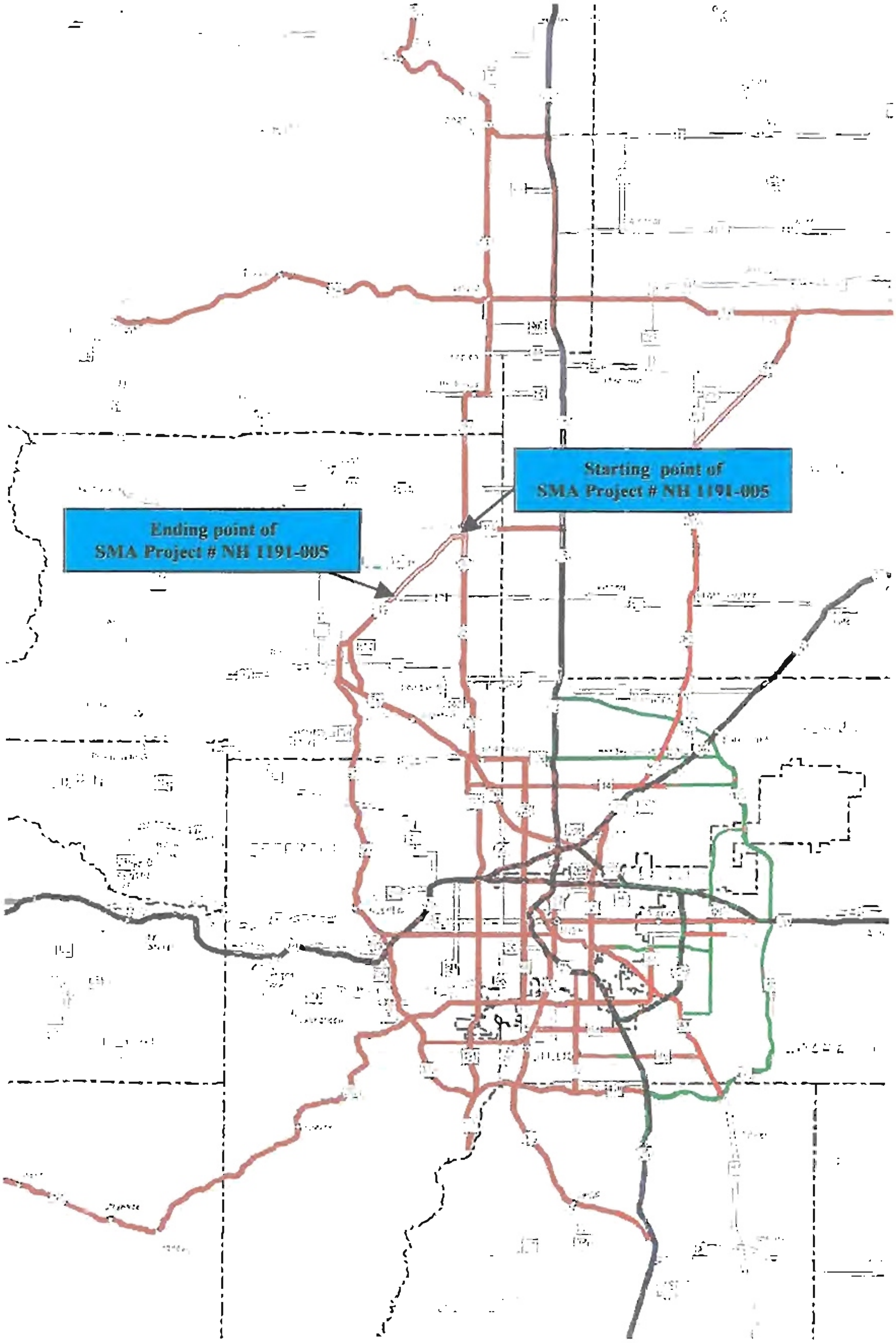


Figure 1. Location map of Project No. NH 1191-005

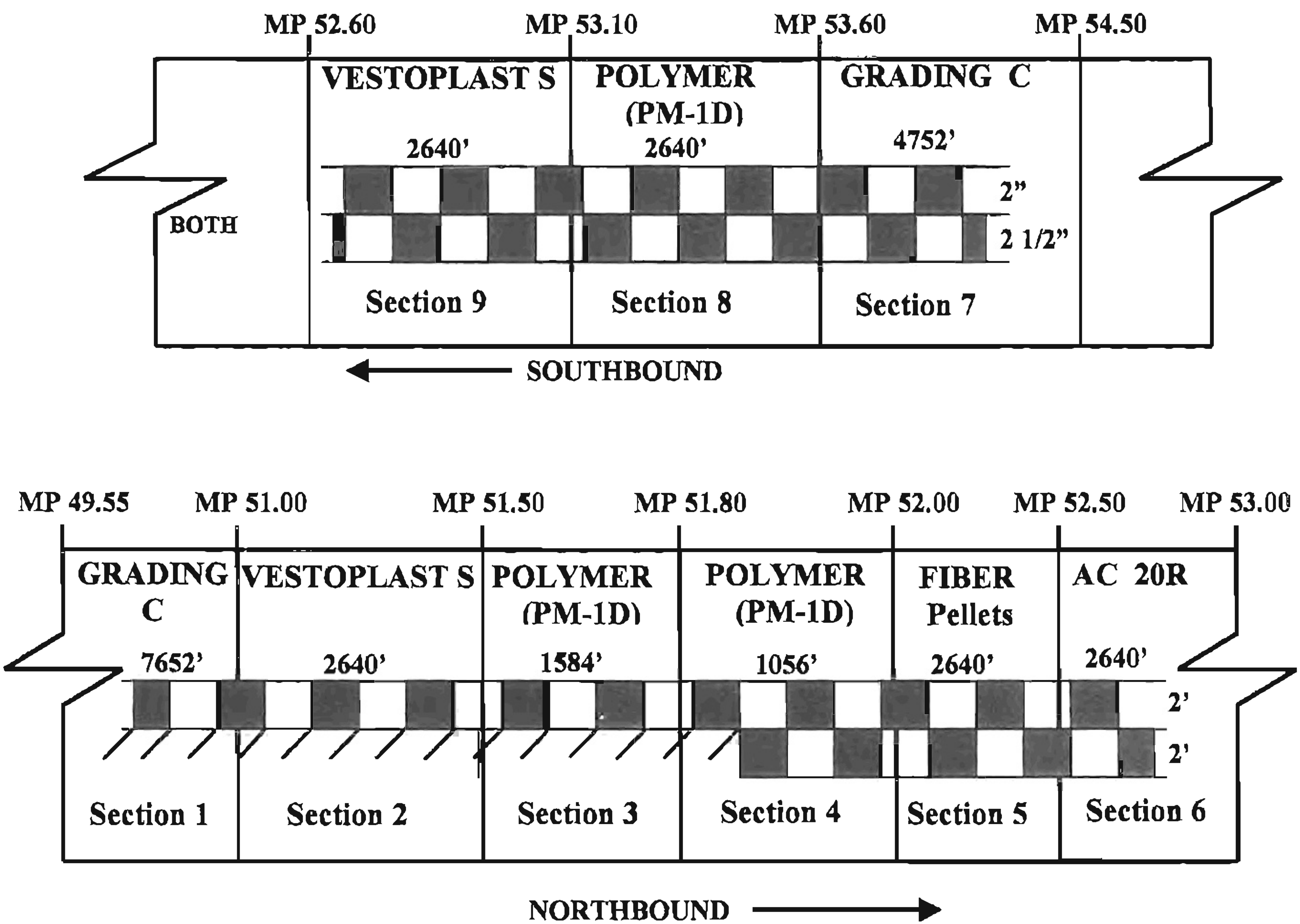


Figure 2. Location map of the evaluation sections.

Figure 3. Overview of existing pavement.

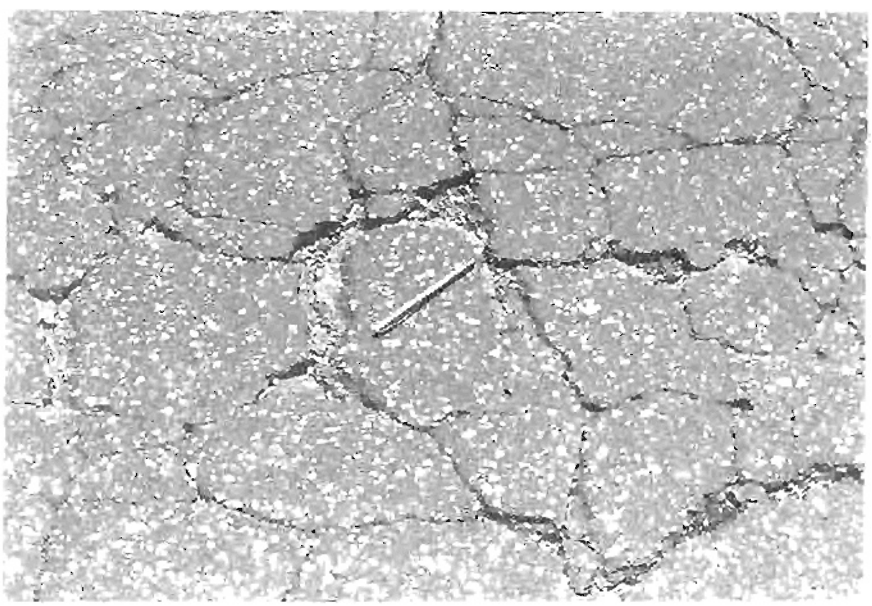


Figure 4. Close-up of existing pavement.

2.2 Mixture Design and Testing

2.2.1 SMA Mix Design The specifications used on this project are shown in Appendix B. The specifications that are currently in place in Colorado for SMA can be found in Appendix C.

2.2.2 SMA Composite Gradation All the aggregates used were granite and came from the Cooley Morrison Quarry. The stockpiles used for the SMA included a 19-mm (3/4 in) rock, a 12.5-mm (1/2 in) rock, a granite sand, and a washed granite sand.

There were two trial blends that were investigated. The blending percentage of the blend that was selected is shown in Table B. The SMA gradation is shown in Table C.

Table B. SMA blend percentages.

Stockpile	Blend
19.0-mm Rock	37%
12.5-mm Rock	34%
Granite Sand	13%
Washed Granite Sand	10%
Limestone Dust	5%
Hydrated Lime	1%

Table C. SMA composite gradation.

Sieve Size	Blend Selected	CDOT Specification	FHWA Recommendation
19.0-mm (3/4)"	100	100	100
12.5-mm (1/2")	84	82-88	85-95
9.5-mm (3/8")	61		75 max
4.75-mm (No. 4)	27	28-32	20-28
2.36-mm (No. 8)	17	18-22	16-24
600 μm (No. 30)	12		
300 μm (No. 50)	11		
75 μm (No. 200)	7.4	9-11	8-10

Although the gradation was slightly outside of the Master Range on the 4.75-mm, 2.36-mm, and 75 μm sieve sizes it was considered acceptable for the following reason. The Master Range specification was recommended based on FHWA's 1992 recommendation. By 1996, FHWA had modified their recommendations based on experience of many projects throughout the country. The gradation was within the new FHWA recommendation.

2.2.3 SMA Mixtures Three SMA mixtures were used on this project, each containing a different additive. The purpose of the additive was to stiffen the asphalt cement to prevent rundown. Part of the research evaluation was to determine the performance of the different additives. The additives that were used were:

<u>Fiber Pellets</u>
Fiber pellets manufactured by Arbocel using cellulose fibers were used in one of the SMA mixtures. The fiber pellets consisting of 66% fibers and 34% asphalt cement and were added through the RAP collar. The fiber pellets were added at a rate of approximately 0.5% by weight of the total mix.

<u>Vestoplast S</u>
Vestoplast S is a polyolefin manufactured by Huls of America. Vestoplast S was added through the RAP collar. It coats the aggregate before the asphalt cement is added. The Vestoplast S was added at a rate of 7% by weight of asphalt cement.

<u>Polymer Modified Asphalt Cement</u>
The polymer modified asphalt cement was supplied directly to the project site from an independent polymer modifying company (Koch Materials Co.). The polymerized asphalt cement was delivered to the mixing plant and placed directly in the asphalt storage tanks used at the plant. The polymer was an SB block copolymer and was added at a rate of 4.5% by weight of asphalt cement. The polymer met the AASHTO Task Force 31, Type 1-D specification. It will be referred to in the remainder of the report as PM-1D. A different base asphalt was used for the PM-10 binder.

The asphalt cement (AC-20) conformed to Table 2 of AASHTO M226. The base asphalt cement and the asphalt cement and additive blends were tested with the standard binder equipment and SHRP dynamic shear rheometer (DSR). The test results indicate that the Vestoplast S and PM-1D increased the high temperature stiffness by one grade. The fibers increased the asphalt cement stiffness by two grades. However, it is not certain the fibers and asphalt cement were chemically bonded and the test results on the DSR with the fibers might not be a true representation of the performance grade. Testing on the AC-20R indicated that the high temperature grade was the same as the AC-20. A summary of the effects of binder modification or Superpave binder properties is found in Table D.

Table D. Asphalt cement test results.

Refinery	Grade	Viscosity Poise @ 60° C	Penetration dmm @ 25° C	DSR Temp. (°C) @ 2.2 kPa	SHRP PG (High Temp.)
Sinclair	AC-20	1800	67	66	64
Sinclair	AC-20 (fibers)	NT	NT	>82	76
Sinclair	AC-20 (VS)	NT	NT	71	70
Conoco	PM-1D	NT	72	73	70
Conoco	Ac-20R	2050	108	65	64

NT – Not tested
VS – Vestoplast S
PM-1D – Polymer modified, Type 1-D

2.2.4 Mixture Test The Marshall mix design was developed by CDOT and tested by the contractor. The Marshall mix design used 50 compaction blows on each side of the specimen. The tests for the mix used are found in Table E.

Table E. Marshall test results.

Property	Specification	Mix Design		
		Fiber	VS	PM-1D
VTM (%)	3-4	3.4	3.2	3.4
Asphalt Content (%)		6.2	6.0	6.0
VMA (%)	15.0 min	16.7	16.4	16.6
Stability, N (lb)	5300 min (1200)	8220 (1850)	9910 (2230)	11420 (2570)
Flow, 0.25 mm (0.01in)	10-18	18	16	18

VTM - Voids in the total mix (Air Voids)
VMA - Voids in the mineral aggregate
VS - Vestoplast S
PM-1D - Polymer modified, Type 1-D

2.2.5 Specification Comments The research results from this project were used to develop CDOT's current SMA specification. The minimum VMA specification of 15% that was used on this project was increased to 17% in the current specification. Although a Marshall mix design was used on this project, CDOT current specification now will allow either a Marshall (50 blow) or a Superpave (100 gyration) mix design. Since this project was designed CDOT adopted Superpave. Work was done to compare the Marshall design to CDOT's 100 mm Superpave design. The comparison can be found in section 4.1.2 of this report. A copy of CDOT's current SMA specification can be found in Appendix C.

2.2.6 Moisture Resistance Testing Moisture resistance testing was performed using AASHTO T 283. The freeze cycle was used. The test results are shown in Table F.

Table F. AASHTO T 283 test results.

Additive	TSR	Air Voids (%)	Saturation (%)
Fiber	0.59	6.3	59
Vestoplast S	0.70	6.3	68
PM-1D	0.81	6.8	59

The PM-1D had the best results and passed the minimum tensile strength ratio (TSR) specification of 0.80. The Vestoplast S did not pass, but was marginally unacceptable. The SMA with fiber pellets did very poorly.

Because the test results were marginally passing at best, concerns developed. However, it was felt SMA should be moisture resistant because it has a very high asphalt content and thick coatings of asphalt on the aggregates.

The Hamburg wheel-tracking device was used to test the SMA for moisture resistance. These tests were performed on material that was produced and sampled from the plant. The results from the Hamburg wheel-tracking device were much more favorable. A summary of the test results from the Hamburg wheel-tracking device is shown in Table G. The mm of deformation after 20,000 passes is shown.

Table G. Test Results (mm of deformation after 20,000 passes) from the Hamburg Wheel-Tracking Device.

Temperature (C°)	SMA PM-1D	SMA Vestoplast S	SMA Fiber	Grading C AC-20R	Specification
45	2.4	2.9	3.2	1.6	10 mm
50	3.5	10.9	8.2	4.6	10 mm
55	12.0	> 20 (12,000)	> 20 (12,000)	>20 (14,000)	10 mm

It should be noted that the specification for this project was a minimum of 10 mm of deformation at 20,000 passes for samples tested at the 50°C test temperature. All of the material tested from this project was considered acceptable, even though the Vestoplast S slightly failed the specification.

The current specification requires a performance-graded binder of 76-28. The test method that is required for moisture resistance is CPL 5109, method B. This is a Colorado procedure modified from AASHTO T-283-89. A copy of this procedure can be found in Appendix D.

2.2.7 Permanent Deformation Testing The French Rutting Tester was used to evaluate the resistance of the SMA to permanent deformation. A summary of the test results from the French rutting tester is shown in Table H. The percent rut depth after 30,000 cycles is shown.

Table H. Test results (% rut depth after 30,000 cycles) from the French Rutting Tester.

Temperature (C°)	SMA PM-1D	SMA Vestoplast S	SMA Fiber	Grading C AC-20R	Specification
60	4.3	3.6	4.2	3.4	< 10%

Test results indicated all of the SMAs would be rut resistant. The Grading C was also very rut resistant.

2.2.8 Low Temperature Cracking The thermal stress restrained specimen test (TSRST) was used to evaluate the resistance of the HMA to low temperature cracking. The fracture temperature and fracture strength of each of the mixtures tested are shown in Table I. The PM-1D sample did the best. It had the lowest fracture temperature and highest fracture strength of any of the others. Although the Vestoplast S improved the binder as much as the PM-ID based on the DSR results for high temperature, the Vestoplast S did not improve the low temperature thermal cracking performance. Additionally, the fiber stiffened the binder significantly at high temperatures based on the DSR results, but the fibers provided no improvement at low temperatures. Finally, the Grading C with AC-20R did surprisingly well.

Table I. TSRST test results.

	Fracture	
	Temperature (C°)	Strength (kPa)
SMA PM-1D	-33	4360
SMA VS	-23	3020
SMA Fiber	-20	2670
Grading C	-30	2340

VS –Vestoplast S
PM-1D –Polymer modified, Type 1-D

2.2.9 Draindown Test Two different draindown tests were performed on the mix used on this project. The National Center for Asphalt Technology (NCAT) developed a procedure that uses a wire basket.[6] Approximately 1200 grams of SMA are held at 153°C (307°F) for one hour. During this time, asphalt cement may drain off the SMA, through the wire basket, and onto a paper plate. The weight of a plate that supports the wire basket is measured before the test starts and after the 1 hour; and the difference is the asphalt draindown. The result is the draindown calculated as a percent of the total weight of the mix.

The Schellenberg procedure is virtually identical to the NCAT method with two exceptions; 1) glass beakers are used instead of the wire basket, and 2) the temperature is 170° C (338°F). The draindown is measured as the amount of asphalt that stays coated onto the glass beaker.

All the tests were performed at the optimum asphalt content. The test results are shown in Table J. The ranking of the different materials to stop draindown was the same for both tests. The fiber pellets did the best and the polymer (PM-1D) did the worst. It should be noted that no problems with draindown were observed with any of the additive stabilizers on the project.

Table J. Draindown test results.

Additive	NCAT	Schellenberg	Specification
Fiber	0.0%	0.0%	<0.3%
Vestoplast S	0.7%	0.2%	
PM-1D	2.8%	0.7%	

2.2.10 Mineral Filler Tests The mineral filler used for this project was a crushed gray limestone (CAL 200) dust that was purchased from Pete Lien Lime and shipped to the project from north of Ft. Collins. The limestone dust was tested for the properties recommended by the FHWA [6]: particle size (AASHTO T 88) and plasticity index (AASHTO T 90); and for the properties used in Europe: Rigden voids index[7] and methylene blue (ISSA Technical Bulletin No. 145). The test results are shown in Table K.

The particle size was measured from the hydrometer analysis (AASHTO T 88) and the results are shown in Table L. The filler was finer than recommended, but since it was not specified, the results are presented for research purposes. Additionally, the Rigden voids did not meet the minimum specification. It should be mentioned that these tests were on the mineral filler only, and the recommendation likely applies to the entire material passing the 75 μm (No. 200) sieve size.

Table K. Test results on the mineral filler.

Test	Result	Recommendation
Particle size smaller than 20μm	42%	< 20%
PI	Non-plastic	< 4%
Methylene blue	4.5 mg/g	< 10 mg/g
Rigden voids index	44.1%	< 40%

Table L. Hydrometer analysis (AASHTO T 88) results on the mineral filler.

Size (μm)	Percent Passing
75	83
20	42
2	2

2.3 Construction

2.3.1 Plant Description A CMI1700 parallel-flow, drum mixer with a production capacity of 275 tons per hour was used on this project. The SMA mixes required four cold feed bins with a retrofit for the addition of mineral filler (limestone). A silo to store the mineral filler was required. The silo used for the mineral filler had a 50-ton capacity. Lime was added with a weigh pod and vane feeder and mixed with damp aggregate in an approved pug mill. A baghouse was used for emission control. The storage silo for the HMA had a 110-ton capacity.

2.3.2 Plant Modifications for SMA The production of the SMA required several modifications to the plant to properly add the different additives.

A cement silo was set up with a metering device to add the mineral filler. The specifications required the mineral filler to be added at the same point as the asphalt cement. Both the mineral filler line and the asphalt cement line entered the rear of the mixing drum and were discharged into a mixing head. This allowed the asphalt cement to coat and capture the mineral filler, which helped to prevent blowing the mineral filler out of the drum and into the baghouse. Although mineral filler was found in the baghouse, extraction tests run on the produced mixes indicate the minus 75μm (No. 200) sieve size material was reasonably close to the job mix proportions specified.

The rate of production was nearly cut in half from the normally expected 275 ton per hour to 165 per hour. Whether or not production is decreased depends on how the plant is modified to add the mineral filler. The rate was cut nearly in half for this project because the mineral filler feed-line was not large enough.

The fiber pellets and Vestoplast S were each added at the RAP collar. The Vestoplast S was conveyed up through a 125 mm (5 in) fixed diameter auger. Due to the gummy consistency and caking of the Vestoplast S, the blades of the auger were sheared from the shaft. The auger that fed the Vestoplast S was then modified to be an open-trough auger with a plate on top. This auger was also unsuccessful. Finally, a shingle conveyor was used to transport the Vestoplast S sliding down the conveyor. This method worked well (except in high wind conditions) and was used for the remainder of the project. The fiber pellets were added only with the shingle conveyor. These plant operations are shown in Figures 5 and 6. It should be noted that no modifications to the plant were necessary to add the PM-1D.

2.3.3 Haul Trucks The HMA was delivered to the project with end-dumps and live-bottom trucks. The round-trip haul time was approximately 60 minutes. The haul trucks were required to have a full tarp cover. The PM-1D mixture was delivered to the project at 143°C to 154°C(290° F to 310° F); the Vestoplast S and fiber mixtures were delivered at 138°C to 143°C(280°F to 290°F).

2.3.4 Laydown Operation One Blaw-Knox 510 paver with a variable width screed and extended augers was used. Paving widths ranged from 3 to 5 m (10 to 16 ft). Three rollers were used to compact the SMA. Because SMAs perform differently during the compaction process, a roller pattern was difficult to establish. The final roller pattern that was established used two steel-wheeled rollers for breakdown (Caterpillar 534B) and one steel-wheeled roller for finishing (Hyster 766). The first roller used for breakdown was a 10-ton roller, which made one pass in the vibratory mode and one in the static mode. The next roller (10 ton) made two passes in the vibratory mode and two passes in the static mode. A 8-ton steel-wheeled roller operated in the static mode as the finish roller. A pneumatic roller was not used on the SMA pavement. It was critical that rollers were kept close to the laydown operation. Construction processes are shown in Figures 7, 8, 9 and 10.

2.3.5 Trial Placement The project plans required the contractor to place a test section prior to construction to evaluate the contractor's ability to both produce and place the SMA. To satisfy this requirement the contractor placed 550 tons of the polymer modified SMA (PM-1D) on the shoulder. During this placement, no problems were encountered.

Figure 5. Auger system initially used for Vestoplast S

Figure 6. Conveyor system used to add Vestoplast S and fiber pellets at the RAP collar.

Figure 7. Typical laydown operation

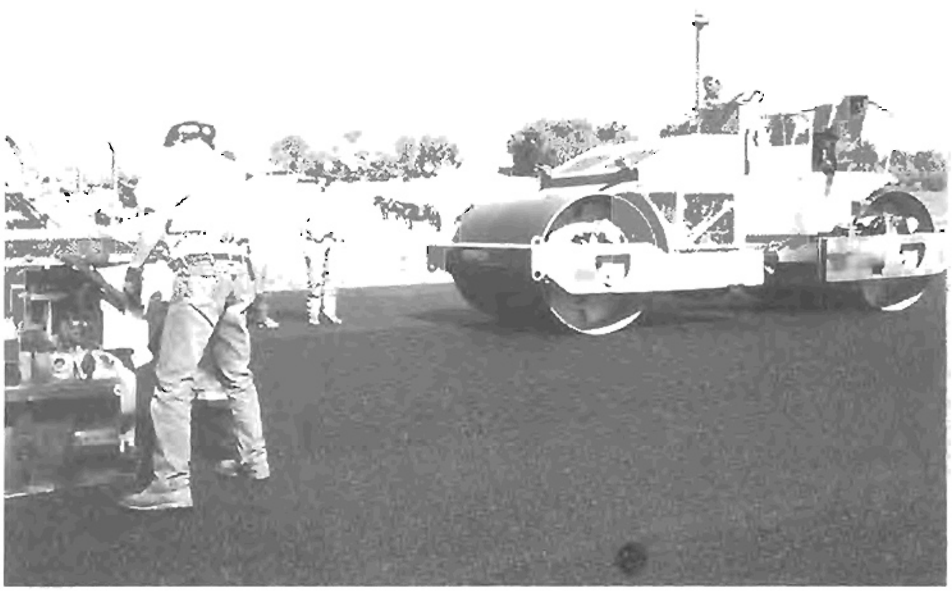


Figure 8. The breakdown roller was kept close to the laydown machine.

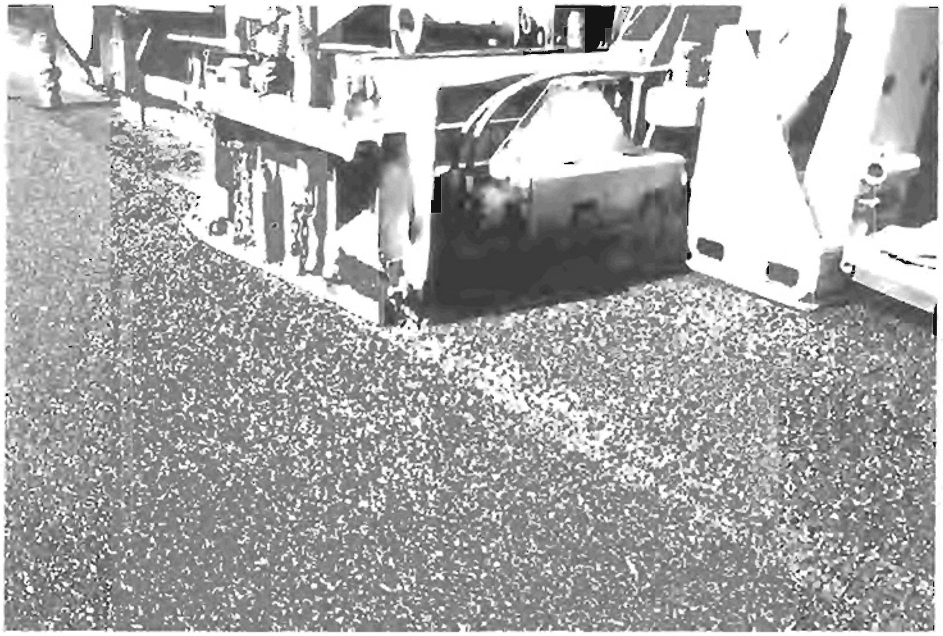


Figure 9. SMAs allow for neat line joints.

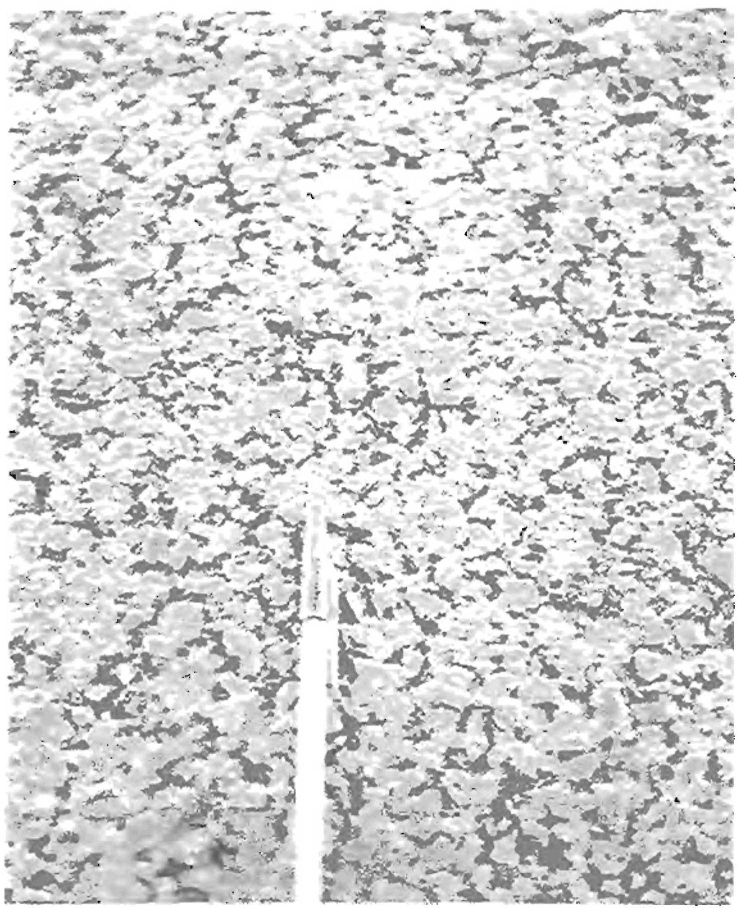


Figure 10. Surface texture of the finished mat.

2.4 Field Verification Test Results

2.4.1 Asphalt Content, Field Compaction and Gradation The SMA sections were placed with varying asphalt cement (AC) percentages. The AC percentages for the Vestoplast S sections ranged from 5.4 to 5.8%, the AC percentages in PM-1 D sections ranged from 5.8 to 6.0%, and the fiber section was placed with 6.0% AC. A summary of the percent AC and the location for all the SMA sections can be found in Appendix E. The Quality Level for the AC percentage of all the SMA mixes were all acceptable based on the limited data available. The results for the various SMA mixes at the designated AC percentage are summarized in Table M.

Table M. Asphalt content and field compaction test results.

Additive	Asphalt Content (%)				% of Maximum Density			
	Avg	S.D.	N	Q.L.	Avg	S.D.	n	Q.L.
Vestoplast S (5.5% AC)	5.4	.11	6	100	92.2	1.58	4	12
Vestoplast S (5.6% AC)	5.7	.08	6	100	92.9	1.14	5	18
Fibers (6.0% AC)	5.8	.22	3	66	94.0	2.26	3	28
PM-1D (6.0% AC)	6.0	.11	9	100	93.0	1.58	9	25

Avg – Average
S.D. – Standard deviation
N – number
Q.L. – Quality Level

Gradation test results are shown in Tables N and O. When compared to the specification gradation, the Quality Level of the materials is low. Although the gradations were not within specification limits, the percent passing for the 12.5 mm (1/2 inch), 4.75 mm (No. 4), 2.36 mm (No. 8), and 75 gm (No. 200) sieves were fairly uniform, and the volumetric properties of the mixes were considered acceptable.

Table N. Quality Level of gradation test results.

Additive	Gradations					
	Quality Level					N
	19.0 mm	12.5 mm	4.75 mm	2.36 mm	75 µm	
Vestoplast S (5.5% AC)	100	55.6	73.6	100	100	4
PM-1D (6.0% AC)	100	71.4	86.4	81.3	91.7	5

Table O. Gradation test results.

Additive	Gradation Specification				
	Sieve size (mm) (% Passing)				
	19.0 (100)	12.5 (82-88)	4.75 (28-32)	2.36 (18-22)	0.75 (9-11)
** Fibers (6.0% AC)	100	88	32	19	8.0
	100	87	32	20	8.3
** Vestoplast S (5.6% AC)	100	88	30	18	8.3
	100	82	30	19	8.4

** Because of the small quantity of this mixture, only two gradations were taken.
Quality Level calculations with less than three tests are not valid.

2.4.2 Volumetrics Four replicate samples were compacted by the contractor for field quality control. The volumetric test results are shown in Table P. The most interesting information is the field verification air voids. The SMA was designed between 3.0 and 4.0% air voids and the target was typically 3.5% air voids. As shown in Table P, the field verification air voids were between 2.0% and 3.0%. Approximately 0.5% to 1.5% air voids were lost during production. It should be noted that field adjustments were made to the SMA with Vestoplast S. The asphalt content was lowered from 5.8% to 5.5% and the air voids increased from 3.0% to 4.0% (Table P).

There was concern that the low field verification air voids could cause performance problems. So, the SMA was tested in the European torture tests (French Rutting Tester and Hamburg Wheel Tracking Device). Test results from the torture tests indicated the SMA was still rut resistant, even with such low field verification air voids. Asphalt content adjustments were not made because the shear strength parameters measured by the European torture tests indicated the SMA was sufficiently strong.

Table P. Volumetric test results of field produced SMA.

Additive	Air Voids (%)			VMA (%)			Marshall Stability			Marshall Flow		
	Avg	S.D.	n	Avg	S.D.	n	Avg	S.D.	n	Avg	S.D.	n
Fiber 5% Mineral Filler 6% AC	2.2	.34	4	15.4	.33	4	2931	133	4	14	.5	4
Vestoplast S 5% Mineral Filler 5.5% AC	4.0	.59	4	16.2	.47	4	2833	141	4	14	1.3	4
Vestoplast S 5% Mineral Filler 5.8% AC	3.0	*	2	15.8	*	2	3130	*	2	14	*	2
Vestoplast S 7% Mineral Filler 5.5% AC	2.6	.54	7	15.0	.51	7	3129	151	7	13	.8	7
Type 1-D Polymer 5%Mineral Filler 5.9% AC	2.0	.97	12	15.0	.84	12	3228	248	12	16	2.0	12

* too few samples were tested to calculate the standard deviation

2.5 Research Data

2.5.1 Post-Construction Evaluation The project was evaluated immediatelyafter construction and each year during the evaluation. The post-construction evaluation included flushing, smoothness, skid resistance, measuring ruts, crack mapping and an overall visual inspection. In addition cores were taken to monitor voids.

Flushing In the entire project there was only one small area that flushed. This was not a concern and could possibly be traced back to an isolated problem at the plant during production. The plant had an emergency shut down at the same time the area that flushed was paved. There may be a correlation between the flushing and the emergency shutdown, but it is not certain. The flushing occurred in the PM-1D. This area was observed during each evaluation, did not appear to progress and was not detrimental to the performance of the pavement. Figures 11 and 12 shows the areas of flushing.

Smoothness There was a smoothness specification on the standard HBP on this project but it was not required on the SMA pavement. The contractor elected to run the profilograph on the nine evaluation sections for information only.

The CDOT smoothness specification requires the use of a 2.5 mm (0.1 inch) blanking band. Any profile index over 110 mm/km (7 inches/mile) falls into the disincentive section of the specification, and any profile index over 189 mm/km (12 inches/mile) requires corrective work.

For the study, the research branch did smoothness testing in the spring following construction and also at the conclusion of the study. Smoothness was measured with an Ames profilograph.

Initial and final smoothness were measured in the right and left wheel paths of the driving lane. The right and left wheel paths measurements were averaged and converted into a profile index value of inches per mile. Smoothness was recorded for each of the nine evaluation sections and the profile index values are shown in Table Q.

Under the CDOT smoothness specification, all but three of the evaluation sections would require corrective work (> 12"/mile). (Since smoothness of the SMA sections was not in the specification, the contractor was not required to correct these sections.) Based on the smoothness index values of the standard HBP on the project, it did not appear that SMA in itself was the cause of the high smoothness values.

Table Q. Smoothness results.

	PROFILE INDEX INCHES/MILE	
	Evaluation Spring after Construction Driving Lane	Final Evaluation Driving Lane
Grading C (NB)	15.8	19.8
SMA with Vestoplast S (NB)	5.9	8.2
SMA with PM-1D (NB)	12.5	14.9
SMA with Fiber Pellets (NB)	9.2	9.3
Grading C (NB) AC20R	13.3	8.9
Grading C (SB)	15.6	11.6
SMA with PM-1D (SB)	25.9	24.0
SMA with Vestoplast S (SB)	6.07	9.8

- The smoothness index value for both PM-1D sections in the northbound direction was reported as one section.

Based on the values taken in the 1000-foot evaluation sections, all but three of the sections would have required corrective action. Comparing the final smoothness evaluation to the initial indicate that four of the sections have gotten rougher, three have improved and one has remained the same (Table Q). Although the smoothness values for the SMA are high, it does not appear that SMA in itself is the cause of the high roughness values, because the smoothness index values of the standard HBP on this project are in the same range.

Skid Resistance Skid testing was performed on the entire project in November following construction. Minimum skid-resistant guidelines reported by other states range from 30 to 40 for interstate highways and all highways with legal speeds in excess of 65 km/h (40 mph).[8]

Skid resistance on this project was measured using the equipment and procedure described in ASTM E 274. The measuring was done with a rib tire (ASTM E 501) at 65 km/h (40 mph) in the left wheel path of the outside driving lane.

The skid values on all the sections recorded immediately following construction were similar. The values for immediately following construction and 6 years after construction are shown in Table R. The average initial values immediately following construction ranged between 52 and 55.9. There was no distinct difference in the values between the SMA pavement and the standard Grading C pavement. However, because of the smoothness specification on the Grading C portion of the project, there were a few areas, which required grinding. Skid numbers measured on the ground areas immediately following construction measured about 10 points lower than the unground areas (41.6 to 44.5).

Table R. Skid resistance results.

	Skid Resistance Immediately Following Construction	Skid Resistance Six-Years After Construction
	Average	Average
Grading "C" (Northbound)	54.6	38.7
Vestoplast S (Northbound)	55.9	44.8
PM-1D (Northbound)	53.5	45.1
PM-1D (Northbound)	55.0	52.0
Fiber Pellets (Northbound)	52.0	49.1
Grading "C" Ground (Northbound)	44.5	
Grading "C" (Northbound)	53.3	50.3
Grading "C" Ground (Southbound)	41.6	
Grading "C" (Southbound)	53.7	52.9
PM-1D (Southbound)	55.2	50.7
Vestoplast S (Southbound)	55.5	42.8

** Location of evaluation section numbers can be found in Figure 2

Avg - Average
S. D. – Standard deviation
N - Number of readings

Comparing the skid values from immediately after construction to 6 years after indicates that most of the sections remained the same. The Vestoplast S sections the skid values decreased but are still considered acceptable.

Cracking Cracking was measured in each evaluation section during each field review. Cracking did not appearing in any sections until the second year following construction. At this time longitudinal cracking was the most prominent in the Grading C section (section 1). Also during this evaluation it was noted that the Grading C sections (sections 1 and 7) and Vestoplast S section (section 2) contained transverse cracking, which was not observed in the other sections. The Vestoplast S sections are the only sections that contained block and alligator cracking at the end of the study period. Cracking for all sections over the evaluation period is shown in Figure 13.

Rutting Rutting in all the sections was minimal at the end of the study. The section with the most rutting was section 1 (Grading C, one 2-inch lift). Rutting in this section was approximately 6 mm (.25 in), which is considered insignificant. Figure 14 shows the rutting in the pavement prior to paving and the final rut measurement.

Figure 11. Limited problems with draindown were encountered.

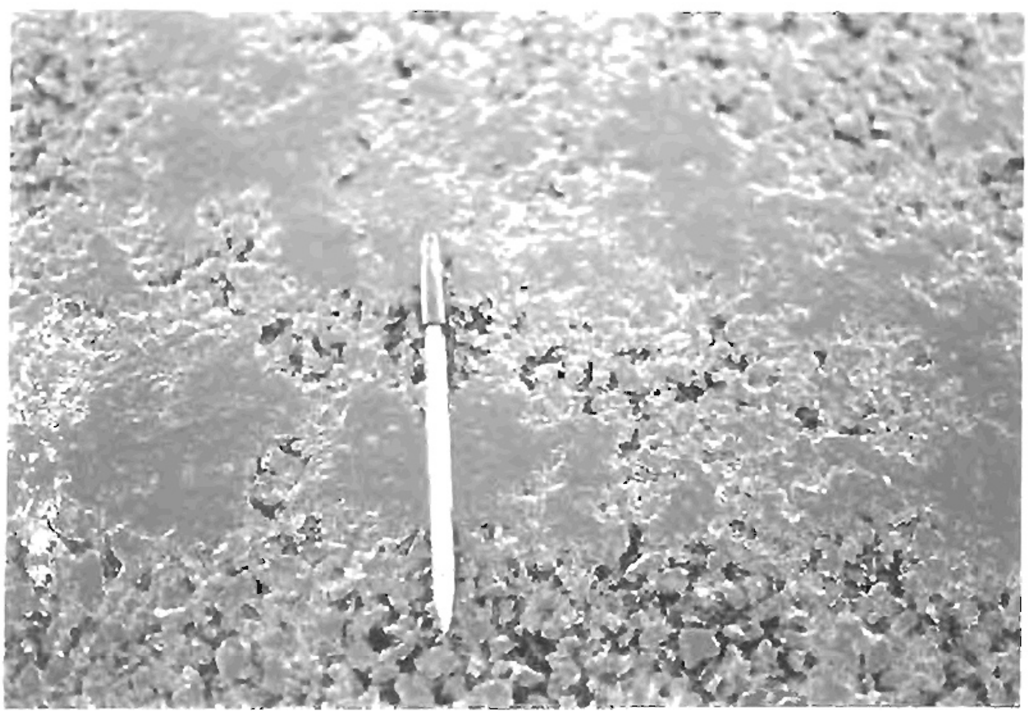


Figure 12. Close-up of flushing area.

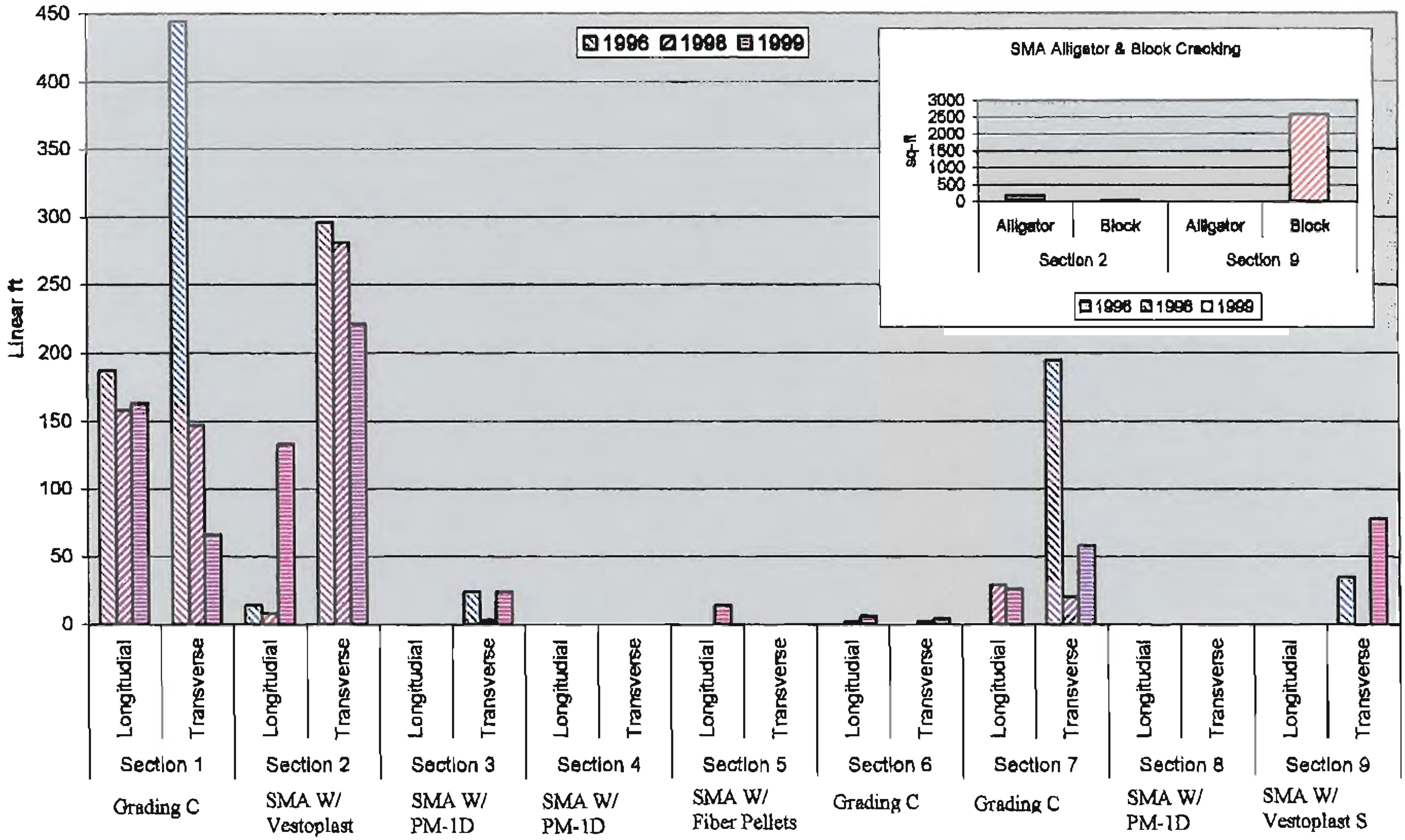


Figure 13. Cracking data.

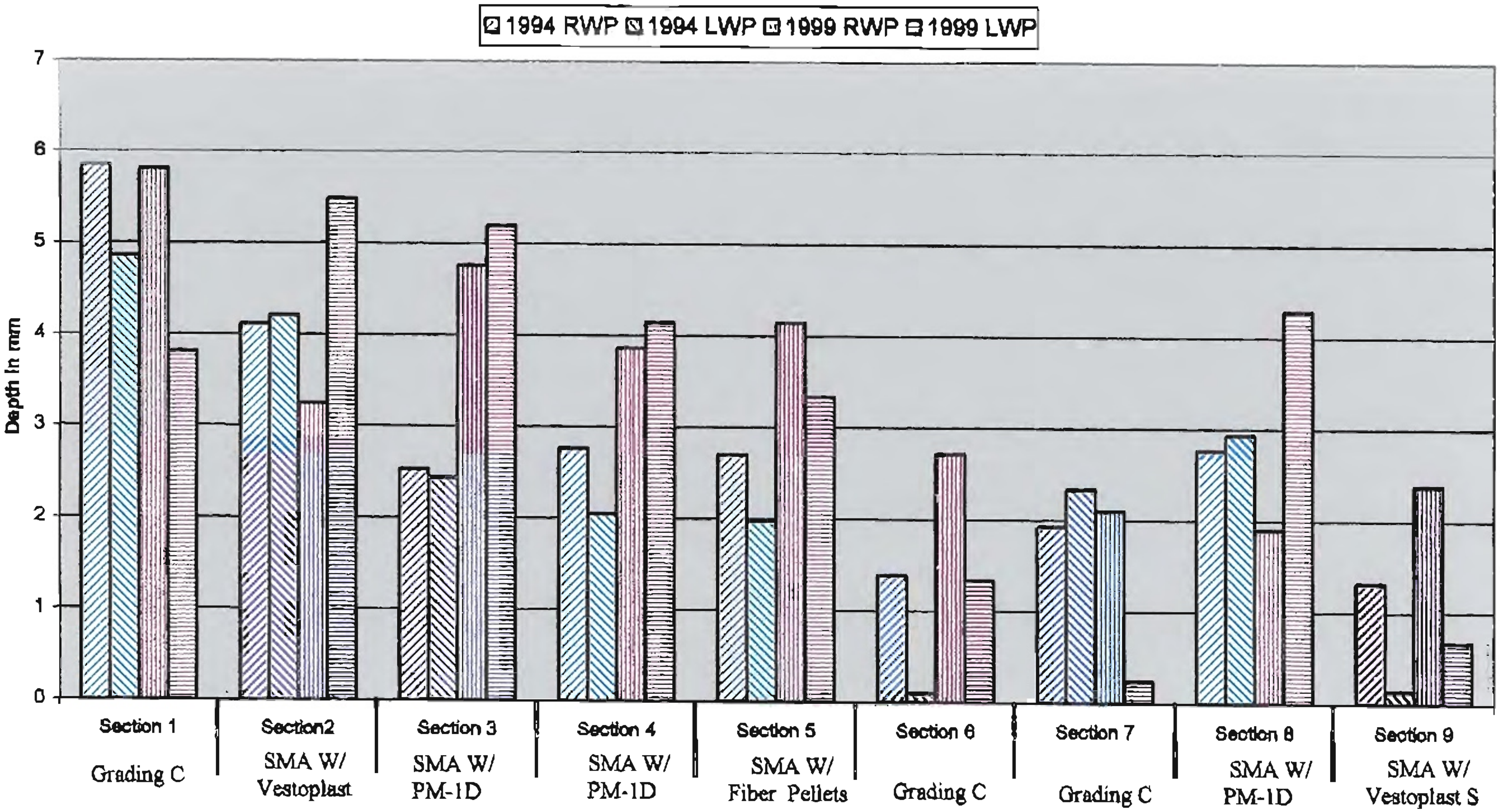


Figure 14. Rutting data.

3.0 SMA –COLFAX AVENUE VIADUCT

Since SMA pavements were shown to be durable and could be placed in thin lifts, other applications for SMA construction were reviewed. Asphalt overlays on bridge decks are common in Colorado and the replacement of the existing asphalt overlay is complicated by the fact that the maximum thickness of the asphalt wearing surface is limited to 4 inches. Based on the success of the SH 119 construction project it was decided to place an SMA pavement on a bridge deck in Denver.

Typically, Colorado bridges are designed to have a maximum of 4 inches of hot bituminous pavement (HBP) on the surface (CDOT design dead load requirement) placed over an asphalt membrane system. When the riding surface on the bridge deck requires rehabilitation, the HBP must be removed before an additional surface treatment is placed so that the maximum of 4 inches of HBP is not exceeded. The existing surface on this Project No. C 0404-030, Colfax Viaduct, consisted of a 2" HBP with membrane and was placed in 1984.

Since SMA pavements are very durable and can be placed in thin lifts it could be advantageous to use them on bridge decks. Using SMAs on bridge decks allows for less milling and the existing deck membrane does not have to be replaced.

Project No. C 0404-030 was a good candidate to try the SMA pavement. This project is located in downtown Denver on the Colfax Viaduct between Federal Blvd. and Osage Street (Figure 15). This project is approximately 1 mile long and has an average daily traffic (ADT) of 46,100 with 9% trucks. The existing pavement surface on this project had began to ravel and needed to be removed. The costs to either remove the existing HBP and membrane by planing and overlaying, or to raise the expansion joints, would have been extremely high and were not considered to be an options. The decision to mill and replace with SMA was considered the most cost-effective solution.

This project consisted of milling 1-1/4 inches of HBP and replacing it with 1-1/4 inches of SMA pavement. Because of the thin lift being placed on this project (CDOT design guidelines require inch minimum for dense grade mixes) there was no control using a dense graded mix established on this project. This project contained approximately 3000 tons of SMA mix and was constructed in 1995.

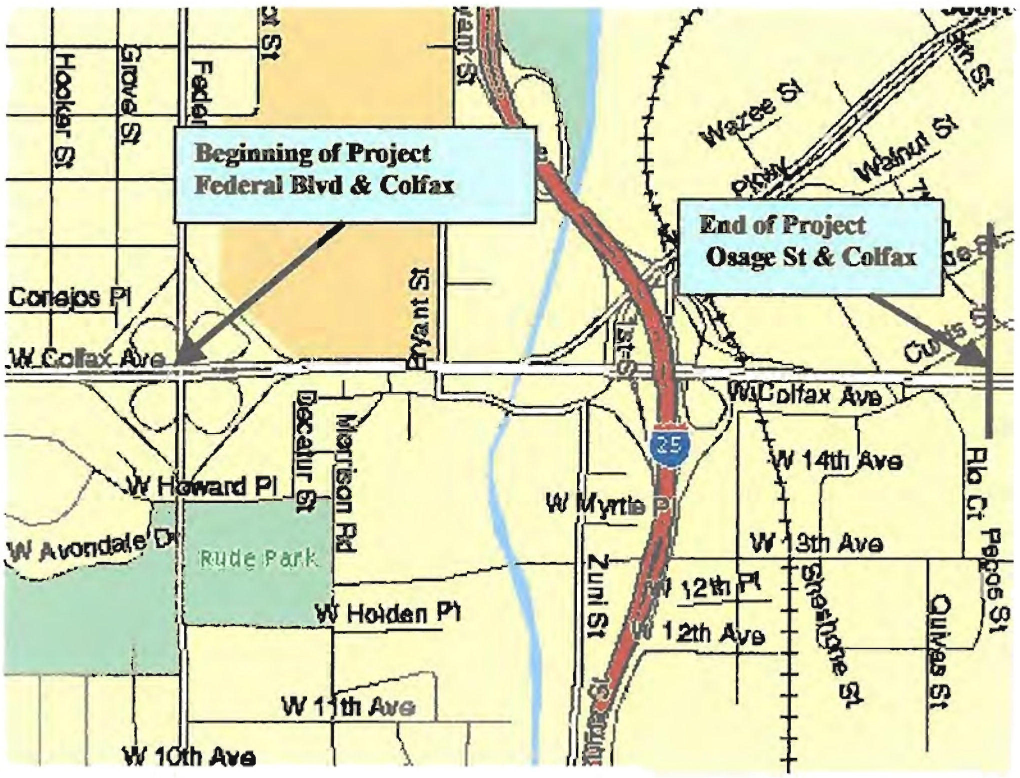


Figure 15. Location map of Project No. C040-030

3.1 Project Development

3.1.2 Evaluation Section A 1000-foot evaluation section was established in the eastbound driving lane. A location map of the evaluation section is shown in Figure 16. The bridge is three lanes in each direction. For safety concerns all the post-evaluations will be conducted by driving through the project.

3.1.3 Existing Distress A preconstruction evaluation was performed on the project, which consisted of measuring ruts and cracks.

Rut depths were measured every 15 meters (50 feet) throughout the test section in both the right and left wheel paths of the two outside lanes. The ruts were measured with a two-meter (six-foot) straight edge and were measured to the nearest 2.5 mm (0.1 in). Rutting in the evaluation section was fairly low. The average in all the wheel paths was around 8 mm (0.3 in). The highest rutting measurement was 18 mm (0.7 in). According to CDOT's standard an average measurement of 8 mm (0.3 in) is considered low severity.

Crack maps were prepared for the evaluation section. Cracking was very extensive so only the transverse cracks were recorded. On the average there were about 14 transverse cracks per 100 foot of pavement. It was observed that on the average there was only 1 transverse crack per 100 foot that ran the entire width of the pavement. This type of cracking does not follow the typical thermal cracking pattern that is found in roadways. Thermal cracking in roadways tends to extend the full width of the pavement. In bridge decks the cracking is due to flexural deflection of the deck under traffic.

The cracks had begun to deteriorate on the edges and there were a number of areas on the mat where the membrane was exposed. These areas ranged in size from 25cm^2 (4in^2) to 0. 1 m^2 (1 ft^2). Prior to paving, the larger areas were repaired. The membrane was removed and a cold pour material was applied. Typical distress found in the existing overlay on the deck surface is shown in Figures 17 and 18 . The removal and repair of the exposed membrane is shown in Figures 19 and 20.

3.1.4 Bids Excluding the patching, a SMA mix was used on the entire project. Table S shows the tonnage used and the cost per ton of the SMA mix.

Table S. Bid Cost of the SMA.

	Tonnage	Cost Per ton
SMA PM-1D	3024	$60.00

Although this project contained a small mix quantity and was more complex because of the construction involving a bridge structure with expansion joints, the bids were consistent with the SMA PM-ID used on SH 119.

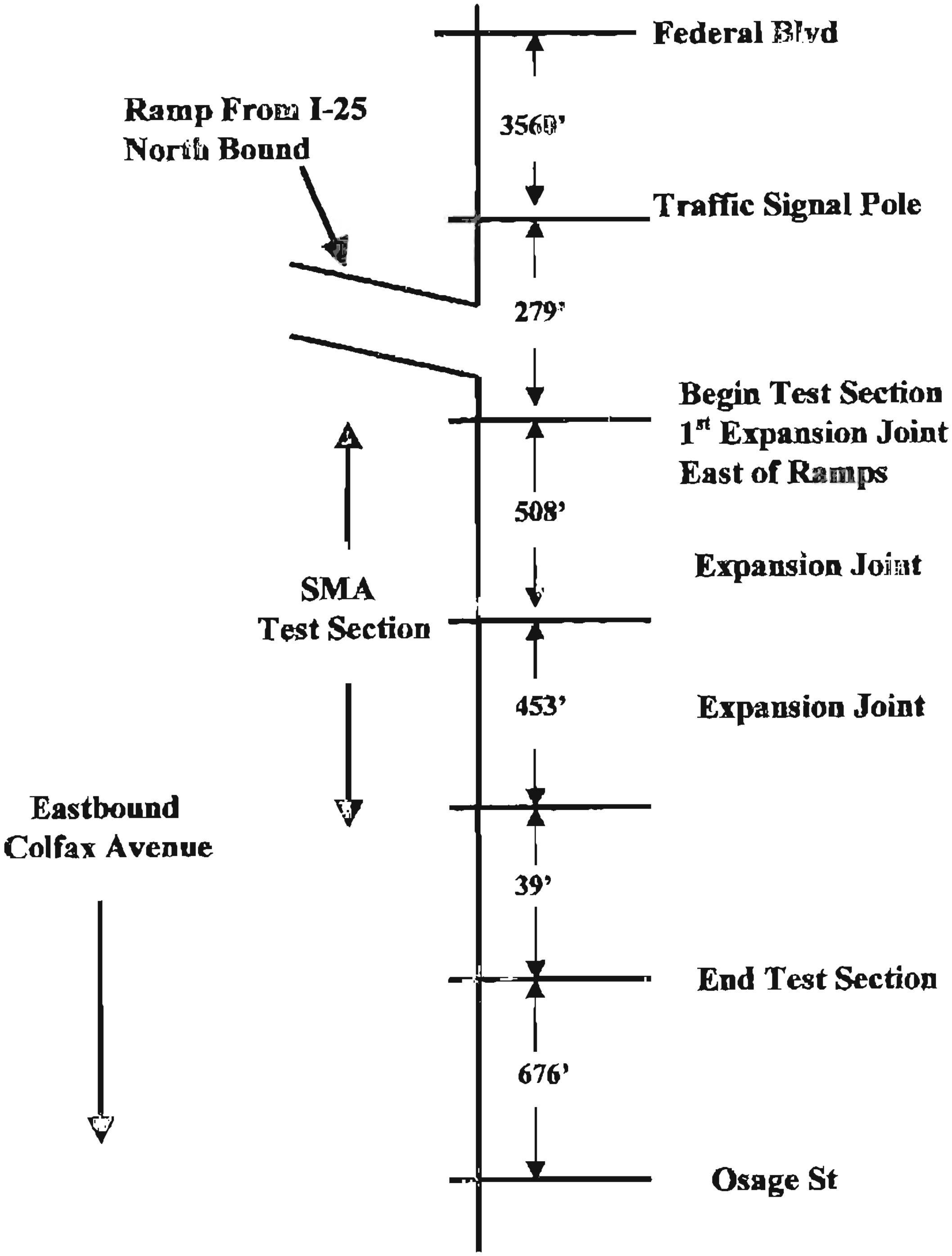


Figure 16. Colfax evaluation section

Figure 17. Typical cracking pattern prior to paving.

Figure 18. Extent of distress prior to paving.

Figure 19. The exposed membrane was removed.

Figure 20. A cold-pour material was used to cover the area where the membrain was removed.

3.2 Mixture Design and Testing

3.2.1 SMA Mix Design The specifications used for the project can be found in Appendix F.

3.2.2. SMA Composite Gradation All the aggregates were granite and came from the Meridian Pit in Meridian, Wyoming. The stockpiles used for SMA included a 19-mm (3/4-in) rock, a 12.5-mm (1/2-in) rock, and a granite sand.

The blending percentages of the blend that was selected are shown in Table T.

Table T. SMA trial blending percentages.

Stockpile	Percent of Blend
19.0-mm Rock	27%
12.5-mm Rock	49%
Granite Sand	18%
Limestone Dust	5%
Hydrated Lime	1%

The SMA gradation is shown in Table U.

Table U. SMA composite gradation.

Sieve Size	Percent Passing	CDOT Specification	FHWA Recommendations
19.0 mm (3/4")	100	100	100
12.5 mm (1/2")	91	90 – 100	85 – 95
9.5 mm (3/8")	70	75 maximum	75 maximum
4.75 mm (No. 4)	24	20 – 30	20 – 38
2.36 mm (No. 8)	19	16 – 24	16 – 24
600 μm (No. 30)	13		
300 μm (No. 50)	11		
75 μm (No. 200)	7.7	7 – 11	8 – 10

The target values of the SMA design were within CDOT's Master Range. The tolerances for the various sieve sizes were: 9.5 mm ±5, 4.75 mm and 2.36 mm ±4 and 75 gm ±2.

3.2.3 Physical Properties The tests results on the fine and coarse aggregates are shown in Table V.

Table V. Aggregate test results.

Test	Procedure	Result	Specification
AASHTO T 96	LA Abrasion	23%	30% max
AASHTO T 104	Sodium Sulfate Soundness	2%	12% max
CP-45	Fractured Faces One or more Two or more	 100% 98%	 100% 90% min
AASHTO T 89	Liquid Limit	NP	NP
AASHTO TP 33	Fine Aggregate	45.7	45 min

All the test results were acceptable. Not all the tests were specified on the project; however, all the tests in Table W, in addition to ASTM D 4791 (Flat and elongated, 3 to 1 and 5 to 1) are recommended by FHWA.

3.2.3 SMA Mixture A polymer modified asphalt cement was used on this project to prevent the asphalt cement from draining down during hauling and placement.

The polymer modified asphalt cement was supplied directly to the contractor's asphalt plant from an independent polymer modifying company (Koch Materials Co.). The polymer met the AASHTO Task Force 31 Type 1D specification.[5] The polymer supplier was the same as on the SH 119 SMA project. The purpose of the polymer in an SMA mix is to stiffen the asphalt cement and prevent draindown.

Asphalt Cement Tests The PM-1D was manufactured by Koch Materials Co. using Conoco asphalt and SB copolymers. The PM-1D was tested to AASHTO MP1 Superpave binder specification. The material conformed to Superpave PG 76-28.

3.2.4 Mixture Tests The tests for the mix design were performed by the contractor. The Marshall mix design used 50 compaction blows on each side of the specimen. The Marshall test results are shown in Table W.

Table W. Marshall test results.

Property	Specification	PM-1D
VTM (%)	3- 4	3.3
Asphalt content (%)		6.43
VMA (%)	16 (min)	15.3
Stability, N (lb)	6200 min (1400)	10400 (2340)

PM-1 D - Polymer Modified, Type 1 -D
VTM - Voids in the Total Mix (Air Voids)
VMA - Voids in the Mineral Aggregate

3.2.6 Specification Comments Based on the results from the SH 119 project, the VMA specification was increased from a minimum of 15% to 16%. The VMA specified in CDOT's current specification is 17%. (Appendix C)

3.2.7 Moisture Resistance Testing During construction on SH 119, the test results using AASHTO T 283 to evaluate moisture resistance on the SMA only passed marginally. However, further evaluation using the Hamburg Wheel-Tracking Device to test the SMA for moisture resistance indicated that the SMA was resistant to moisture. It was concluded that possibly the AASHTO T 283 tests may not accurately represent the moisture susceptibility of the SMA . For this reason only the Hamburg wheel-tracking device was used to test the SMA for moisture resistance on the Colfax viaduct project.

All tests were performed on material that was produced at the plant and sampled from behind the augers in the test section. Replicate samples were tested and the averages were reported. The test results from the Hamburg wheel-tracking device are shown in Table X. The mm of deformation after 20,000 passes are shown.

Table X. Test Results (mm of deformation after 20,000 passes) from the Hamburg Wheel-Tracking Device.

Temperature (°C)	SMA (PM-1D)	Specification
50	3.05 mm	10.mm (max)

PM-1D - Polymer modified, Type 1-D

The Hamburg test results from the SMA mix placed on this project were acceptable. The results from this project were consistent with the SMA containing the PM-1 D on the SH 119 project.

3.2.8 Permanent Deformation Testing The French Rutting Tester was used to evaluate the resistance of the SMA to permanent deformation. The French Rutting Tester result is shown in Table Y. The percent rut depth after 30,000 cycles is shown.

Table Y. Test results (% rut depth after 30,000 cycles) from the French Rutting Tester.

Temperature °C	SMA PM-1D	Specification (Maximum)
60	3.21%	10%

PM-1D - Polymer Modified, Type 1D

The test results indicate that this SMA mix will be rut resistant. These results were consistent with the SH 119 project.

3.2.9 Low Temperature Cracking The thermal restrained specimen test (TSRST) was used to evaluate the resistance of the HMA to low temperature cracking. The fracture temperature and fracture strength of each of the mixtures tested are shown in Table Z. The tests results are similar to the PM-1D test results for the SMA containing the PM-1D used on the SH119 project.

Table Z. TSRST test results.

	Fracture	
	Temperature (°C)	Strength (kPa)
SMA PM-1D	-35.7	4335
SMA PM-1D	-42.4	3492

3.2.10 Draindown Tests Draindown tests were not performed on the mix. However, it should be noted that during construction no draindown problems were observed.

3.2.11 Mineral Filler Tests The mineral filler used for this project was a crushed gray limestone (CAL 200) dust. The limestone dust properties measured were particle size (AASHTO T 88) and plasticity index (AASHTO T 90). Test results are shown in Table AA.

Table AA. Test results on the mineral filler.

Test	Result	Recommendation
Particle size smaller Than 20μm	44%	< 20%
PI	Non-plastic	< 4%

The particle size was measured by the contractor using the hydrometer analysis (AASHTO T 88). The mineral filler was finer than recommended by FHWA .[6] However; it was similar in gradation to the mineral filler used on SH 119. The test results are shown in Table BB.

Table BB. Hydrometer analysis (AASHTO T 88) results on the mineral filler.

Size (μm)	Percent Passing
75	83
20	44
2	5

3.3 Construction

3.3.1 Plant Description A Gencor continuous mixer with a capacity of 550 tons per hour was used on this project. The fuel source was natural gas. The SMA mix required four cold feed bins, with a retrofit for the addition of mineral filler (limestone). The silo used for the mineral filler had a 60-ton capacity. Lime was added with a weigh pod and vane feeder and mixed with damp aggregate in an approved pug mill. A baghouse was used for emission control. The storage silo for the HBP had a 220-ton capacity. The average time the HBP was in the silo was 15 minutes.

3.3.2 Plant Modifications for SMA Unlike other modifiers that are used in SMA designs, the polymer modifier used on this project did not require any modification to the plant to properly add the additive. However, a cement silo was set up with a metering device to add the mineral filler. The specifications required the mineral filler be added at the same point as the asphalt cement. Both the mineral filler line and the asphalt cement line entered the rear of the mixing drum and were discharged into a mixing head. This allowed the asphalt cement to coat and capture the mineral filler, which helped to prevent blowing the mineral filler out of the drum and into the baghouse.

The rate of production of the plant was cut in half from a capacity of 550 tons per hour to 275 tons per hour. However, according to plant personnel the SMA did not reduce production at the plant. The rate of production was reduced to match the placement rate.

3.3.3 Haul Trucks The HBP was delivered to the project with end-dumps. The haul time from the plant to the project was approximately 35 minutes. The haul trucks were not covered with a tarp. The temperature of the mix behind the paver was 138^0C (280^0F) to 146^0C (295^0F).

3.3.4 Laydown Operation One Blaw Knox 510 paver was used. The majority of the paving was done in a 12.5-foot width. Three rollers were used to compact the SMA. The final rolling pattern established used three steel-wheeled rollers. A 8-ton Hyster 350D was used for breakdown and was kept right behind the lay down operation. This roller made two coverages. Two 10-ton Hyster C766Bs were operated in tandem right behind the breakdown roller. Each of these rollers made three coverages a piece. Rolling was stopped when the surface temperature reached 88^0C (190^0F). All the rollers were operated in the static mode.

The specification for density of an SMA is 94% of rice. Densities obtained using this rolling pattern and using the thin lift nuclear gage to measure densities only produced densities of 92% at the highest.

3.3.5 Trial Placement The project plans require the contractor to place a test section prior to construction to evaluate the contractor's ability to both produce and place the SMA. Two days prior to the start of the project the contractor placed a short section of the SMA mix in the driving lane. On this test strip, cores were used to calibrate the thin lift nuclear gage. Since this project was entirely on a bridge deck the number of cores taken were limited. During the placement of this test strip no problems were encountered. However, during placement the mix appeared to be rich and the materials engineer lowered the asphalt cement content from 6.7% to 6.5%. Reduction in the asphalt content was the only adjustment made.

This trial placement also gave the contractor an opportunity to develop the best technique to work with the SMA mix at the expansion joints.

3.3.6 Construction Techniques The construction schedule was designed such that traffic disruption was m;inimal. The existing pavement was milled on one weekend and the following weekend the SMA pavement was placed. This schedule was altered because of weather conditions but as a whole the work schedule caused little disruption to traffic.

Tapers were placed at all expansion joints once the pavement was milled. These tapers were removed prior to placing the SMA pavement. Although handwork is difficult with SMAs the contractor did not have much difficulty working with the SMA material at the expansion joints.

Figures 21 and 22 show the preparation at the expansion joints. Figure 23 shows the required hand work at the expansion joint.

Figure 21. Removing the taper at the expansion joint.

Figure 22. Preparing the joint prior to SMA placement.

Figure 23. Handwork is required at the expansion joint.

3.4 Field Verification Test Results

3.4.1 Asphalt Content and Field Compaction The design AC content was 6.5%. The density requirement was 94% to 96% of the Rice (AASHTO T 209 value).

The field verification test results are summarized in Table CC.

Table CC. Asphalt content and field compaction test results.

Additive	Asphalt Content (%)				% of Maximum Density			
	Avg	S.D.	n	Q.L.	Avg	S.D.	n	Q.L.
PM-1D (6.5%)	6.39	.12	6	98.9	92.6	.61	6	*

Avg - Average
S.D. - Standard deviation
n - Number
Q.L. - Quality Level
PM-1 D - Polymer modified, Type 1 -D

* Although measured densities were lower than the specification, no price reduction was applied as per project special provision.

Since this project was located on a bridge deck cores, were limited to the compaction test section. A thin lift nuclear gauge was used to determine densities and provided a good correlation with the cores.

3.4.2 Volumetrics Three replicate samples were compacted by the contractor for field quality control. The volumetric test results are shown in Table DD. The volumetric properties were acceptable.

Table DD. Volumetric test results of field produced SMA.

Air Voids (%)			VMA (%)			Marshall Stability			Marshall Flow		
Avg	S.D.	N	Avg	S.D.	N	Avg	S.D.	N	Avg	S.D.	N
3.4	.38	7	16.7	.39	7	2146	156	7	16.5	.67	7

VMA - Voids in mineral aggregate
Avg - Average
S.D. - Standard deviation
n – number

3.5 Research Data

3.5.1 Post-Construction Observations A visual inspection of the mat followingpaving showed the surface of the mat to be uniform throughout the project. There were no visual signs of distress. The only quantitative test performed on the finished mat was smoothness. Due to safety concerns only visual observations were made during the field evaluations. To date there the pavement is showing no signs of distress.

Smoothness The plans for this project contained Colorado's 1995 smoothness specification. The smoothness specification requires that the contractor take the measurement using a computerized California-type profilograph. Smoothness measurements were taken on the existing paving, on the milled pavement and on the finished mat. Typically smoothness is measured down the center of each wheel path and is taken following each day's paving, however due to the small quantity of SMA material on this project each lane was measured and recorded separately. The 1995 CDOT specification uses a 2.5 mm (0.1 inch) blanking band. In urban areas smoothness is measured on percent improvement. Smoothness results are shown in Table EE.

Table EE. Smoothness results.

	Exiting Pavement In/mile	Milled Surface In/mile	Finished Mat In/mile	Percent Improvement
Eastbound Right Lane	40.19	32.41	37.6	6
Westbound Right Lane	38.53	31.80	33.97	12
Eastbound Middle Lane	52.86	42.55	34.28	35
Westbound Middle Lane	49.90	36.37	24.79	50
Eastbound Left Lane	78.09	44.83	47.68	39
Westbound Left Lane	66.54	43.69	46.45	30

4.0 SUMMARY AND RECOMMENDATIONS

CDOT's first SMA project was located on SH 119, west of Longmont and successfully demonstrated design, production and placement of the European SMA. The Colfax viaduct project was Colorado's second SMA project but their first attempt to use it on a bridge deck. The Colfax viaduct project was different than the project placed on SH 119 in that it was constructed on a bridge deck requiring a different paving technique. This project successfully demonstrated the placement of the European SMA on a bridge deck. Since these two projects were placed 5 additional projects have been placed. Table FF contains a summary of the projects placed through June 2000.

Table FF. Summary of Colorado's SMA projects.

Year Constructed	Location and Project No.	Tons	$/ton	Aggregate size	Regio n
1994	SH119, Longmont diagonal Demonstration Project No. NH 1191-005	5506 1414 4403	54.00 59.00 63.00	¾ Vestoplast S ¾ Fibers ¾ PMA	4
1995	US 40, Colfax Viaduct Project No. C 0404-030	2749	60.00	¾ PMA	6
1996	I 70, Gypsum to Eagle NH 0702-193	31827	37.66	½ PMA	3
1997	I-70, Glenwood Springs NH 0707-198	20406	43.53	¾ PMA	3
1997	I-70, Brighton Blvd to Colorado Blvd. (elevated I-70) BR 0704-175	7758	52.00	¾ PMA	6
1999	US 6, Federal Blvd. To Raritan NH 0061-066	8382	59.00	¾ PMA	6
1999	SH 285, Turkey Creek Canyon NH 2854-069	5649	70.90	3/8 PMA	1

Notes: 1) Region 3 paid for binder separately, so the $/ton is calculated from the bid prices of mix plus anticipated %AC
2) The Region 1 project was a metric project. The tons ad cost was converted to English Units.

There has been a total of 82,445 tons of SMA placed. The cost per ton ranged from $37.66 for a ½ in polymer modified SMA to $70.90 for a 3/8 in polymer modified SMA.

4.1 Mix Design

4.1.1 VMA In 1994, the VMA level on SH 119 was set at 15% and on the Colfax Viaduct project the following year, a VMA of 16% was required. The current VMA requirement by CDOT is 17%. These changes were a result of a change in the recommended VMA on the national level to provide VMA requirements for the best performing Stone Mastic Asphalt mixes. At the same time, the allowable gradation bands were also widened. The widening of the gradation bands allows a contractor more flexibility in blending the aggregate to achieve the new higher level of VMA. By current specification, a VMA of 17% is required regardless of the nominal maximum aggregate size used in the SMA mix.

4.1.2 Superpave versus Marshall Mix Designs To date, all of the mixes used on CDOT projects have been developed using a 50 blow Marshall mix design method. During 1998 and 1999, NCAT was performing research to design SMA mixes using the Superpave mix design method. CDOT has adopted Superpave, and would like to design and verify SMA mixes using our own test methods. (CDOT used the Hveem system prior to Superpave, and relied on consultant testing for the Marshall SMA mixes.) Many of the recommendations from the NCAT study were adopted by DCOT, for example, the wider gradation band and the VMA of 17% regardless of nominal maximum aggregate size. However, CDOT's mix design procedures use the Superpave gyratory compactor, and 100 mm molds instead of 150 mm molds used in the NCAT SMA Study.

To address SMA mixes in the CDOT mix testing and design system, it was decided to test SMA mixes from the 1999 projects in two fashions.

The first method would be to save the ingredients from the mixes (aggregates, mineral filler, AC< and lime, and perform mix designs using Superpave compactor with 100 mm molds, and two compaction levels, 80 and 100 gyrations. (At that time, NCAT had not made their final recommendations for a SMA compaction level.)

The second method was to save split samples of the project-produced mixes, and compact samples in the lab over the winter to compare with the Marshall results for these samples. It was hoped that this would yield information on mix verification of project-produced samples.

Two SMA mixes were produced in 1999, and the materials and samples were saved for winter testing.

Figure 24 contains the mix design information for the nominal 19 mm (3/4 inch) mix used in the Denver area. As can be seen, the 100-gyration design selects an asphalt content 0.2% higher than the Marshall method, close to the same asphalt content. The 80-gyration design yielded an asphalt content much too high.

Figure 24. ¾" SMA mix designs.

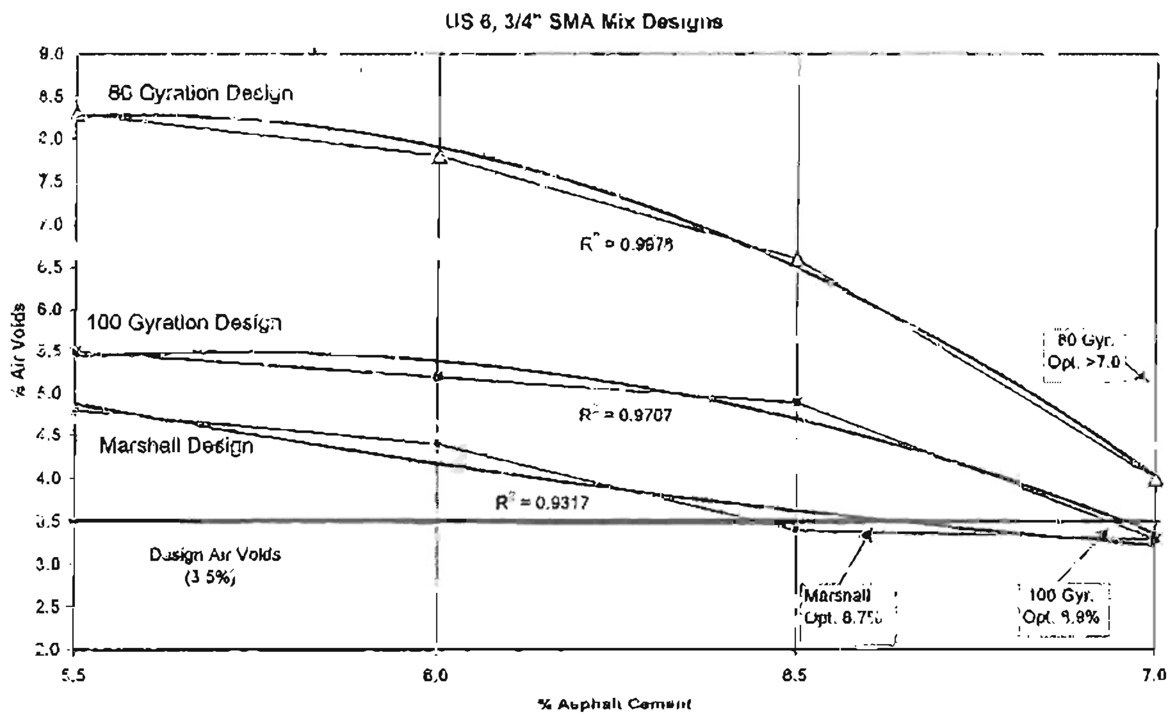
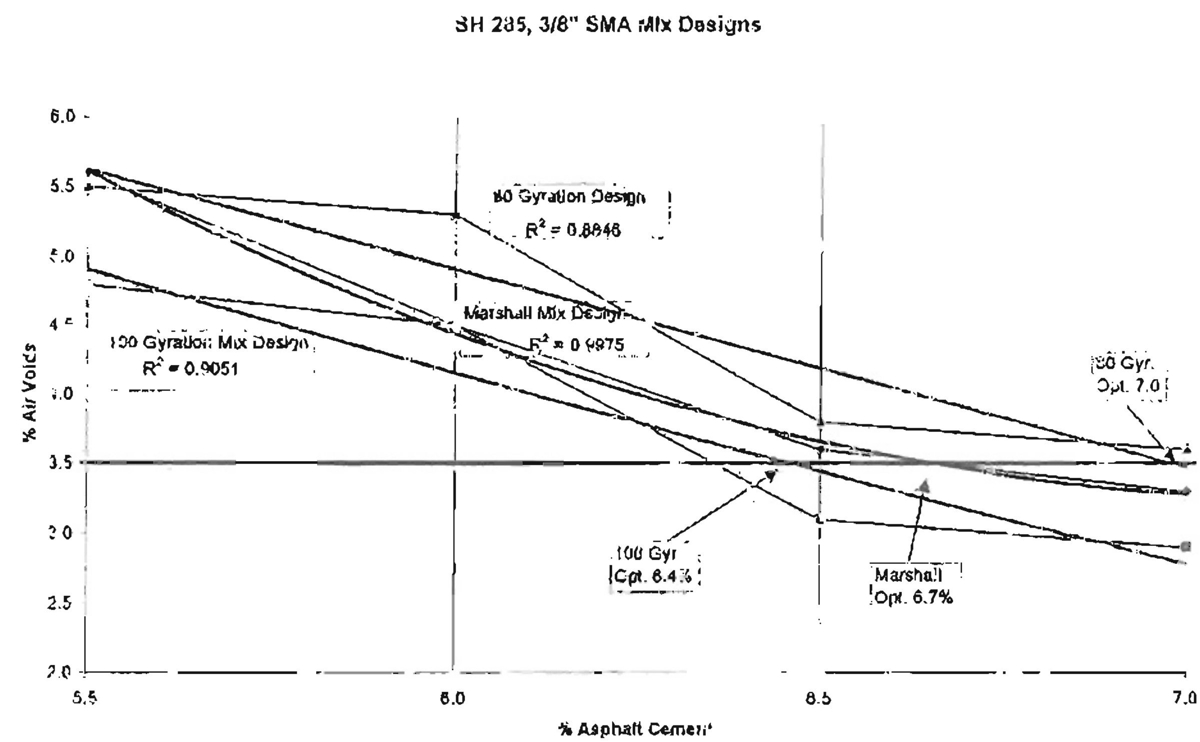


Figure 25 graphs the results of a 3/8 nominal aggregate mix design for the 100 gyration Superpave design and the Marshall design. The 100 gyration Superpave design would select an asphalt content 0.3% lower than the Marshall design. On this particular project, the asphalt content on the project-produced mix was lowered by 0.3% during production. Again the 80-gyration mix yielded a binder content much too high.

Figure 25. 3/8" SMA mix designs.



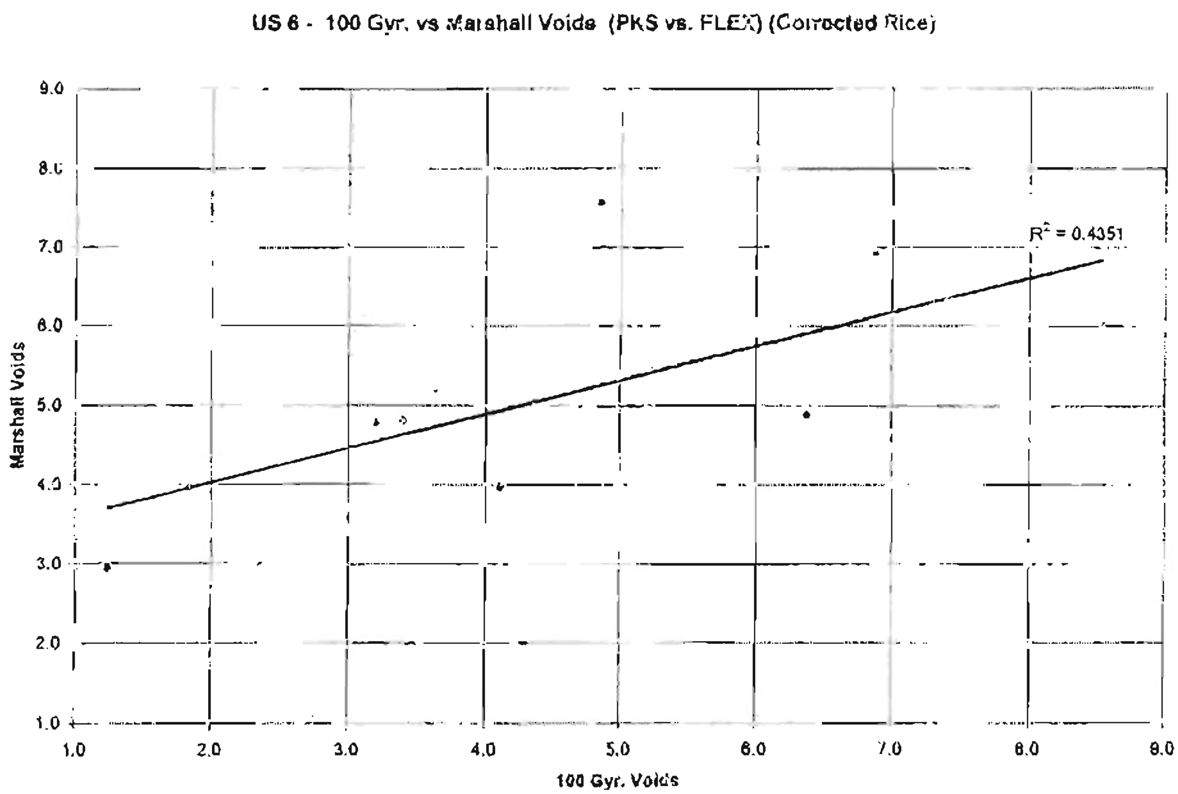
After these test results, coupled with the NCAT study data and recommendations, it was felt that a compaction level of 100 gyrations using the 100 mm molds in the CDOT mix design system would result in an accurate optimum binder content.

To transition SMA mixes into the Superpave mix design method, CDOT's test procedures were amended to address a 100-gyration mix design. The contract specifications for mix designs were changed to allow either a Marshall or Superpave mix design for contracts. These changes were adopted in mid-2000.

The second phase of the Superpave testing addressed mixture void verification comparing Marshall compacted samples, and Superpave compactions.

Figure 26 is a graph comparing 100 gyrations voids (100 mm mold Superpave compactions) to Marshall compactions on split samples. As can be seen, the correlation is only fair at best, with the Marshall compactions yielding slightly higher voids. It should be noted, that while these are split samples, the Marshall samples were tested immediately at the plant, while the Superpave testing was done the following winter, so a close correlation was not expected.

Figure 26. Superpave versus Marshall voids.



This testing however did help our staff in learning how to handle SMA mixes both in the design phase and in the mix verification phase. A large number of technicians, were involved, and after the testing was completed, a list of technician tips for handling SMA mixes both field and lab produced as identified and added to CPL 5155 (TP4 using 100 mm molds). These tips are listed in Appendix G.

4.2 Constructibility

During construction of the SH119 project the nuclear gauge was used to determine densities. It was soon concluded that there did not appear to be any correlation between the densities obtained with the nuclear gauge and the cores. The densities obtained using the nuclear gauge were always lower than the densities for the cores, and the correlation was very inconsistent. Therefore, densities of the SMA were controlled using cores.

The minimum compaction specification for the SH 119 project was set at 94% of the Rice (AASHTO T 209) value. The average compactions obtained for the SMA mixes ranges from 92% to 94%. Despite a joint effort between the contractor and CDOT to optimize various compaction techniques, obtaining the minimum compaction of 94% was difficult.
As a result, the in-place densities for SMA are specified in the current specification to be 93% to 97% of the Rice (AASHTO T 209) value. (Appendix C)

The current specification states that the relative compaction for all SMA mixtures will be measured from roadway cores in accordance with CP-44, Method C, unless the SMA mixture is being placed on a structure (bridge deck) in which case the Engineer may specify that nuclear gauge measurements be used.

Based on the performance results and complexity of adding modifiers at the plant on the SH 119 project the addition of fiber pellets and Vestoplast S was not considered for future evaluation.

Because the polymer modified asphalt cement was delivered directly to the plant and the contractor did not have to modify the plant, the polymer modified asphalt cement was specified in CDOT's current specification. PG 76 –28 is currently being specified for SMA. (Appendix C)

SMA mixes are designed with high asphalt contents and problem with rundown can occur. Special consideration should be taken by the contractor to deliver the material to the lay down machine with minimum delay. More attention needs to be placed on the haul time and the downtime in the truck to control rundown.

An extra awareness of the truck scheduling is necessary when paving with a SMA on a bridge deck to maintain a smooth paving operation and to avoid a back up of paving trucks. Good scheduling that eliminates back-ups will in turn avoid draindown in the truck and cooling of the material.

The high asphalt content, lack of fines and the polymerized asphalt used in SMA mixes limits the ability to do extensive handwork. Because of the handwork that is required at the expansion joints additional care and caution must be taken when using a SMA mix on a bridge deck.

4.3 Performance

Initially there was a concern with the openness of the surface of the SMA. Would this type of mix segregate more, would rundown be a problem and how difficult would it be to check density (cores versus gauges)? European experience had shown exceptional performance with SMA. However, CDOT's lack of experience left many questions. To date SMA projects have exceeded CDOT's original expectations.

Because of the stone on stone contact the SMA projects performed exceptionally well and based on the final evaluation rutting was virtually non-existence. (Figure 13) This characteristic would allow SMAs to be a superior wearing surface.

Unlike CDOT's previous experience with plant mixed seal coats (PMSC) SMAs do not exhibit detrimental effects due to moisture.

The performance of SMA on bridge decks has exceeded CDOT expectations. To date there is no evidence of cracking as typically found with standard HBP.

The high asphalt content, lack of fines and the polymerized asphalt used in SMA mixes limits the ability to do extensive handwork. Because of the handwork that is required at the expansion joints additional care and caution must be taken using a SMA mix on a bridge deck.

Limited problems with flushing have been observed. These problems could be attributed to rundown and can be mitigated with efficient delivery methods to the lay down machine.

Obtaining appropriate smoothness was not an issue on SMA projects. Throughout the evaluation the SMA smoothness performed as a HBP.

Comparison of the skid values taken immediately after construction to the final skid numbers taken 6 years after construction indicate that SMAs are performing well.

4.4 Costs

Cost of the SMA on both projects was substantially higher than the cost for hot bituminous pavement. Contractors have experienced the risk and the uncertainty of the SMA mix no longer a major factor in the bid process. Contractors have indicated that as SMAs are used the cost of the SMA will become more competitive with HBP.

5.0 IMPLEMENTATION

Colorado recognized the need for high quality wearing surfaces as being cost-effective with the implementation of Superpave. With the performance history of SMA in Colorado it was decided that SMA would be the best product for wearing surfaces. As a result a task force was organized to develop guidelines and a best practice guide for SMAs.

In addition, CDOT's Bridge Branch has developed a specification for using SMA as part of the overlay system.

Based on overall performance, the design procedures and project selection guidelines have been adopted for statewide use.

Recommended Uses by CDOT:
SMA is recommended as a surface course on any high profile, high volume roadway where a skid resistant durable surface is required. Examples of possible SMA locations are Colorado's National Highway System routes, urban arterial roadways, and bridge decks.

SMA application should be limited to roadways with existing pavement conditions having only moderate or lower level distresses for cracking or raveling and as with any overlay, any rutting or base problems should be addressed before placement of the surface course.

SMA pavements are normally 2 inches thick using agnominal ¾ inch aggregate size, but wearing courses have also been placed at a 1-1/2" or 1" thickness using a ½ inch or 3/8 inch nominal aggregate respectively. All three nominal mix sizes have been successfully placed on CDOT projects. Bridge deck SMA overlays will normally be 3 inches thick.

SMA pavements have performed well as wearing courses in high traffic volume conditions by providing a rut resistant pavement with a skid resistant surface. The anticipated useful life is 5-15 years. SMA mixes have also provided excellent service on bridge decks as a wearing surface to protect deck membranes.

CDOT has developed special handling and operating procedures for SMA. These procedures can be found in Appendix G.

Cost of the SMA on both projects was substantially higher than the cost for hot bituminous pavement. Contractors have experienced the risk and the uncertainty of the SMA mix is no longer a major factor in the bid process.

Contractors have indicated that as SMAs are used the cost of the SMA will become more competitive with HBP.

REFERENCES

1. Officials "European Asphalt Study Tour," Prepared by American Association of State Highway and Transportation, June 1991

2. Roberts, Freddy. Kandhal, Prithvi. Brown, Ray. Lee Dah-Yinn and Kennedy,Thomas. "Hot Mix Asphalt Materials, Mixture Design, and Construction." National Center for Asphalt Technology, 1996

3. Harmelink, Donna, Aschenbrener, Timothy and Wood, Ken "Demonstration of the Placement of Stone Matrix Asphalt in Colorado," Colorado Department of Transportation, CDOT-DTD-R-95-1, March 1995

4. Aschenbrener, Timothy and Harmelink, Donna " SMA (Stone Matrix Asphalt) Colfax Avenue Viaduct," Colorado Department of Transportation, CDOT-DTD-R-96-7, April 1996

5. Shuler, T.S., Chairman (1991), AASHTO-AGC-ARTBA Joint Committee, Subcommittee on New Materials, Task Force 31, "Proposed Specification for Polymer Modified Asphalt," 18 pages

6. Guidelines for Materials, Production, and Placement of Stone Matrix Asphalt (SMA) (August 1994), National Asphalt Pavement Association, Information Series 118, 18 pages

7. Anderson, D.A. (1987), "Guidelines on the Use of Baghouse Fines," National Asphalt Pavement Association, Information Series 101-11/87, 31 pages

8. Criteria for Use of Asphalt Friction Surfaces 104 (1983), National Cooperative Highway Research Program Synthesis of Highway Practice, Transportation Research Board, 41 pages

Appendix A:

Aggregates for Hot Plant Mix Bituminous Pavement

703.04 Aggregate for Hot Plant Mix Bituminous Pavement. Aggregates for hot plant mix bituminous pavement shall be of uniform quality, composed of clean, hard, durable particles of crushed stone, crushed gravel, natural gravel, or crushed slag. Excess of fine material shall be wasted before crushing. For Gradings C, CX, and G, a percentage of the aggregate retained on the No. 4 sieve shall have at least two mechanically induced fractured faces when tested in accordance with Colorado Procedure 45. This percentage will be specified in Table 403-1, as revised for the project in Section 403. The natural sand content shall not exceed 20 percent of the weight of the total aggregate blend for Gradings C and CX and 15 percent for Grading G. Natural sand is unprocessed, naturally occurring fine aggregate composed mostly of round particles. All aggregates shall be non-plastic when tested in accordance with AASHTO T 90.

Reclaimed material shall be of uniform quality. The maximum size of the reclaimed asphalt pavement shall be 1 1/2 inches prior to introduction into the mixer. The maximum aggregate size contained in the combination of reclaimed asphalt pavement and new aggregate shall not exceed the maximum specified in Table 703-3. The hot bituminous pavement shall not contain more than 30 percent reclaimed asphalt pavement.

The material shall not contain clay balls, vegetable matter, or other deleterious substances. The aggregate for Gradings C, CX, and G shall have a percentage of wear of 45 or less when tested in accordance with AASHTO T 96.

TABLE 703-3

Master Range Table for Hot Bituminous Pavement

Sieve Size	Percent by Weight Passing Square Mesh Sieves			
	Grading G	Grading C	Grading CX	Grading F
1½"	100			
1"				100
¾"	63-85	100		
½"	46-78	70-95	100	
⅜"		60-88	74-95	
#4	22-54	44-72	50-78	
#8	13-43	30-58	32-60	45-85
#30	4-22	12-34	12-34	
#200	1-8	3-9	3-9	7-13

Appendix B:

Project No. NH 1191-005

SMA Specifications.

REVISION OF SECTIONS 401, 403, AND 703
STONE MASTIC ASPHALT PAVEMENT

Sections 401, 403, and 703 of the Standard Specifications and Standard Special Provisions are hereby revised for this project as follows:

Subsection 401.02 shall include the following:

Recycled Asphalt Pavement (RAP) shall not be used in Stone Mastic Asphalt (SMA) mix.

Subsection 401.02, Table 401-1 shall include the following:

**Stone Mastic Asphalt Pavement - Item 403

Passing 1/2" sieve	± 5%
Passing No. 4 and No. 8 sieves	± 4%
Passing No. 200 sieve	± 2%

The temperature requirement at the time of discharge in Table 401-1 shall not apply to stone mastic asphalt pavements.

In subsection 401.02, second paragraph, delete items (1) and (2) and replace with the following:

(1) A proposed job-mix gradation for each mixture required by the Contract, except stone mastic asphalt (SMA) mix, which shall be wholly within the master range table, Table 703-3 or 703-6, before tolerances shown in Table 401-1 are applied. Also, a proposed job-mix gradation for SMA mixes required by the Contract which shall be wholly within the master range table, 703-3, before the tolerances shown in Table 401-1 for stone mastic asphalt pavement - Item 403 are applied. The weight of lime shall be included in the total weight of the material passing the No. 200 sieve.

(2) The aggregate source, percentage of each element used in producing the final mix, the gradation of each element, and the proposed job mix formula (JMF) gradation. The gradation used shall be based on the Contractor's JMF. Before the design is performed, adjustments to the gradation of each element as determined by the Division shall be made only on the aggregates retained on the No. 4 sieve or larger.

When approved, laboratory test results submitted by the Contractor may be used to modify the mixing and compaction temperatures for SMA mixtures. Except for the VESTOPLAST-S, the minimum mixing temperature shall be that at which the kinematic viscosity is a maximum of 350 centistokes. The minimum compaction temperature shall be that at which the kinematic viscosity is a maximum of 1000 centistokes.

[3]-Ash Content:	18% (+/- 5%) non-volatiles
[4]-Ph:	7.5 (+/- 1.0)
[5]-Oil Absorption:	5.0 (+/- 1.0) (times fiber weight)
[6]-Moisture Content:	< 5% (by weight)

1 **Method A - Alpine Sieve Analysis**. This test is performed using an Alpine Air Jet Sieve (Type 200 LS). A representative five gram sample of fiber is sieved for 14 minutes at a controlled vacuum of 22 inches (+/-3) of water. The portion remaining on the screen is weighed.

2 **Method B - Mesh Screen Analysis**. This test is performed using standard Nos. 20, 40, 60, 80, 100, and 140 sieves, nylon brushes and a shaker. A representative 10 gram sample of fiber is sieved, using a shaker and two nylon brushes on each screen. The amount retained on each sieve is weighed and the percentage passing calculated.

3 **Ash Content**. A representative 2-3 gram sample of fiber is placed in a tared crucible and heated between 1100 and 1200 F for not less than two hours. The crucible and ash are cooled in a desiccator and reweighed.

4 **Ph Test**. Five grams of fiber is added to 100 ml of distilled water, stirred and let sit for 30 minutes. The Ph is determined with a probe calibrated with Ph 7.0 buffer.

5 **Oil Absorption Test**. Five grams of fiber is accurately weighed and suspended in an excess of mineral spirits for not less than five minutes to ensure total saturation. It is then placed in a screen mesh strainer (approximately 0.5 square millimeter hole size) and shaken on a wrist action shaker for ten minutes (approximately 1-1/4 inch motion at 240 shakes/minute). The shaken mass is then transferred without touching, to a tared contained and weighed. Results are reported as the amount (number of times its own weight) the fibers are able to absorb.

6 **Moisture Content**. Ten grams of fiber is weighed and placed in a 250 F forced air oven for two hours. The sample is then reweighed immediately upon removal from the oven. (Moisture Content = (Original Fiber Weight - Oven Dry Weight)/Oven Dry Weight)

FIBER PROPERTIES

Mineral (Basalt) Fibers

-Size Analysis:

[1] Fiber Length:	0.04 inches +/- 0.01 inches
[2] Thickness:	0.0002 inches +/- 0.0001 inches

[3]-Shot Content:	No. 60 sieve	90% passing (+/- 5%)
	No. 230 sieve	70% passing (+/- 10%)

[1] The fiber length is determined according to the Bauer McNett fractionation.

[2] The fiber diameter is determined by measuring at least 200 fibers in a phase contrast microscope.

[3] Shot content is a measure of non-fibrous material. The shot content is determined on vibrating sieves. Two sieves, No. 60 and No. 230 are typically utilized, for additional information see ASTM C612.

Note: For the VESTOPLAST-S the dry mixing time is 5 seconds total. The wet time is same as above. VESTOPLAST-S is added to the pugmill at the start of the dry cycle. Quantity: VESTOPLAST-S shall be 7% by weight of the liquid asphalt cement required for the mix. This 7% replaces an equal amount of asphalt cement.

For drum plant operations, the following alternate can be used:

Cellulose bitumen granulate 66/34 meeting the cellulose fiber properties can be used.

Note: Cellulose bitumen granulate and VESTOPLAST-S shall be added through RAP inlet.

*The producer shall provide certified test results.

All additive representatives shall be present at the time of start up for technical assistance.

Subsection 401.07 shall include the following:

Placement of SMA shall be permitted only when minimum air and surface temperatures are 50°F. or above.

Subsection 401.09 shall include the following:

The time between plant mixing and placement of SMA shall not exceed one hour. Each load shall be covered with a full tarp extending a minimum of 6 inches over the sides of the truck and securely fastened.

Subsection 401.15 shall include the following:

All SMA pavements, except those containing polymer modified (Type I-D) asphalt cements, shall have a mixture temperature at the time of placement between 275°F. and 310°F.

REVISION OF SECTIONS 401, 403, AND 703
STONE MASTIC ASPHALT PAVEMENT

Subsection 401.17 shall include the following:

Compaction of SMA shall be accomplished using a minimum of two steel wheel rollers weighing 10 to 12 tons. Additional steel wheel rollers may be required by the Engineer. The initial breakdown roller shall follow the laydown operation as closely as feasible. All rollers must operate within 500 feet of the paver. The Engineer must approve, and may request changes in this distance. In-place density shall comply with subsection 401.17 except the minimum acceptable level shall be 94 percent of voidless density. Price adjustments shall not apply.

Rollers shall not be used in a vibratory mode unless they are first used successfully in the demonstration control strip. Pneumatic wheel rollers shall not be used on SMAP mix. Roller speed shall be between 1 and 3 mph.

Compaction in test sections using the AC-20P modified asphalt shall be completed before the mix cools down to 275°F. and for VESTOPLAST-S 240°F.

The method of measuring relative compaction for all SMA mixtures will be in accordance with CP-44 Method B (cores).

In-place density shall be expressed as a percentage of the maximum specific gravity determined for each lot of material.

Subsection 403.02 shall include the following:

Mixture design and field control testing of SMA shall be performed using the Marshall Method (AASHTO T-245-90).

A minimum of two weeks prior to the proposed use of any stone mastic asphalt pavement on the project, the Contractor shall submit to the Engineer a mix design meeting the appropriate specification requirements, including the following:

Stability, Marshall Compactor (50 blow)	1200 lbs. minimum
% Voids in total mix	3-4%
VMA (% voids in aggregate)	15
Flow	0.10 inches to 0.18 inches
Lottman, CPL 5109	80
Dry Tensile Strength, PSI, Min. CPL 5109	30

The three SMA designs must be approved by the Engineer before any pavement is placed on the project. In addition the Contractor will provide field control testing during production of all mixtures used in the test sections. The following tests will be required for each design mix and their results provided to the Project Engineer during production:

TEST	FREQUENCY
Stability	1/400 ton or fraction there of
Flow	1/400 ton or fraction there of
% Voids in total mix	1/400 ton or fraction there of
VMA, (% voids in mineral aggregate)	1/400 ton or fraction there of
Lottman, CPL 5109	1/mix design
Dry Tensile Strength, PSI, CPL 5109	1/mix design

The person responsible for the SMA mixture designs and field control tests and the technicians performing them shall be identified at the preconstruction conference. The person responsible must possess one of more of the following qualifications:

1. Registration as a Professional Engineer in the State of Colorado

2. NICET certification at Level II or higher in the subfield of Highway Materials or Asphalt, Concrete and Soils.

3. A minimum of five years testing experience with soils, asphalt pavement and concrete.

Technicians performing the tests shall have previous design experience with the Marshall Method and must possess one or more of the following:

1. A minimum of two years testing in the specialty field.

2. Certification by a nationally recognized organization such as NICET.

3. For the appropriate specialty field, Certification by the American Concrete Institute (ACI), or by the Colorado Asphalt Producers Association (CAPA).

Subsection 403.03 shall include the following:

This work includes placing a Stone Mastic Asphalt (SMA) pavement in test sections as shown on the plans. Before proceeding with the actual work, the Contractor shall demonstrate the ability to produce and place a satisfactory mix. The actual work may proceed when a full lane width demonstration control strip, having a minimum length of 400 feet, has been successfully placed. The control strip will be used by the Engineer to determine the compactive effort required for density. No other SMA production and placement will be allowed until densities are determined. The SMA used in the demo control strip will be produced and placed using AC-20P. The control strip will be placed in a bottom lift of pavement. The Contractor will designate the location when he submits to the Engineer his paving schedule for the test strip and the Stone Mastic Asphalt Pavement demonstration.

REVISION OF SECTIONS 401, 403, AND 703
STONE MASTIC ASPHALT PAVEMENT

Tack coat between the existing pavement and SMA shall be placed at a rate between 0.03 and 0.05 gallons per square yard.

Subsection 403.04 shall include the following:

Stone mastic asphalt pavement will be measured by the ton.

Subsection 403.05 shall include the following:

Pay Item	Pay Unit
403 - Stone Mastic Asphalt (Vesto Plast)(Asphalt)	Ton
403 - Stone Mastic Asphalt (Fibers)(Asphalt)	Ton
403 - Stone Mastic Asphalt (Asphalt)(Polymer Modified)	Ton

Payment for Stone Mastic Asphalt Pavement will be full compensation for demonstrating, furnishing, hauling, preparing, and placing all materials, hydrated lime, tack coat, and approved control strip; for labor, equipment, tools, setting of lines and guides where specified, and incidentals necessary to complete the item.

Subsection 703.04 shall include the following: Coarse Aggregate:

Aggregate for Stone Mastic Asphalt Pavement shall conform to the following:

Coarse aggregate for SMA shall meet the requirements of this subsection with the following additions:

1) L.A. Abrasion Loss (AASHTO T96) 30% max
2) Sodium Sulphate Soundness Loss (AASHTO T104) 12% max

100% crushed gravel shall be used in SMA mix. A minimum of 90% of the materials retained on the #4 screen shall have two or more fractured faces. Aggregates used in SMA shall be from a single source.

Fine Aggregate: Fine aggregate shall meet the following requirements:

Sodium Sulphate Soundness Loss (5 cycles, AASHTO T109) 12% max

Fine aggregate shall consist of 100 percent crushed aggregate and shall be nonplastic (AASHTO T 90).

REVISION OF SECTIONS 401, 403, AND 703
STONE MASTIC ASPHALT PAVEMENT

Subsection 703.04, Table 703-3 shall include the following:

Sieve Size	Grading SMAP
3/4"	100
1/2"	82-88
3/8"	
#4	28-32
#8	18-22
#16	
#30	
#50	
#100	
#200	9-11

Subsection 703.06 shall include the following:

Mineral filler for the Stone Mastic Asphalt pavement shall be hydrated lime, rock, or limestone dust and shall meet the requirements of this subsection and the following:

Plasticity Index (AASHTO T-90) 4% max.

The Contractor shall submit hydrometer analysis (AASHTO T88) for mineral filler. The Contractor shall submit test number along with the reference used to perform hydrometer analysis.

The mineral filler shall be stored in a silo and added automatically in the correct proportion. The mineral filler shall be added at the point the asphalt cement is added.

Appendix C
Current Specification for SMA

REVISION OF SECTIONS 401 AND 703
STONE MASTIC ASPHALT PAVEMENT

Sections 401 and 703 of the Standard Specifications are hereby revised for this project as follows:

Subsection 401.02 shall include the following:

Recycled Asphalt Pavement (RAP) shall not be used in Stone Mastic Asphalt (SMA) mix.

Subsection 401.06 shall include the following:

Asphalt Cement for SMA shall be Superpave, Performance Graded Binder PG 76-28.

Subsection 401.16 shall include the following:

The SMA mixture shall be transported and placed on the roadway without drain-down or flushing. All flushed areas behind the paver shall be removed immediately upon discovery. If more than 5 m^2 (50 square feet) of flushed SMA pavement is ordered removed and replaced in any continuous 150 m (500 linear feet) of paver width laydown, operations shall be discontinued until the source of the flushing has been found and corrected.
The contractor is responsible for all expenses associated with removal and replacement of all flushed areas. The Engineer shall designate the depth and area of all flushed areas requiring removal and replacement.

Subsection 401.17 shall include the following:

Rollers shall not be used in a vibratory mode on SMA unless they are first used successfully in the demonstration control strip specified in subsection 403.03. Pneumatic wheel rollers shall not be used on SMA mix.

Stone Mastic Asphalt Pavement shall be placed and compacted in accordance with the temperatures listed in subsection 401.07 as revised for this project.

The relative compaction for all SMA mixtures will be measured from roadway cores in accordance with CP 44, Method C, unless the SMA mixture is being placed on a structure (bridge deck) in which case the Engineer may specify that nuclear gauge measurements be used.

When cores are used, the Contractor shall provide all labor and equipment for the coring operation and filling the core holes. When nuclear density gauges are used, the tests will be performed in accordance with CP 81 and CP 82.

In-place density for SMA shall be 93 to 97% of the SMA mix maximum specific gravity as measured according to CP 51.

Subsection 401.22 shall include the following:

Acceptance, testing, and pay factors for SMA shall be in accordance with subsections 105.03 and 106.03 as revised for this project for Hot Bituminous Pavement.

REVISION OF SECTIONS 401 AND 703
STONE MASTIC ASPHALT PAVEMENT

Subsection 703.04 shall include the following:

Aggregate for Stone Mastic Asphalt (SMA) shall conform to the following:

Aggregates for SMA shall consist of clean, hard, durable fragments of crushed stone, crushed gravel, or crushed slag. A minimum of 90% of the particles retained on the 4.75 mm (No. 4) sieve shall have at least two fractured faces when tested in accordance with CP 45. Aggregate passing the No. 4 sieve shall be the product of fracture of crushing rock larger than 12.5 mm (1/2 inch) and shall be non-plastic when tested according to AASHTO T 90.

Additionally, aggregate for SMA shall meet the following requirements:

L. A. Abrasion Loss (AASHTO T96) 30%, max. (for each source)

Sodium Sulphate Soundness Loss (AASHTO T104) 12%, max (for each source)

Subsection 703.04, Table 703-3 shall include the following for SMA aggregate:

@SMA Master Range Table

Sieve Size	***Percent by Weight Passing***		
	SMA 9.5 mm (3/8") nominal	SMA 12.5 mm (1/2") nominal	SMA 19 mm (3/4") nominal
3/4" (19 mm)	100	100	100
1/2" (12.5 mm)	100	100	85-95
3/8" (9.5 mm)	90-100	85-95	55-75
#4	30-55	24-32	24-32
#8	20-42	16-24	16-24
#30	12-25	10-16	10-16
#200	8-12	8-12	8-12

REVISION OF SECTIONS 401 AND 703
STONE MASTIC ASPHALT PAVEMENT

Subsection 703.06 shall include the following:

Mineral filler for the Stone Mastic Asphalt pavement shall be limestone dust and shall meet the requirements of this subsection and the following:

Plasticity Index (AASHTO T90)	4% Maximum

The Contractor shall submit hydrometer analysis (AASHTO T88) for the mineral filler used in the SMA mix.

****

INSTRUCTIONS TO DESIGNERS (delete instructions and symbols from final draft):

@Check gradation desired and/or delete gradation not used on the project.

Delete Units not used.

REVISION OF SECTION 403
STONE MASTIC ASPHALT PAVEMENT

Section 403 of the Standard Specifications is hereby revised for this project as follows:

Subsection 403.01 shall include the following:

This work includes placing a Stone Mastic Asphalt (SMA) pavement as shown on the plans.

Subsection 403.02 shall include the following:

Mixture design and field control testing of SMA shall be performed using either the Superpave (CPL 5115, 100 Gyrations) or the Marshall Method (AASHTO T245, 50 Blow).

A minimum of two weeks prior to the proposed use of any Stone Mastic Asphalt pavement on the project, a pre-paving conference will be conducted. At that time, the contractor shall submit to the Engineer, a mix design meeting the appropriate specification requirements for one of the following:

The Superpave SMA mix design shall conform to the requirements of Table 403-1a:

TABLE 403-1a

Property	Test Method	Value for SMA
Air Voids, percent at: N(design)	CPL 5115	3.0 – 4.0
Lab compaction (Revolutions) N(Design)	CPL 5115	100
Accelerated Moisture Susceptibility, tensile strength Ratio, (Lottman), minimum	CPL 5109, Method B	70
Minimum Dry Split Tensile Strength, psi (kPa)	CPL 5109, Method B	30
Grade of Asphalt Cement		PG 76-28
Voids in the Mineral Aggregate (VMA) %, minimum	CP 48	17

Note: The current version of CPL 5115 is available from the Region Materials Engineer

Delete Table 1 of CPL 5115 and replace with the following:

REVISION OF SECTION 403
STONE MASTIC ASPHALT PAVEMENT

CPL 5115 TABLE 1

Superpave Binder Grade	Laboratory Mixing Temperature, °C (°F)	Laboratory Compaction Temperature, °C (°F)
PG 58-28	154 (310)	138 (280)
PG 58-22	154 (310)	138 (280)
PG 58-34	154 (310)	138 (280)
PG 64-22	163 (325)	149 (300)
PG 64-28	163 (325)	149 (300)
PG 70-28	163 (325)	149 (300)
PG 76-28	163 (325)	149 (300)

The Marshall SMA mix design shall conform to the following:

MIX PROPERTIES	VALUE
Stability, Marshall Compactor	6228 Newtons (1400 lbs.), min.
% Voids in Total Mix	3 – 4%
VMA (% Voids in the Mineral Aggregate)	17 min.
Lottman, CPL 5109, Method B	70% min.
Dry Tensile Strength, (CPL 5109)	205 kPa (30 psi), min.

Regardless of mix design method, a minimum of one percent hydrated lime by weight of the combined aggregate shall be added to the aggregate for all Stone Mastic Asphalt.

The SMA mix design must be approved by the Engineer before any pavement is placed on the project. In addition, the Contractor shall provide field control testing during production of the SMA mix and for the demonstration control strip. The Contractor shall perform the following tests and provide the results to the Engineer during production:

If a Superpave SMA mix design is used, the Contractor shall perform the following tests and provide the results to the Engineer during production:

SUPERPAVE MIX PROPERTY	FREQUENCY
% Voids in the total mix @ $N_{(design)}$	1/1000 tons* or fraction thereof
VMA (% Voids in the Mineral Aggregate) @ $N_{(design)}$	1/1000 tons* or fraction thereof
Lottman, CPL 5109, Method B	1/5000 tons* or fraction thereof
Dry Tensile Strength, CPL 5109	1/5000 tons* or fraction thereof
% AC & Aggregate Gradation CP 5120	1/1000 tons* or fraction thereof

* English or metric

REVISION OF SECTION 403
STONE MASTIC ASPHALT PAVEMENT

If a Marshall SMA mix design is used, the Contractor shall perform the following tests and provide the results to the Engineer during production:

MARSHALL MIX PROPERTY	FREQUENCY
Stability (Marshall)	1/1000 tons* or fraction thereof
% Voids in the total mix	1/1000 tons* or fraction thereof
VMA (% Voids in the Mineral Aggregate)	1/1000 tons* or fraction thereof
Lottman, CPL 5109, Method B	1/5000 tons* or fraction thereof
Dry Tensile Strength, CPL 5109	1/5000 tons* or fraction thereof
% AC & Aggregate Gradation CP 5120	1/1000 tons* or fraction thereof

* English or metric

The personnel responsible for SMA mix design and field control tests shall be qualified according to the requirements of CP 10.

Subsection 403.03 shall include the following:

The mineral filler for SMA shall be stored in a separate silo and added automatically in the correct proportion. The mineral filler addition equipment shall be electronically or mechanically interlocked to the aggregate feed sensors so that the proper amount of mineral filler is added whenever SMA is produced.

The SMA mineral filler shall be added at the same point the asphalt cement is added to the aggregate.

Tack coat between the existing pavement and Stone Mastic Asphalt pavement shall be placed at a rate between 0.14 and 0.23 liters per square meter (0.03 and 0.05 gallons per square yard).

Before proceeding with SMA placement, the Contractor shall demonstrate the ability to produce and place a satisfactory mix. The actual work may proceed when a full lane width demonstration control strip, having a minimum length of 300 meters (1000 feet) has been successfully placed. The Contractor shall determine properties (VMA, Voids, in-place density, and Marshall Stability, if required) of the project produced mix that is used in the demonstration control strip and provide the results to the Engineer. No other SMA production or placement will be allowed until densities are determined. If the material in the demonstration control strip is not in close conformity with the specifications, the demonstration control strip will be removed and replaced at the Contractors expense. The Engineer will designate the location of the control strip.

REVISION OF SECTION 403
STONE MASTIC ASPHALT PAVEMENT

Subsection 403.04 shall include the following:

Stone Mastic Asphalt (SMA) will be measured by the Metric Ton (Ton) of work completed and accepted.

Subsection 403.05 shall include the following:

Pay Item	**Pay Unit**
Stone Mastic Asphalt (SMA)	Metric Ton (Ton)

@ Mix design, furnishing, hauling, preparing, and placing all materials, including aggregates, asphalt cement, limestone dust, hydrated lime, tack coat, and approved demonstration control strip; labor, equipment tools, setting of lines and guides where specified, and all other work necessary to complete the item will not be paid for separately but shall be included in the work.

****

INSTRUCTIONS TO DESIGNERS (delete instructions and symbols from final draft):

@If asphalt cement is to be paid ***for*** separately, the above note should read:

Mix design, furnishing, hauling, preparing, and placing all materials, including aggregates, limestone dust, hydrated lime, tack coat, and approved demonstration control strip; labor, equipment tools, setting of lines and guides where specified, and all other work necessary to complete the item will not be paid for separately but shall be included in the work.

Asphalt Cement will be measured and paid for in accordance with Section 411.

Delete unused paragraphs.

Delete the units not used.

Appendix D
Colorado Procedure L 5109

Colorado Procedure
L 5109

Method of Test For

Resistance of Compacted Bituminous Mixture to Moisture Induced Damage

This procedure modifies AASHTO T 283-89, AASHTO T 283-89 may not be used in-place of this procedure.

1. Scope

1.1 This method covers preparation of specimens and measurement of the change of diametral tensile strength resulting from the effects of saturation and accelerated water conditioning of compacted bituminous mixtures in the laboratory. The results may be used to predict long-term stripping susceptibility of the bituminous mixtures, and evaluating liquid anti-stripping additives which are added to the asphalt cement or pulverulent solids, such as hydrated lime, which are added to the mineral aggregate.

2. Referenced Documents

2.1 *AASHTO Standards*:

- M 156 Requirements for Mixing Plants for Hot Mixed, Hot-Laid Bituminous Paving Mixtures
- T 166 Bulk Specific Gravity of Compacted Bituminous Mixtures
- T 167 Compressive Strength of Bituminous Mixtures
- T 168 Sampling Bituminous Paving Mixtures
- T 209 Maximum Specific Gravity of Bituminous Paving Mixtures
- T 245 Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus
- T 246 Resistance to Deformation and Cohesion of Bituminous Mixtures by Means of Hveem Apparatus
- T 247 Preparation of Test Specimens of Bituminous Mixtures by Means of California Kneading Compactor
- T 269 Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures

2.2 *ASTM Standards*:

- D 3387 Test for Compaction and Shear Properties of Bituminous Mixtures by Means of the U.S. Corps of Engineers Gyratory Testing Machine (GTM)
- D 3549 Test for Thickness or Height of Compacted Bituminous Paving Mixture Specimens
- D 4013 Standard Practice for Preparation of Test Specimens of Bituminous Mixtures by Means of Gyratory Shear Compactor

2.2 *Colorado Procedures:*

- CP-L 5102 Maximum Specific Gravity of Bituminous Paving Mixtures
- CP-L 5105 Standard Practice for Preparation of Test Specimens of Bituminous Mixtures by Means of Gyratory Shear Compactor
- CP-L 5115 Standard Method for Preparing and Determining the Density of Bituminous Mixture Test Specimens by Means of the Superpave Gyratory Compactor

3. Significance and Use

3.1 As noted in the scope, this method is intended to evaluate the effects of saturation and accelerated water conditioning of compacted bituminous mixtures in the laboratory. This method can be used (a) to test bituminous mixtures in conjunction with mixture design testing, (b) to test bituminous mixtures produced at mixing plants, and (c) to test the bituminous concrete cores obtained from completed pavements of any age.

3.2 Numerical indices of retained indirect tensile properties are obtained by comparing the retained indirect properties of saturated, accelerated water-conditioned laboratory specimens with the similar properties of dry specimens.

4. Summary of Method

4.1 Test specimens of laboratory produced material are tested using the proposed asphalt binder at the optimum asphalt cement content (Note 1). Each set of specimens is divided into subsets. One subset is tested in dry condition for indirect tensile strength. The other subset is subjected to vacuum saturation followed by a freeze and warm water soaking cycle and then tested for indirect tensile strength. Numerical indices of retained indirect tensile strength properties are computed from the test data obtained on the two subsets: dry and conditioned.

NOTE 1—It is recommended to prepare two additional specimens for the set. These specimens can then be used to establish the vacuum saturation technique as given in Section 9.3.

5. Apparatus

5.1 Equipment for preparing and compacting specimens from one of the following: CP-L 5105 or CP-L 5115.

5.2 Vacuum container, preferably Type D, from ASTM D 2041 and vacuum pump or water aspirator from CP-L 5102 including manometer or vacuum gauge.

5.3 Balance and water bath from T 166.

5.4.1 Water bath capable of maintaining a temperature of 140 ± 1.8°F (60 ± 1 °C).

5.4.2 Water bath capable of maintaining a temperature of 77 ± 1.8°F (25 ± 1°C).

5.5 Freezer maintained at 0 ± 5°F (-18 ± 3°C).

5.6 A supply of plastic film for wrapping, heavy-duty leak proof plastic bags to enclose the saturated specimens and masking tape.

5.7 10 ml graduated cylinder.

5.8 Aluminum or steel pans having a surface area of 40-100 square inches (250-640 cm^2) in the bottom and a depth of approximately 1 to 3 inches (25 mm to 75 mm).

5.9 Forced air draft oven capable of maintaining a temperature of 140 ± 1.8°F (60 ± 1°C).

5.10 Loading jack and ring dynamometer from AASHTO T 245, or a mechanical or hydraulic testing machine from AASHTO T 167 to provide a range of accurately controllable rates of vertical deformation including 0.2 and 2 in. per minute (5.1 and 50.8 mm per minute).

5.11 *Loading Strips*—If used, steel loading strips with a concave surface having a radius of curvature equal to the nominal radius of the test specimen. For specimens 4 inches (101.6 mm) in diameter the loading strips shall be 0.5 inches (12.7 mm) wide, and for specimens 6 inches (152.4 mm) in diameter the loading strips shall be 0.75 in. (19.05 mm) wide. The length of the loading strips shall exceed the thickness of the specimens. The edges of the loading strips shall be rounded by grinding.

6. Preparation of Laboratory Mixed and Field Produced Test Specimens

6.1 Specimens 4 inches (101.6 mm) in diameter and 2.5 inches (63.5 mm) thick are usually used. Specimens of other dimensions may be used if desired and should be used if aggregate larger than 1 inch (25.4 mm) is present in the mixture and/or is not permitted to be scalped out.

6.2 *Laboratory Mixed Material* - After mixing, the mixture shall be placed in an aluminum or steel pan having a surface area of 40-100 square inches (250-640 cm^2) in the bottom and a depth of approximately 1 to 3 inches (25.4 mm to 75 mm) and cooled at room temperature for 2 ± 0.5 hours. Then the mixture shall be placed in a 140°F (60°C) oven for 16 to 24 hours for short-term aging. The pans should be placed on spacers to allow air circulation under the pan if the shelves are not perforated. This short term aging procedure is used for laboratory mixed samples only. Field produced material is not short-term aged before the compaction procedure.

6.3 After short-term aging for laboratory mixed samples or splitting to the proper sample weight for field produced material, place the mixture in an oven using the applicable procedure of CP-L 5105 or CP-L 5115. The mixture shall be compacted to 7.0 ± 1.0 percent air voids (calculated in Section 8). This level of voids can be obtained as specified in CP-L 5105 or CP-L 5115.

NOTE 2—Procedure 6.2 is used only for laboratory mixed test specimens. It does not apply to test specimens of plant produced material.

NOTE 3—Adjustment of sample voids may be done by adjusting sample weights. If a sample has a sample weight of 1150 grams and a specific gravity of 94.5 % of theoretical maximum specific gravity (Rice value) (5.5 % air voids) and the target specific gravity is 93 % of the theoretical maximum specific gravity (7 % air voids), the sample weight may be reduced according to the formula: target sample weight = 1150 x 93 % / 94.5 %. The target sample weight would be approximately 1132 grams.

7. Preparation of Core Test Specimens

7.1 Select locations on the completed pavement to be sampled, and obtain cores. The number of cores shall be at least 6 for each set of mix conditions.

7.2 Separate core layers as necessary by sawing or other suitable means, and store layers to be tested at room temperature.

7.3 Four inch (101.6 mm) diameter core samples should have a minimum height of 2.25 inches (57 mm) and a maximum height of 2.75 inches (70 mm). Samples with heights smaller than the minimum height should be remolded to the in-place air void content.

8. Evaluation of Test Specimens and Grouping

8.1 Determine theoretical maximum specific gravity of mixture by CP-L 5102.

8.2 Determine specimen thickness by CP-L 5105.

8.3 Determine bulk specific gravity by CP-L 5103. Express volume of specimens in cubic centimeters.

8.4 Calculate air voids using the formula:

$$V_a = (100 \times (1 - (G_{mb} / G_{mm}))$$

where:

V_a = air voids content (percent)
G_{mb} = bulk specific gravity of compacted sample
G_{mm} = theoretical maximum specific gravity of mixture

8.5 Sort specimens into two subsets of three specimens each so that average air voids of the two subsets are approximately equal.

METHOD A

9. Moisture Conditioning of Test Specimens (55 to 80 Percent Saturation)

NOTE 4: This method is to be used unless specified otherwise.

9.1 One subset will be tested dry and the other will be moisture conditioned before testing.

9.2 The dry subset will be stored at room temperature until testing. The specimens shall be wrapped with plastic or placed in a heavy duty leak proof plastic bag. The specimens shall then be placed in the 77°F (25°C) water bath with the conditioned specimens for a minimum of 2 hours and not longer than 4 hours and then tested as described in Section 10. It is critical that the dry specimens remain dry if this method is used. Alternatively, the specimens may be stored in an incubator capable of holding a temperature of 77 ± 1.8°F until tested as described in Section 10.

9.3 The other subset shall be conditioned as follows:

9.3.1 Place the specimen in the vacuum container supported above the container bottom by a spacer or standing on its side. Fill the container with clean tap water at room temperature so that the specimens have at least one inch of water above their surface. Apply partial vacuum for a short time (5 to 20 seconds or long enough to achieve the degree of saturation outlined in 9.3.3. Slowly remove the vacuum and leave the specimen submerged in water for a short time (greater than 5 seconds).

9.3.2 As soon as possible after removing specimen from the water, determine bulk specific gravity of the saturated specimen by CP-L 5103. Calculate the level of saturation and swell as defined in Section 11.

9.3.3 If the level of saturation is between 55 percent and 80 percent, proceed to Section 9.3.4. If level of saturation is less than 55 percent, repeat the procedure beginning with Section 9.3.1 using more vacuum and/or time. If level of saturation is more than 80 percent, specimen has been damaged and is discarded. Repeat the procedure beginning with Section 9.3.1 using less vacuum and/or time.

9.3.4 Cover the wet, vacuum saturated specimens tightly with a plastic film (saran wrap or equivalent). Place each wrapped specimen in a plastic bag and seal the bag.

9.3.5 Place the plastic bag containing specimen in a freezer at 0 ± 5°F (- 18 ± 3°C) for a minimum of 16 hours.

9.3.6 After removal from the freezer, place the specimens into a 140 ± 1.8°F (60 ± 1°C) water bath for 24 ± 1 hours. As soon as possible after placement in the water bath or, if possible, before placement in the water bath, remove the plastic bag and film from the specimens.

9.3.7 After 24 ± 1 hours in the 140°F (60°C) water bath, remove the specimens and place them in a water bath already at 77 ± 1°F (25 ± 0.5°C) for 3 ± 1 hours. It may be necessary to add ice to the water bath to prevent the water temperature from rising above 77°F (25°C). Not more than 15 minutes should be required for the water bath to reach 77°F (25°C). Test the specimens as described in Section 10.

METHOD B

Moisture Conditioning of Test Specimens (5 Minute Saturation Method)

NOTE 5: This method is included for documentation purposes only. Method B should be used only if a 5 minute specimen saturation time is specified. Otherwise Method A should be used. To use Method B, replace Sections 9.3 to 9.3.3 above with the following Sections

9B.3 The other subset shall be conditioned as follows:

9B.3.1 Place the specimen in the vacuum container supported above the container bottom by a spacer or standing on its side. Fill the container with distilled water at room temperature so that the specimens have at least one inch of water above their surface. Apply a vacuum of 28 ± 2 mm of Hg for a period of 5 ± 0.25 minutes. The vacuum shall be monitored using a mercury manometer and adjusted using a needle valve. Begin timing the vacuum application when the applied vacuum reaches the specified level. Slowly remove the vacuum and leave the specimen submerged in water for a short time (greater than 5 seconds).

9B.3.2 As soon as possible after removing specimen from the water, determine bulk specific gravity of the saturated specimen by CP-L 5103. Calculate the level of saturation and swell as defined in Section 11.

10. Testing

10.1 Determine the indirect tensile strength of dry and conditioned specimens at 77°F (25°C).

10.2 Remove the specimen from 77°F (25°C) water bath and place between the two bearing plates in the testing machine. Care must be taken so that the load will be applied along the diameter of the specimen as illustrated in Figure 1. Apply the load to the specimen by means of the constant rate of movement of the testing machine head of 0.2 inches (5.1 mm) per minute.

10.3 If steel loading strips are used, record the maximum compressive strength noted on the testing machine. If desired, continue loading until a vertical crack appears. Remove the specimen from the machine and pull apart at the crack. Inspect the interior surface for stripping and record the observations.

10.4 If steel loading strips are not used, stop loading as soon as the maximum compressive load is reached. Record the maximum compressive load. Remove the specimen, measure and record the side (edge) flattening to the nearest 0.1 inch. The flattening may be easier to measure if the flattened edge is rubbed with the lengthwise edge of a piece of chalk. If desired, after recording the flattening, replace the specimen in the compression machine and compress until a vertical crack appears. Remove the specimen from the machine and pull apart at the crack. Inspect the interior surface for stripping and record the observations.

11. Calculations

11.1 If steel loading strips are used, calculate the tensile strength as follows:

$$S_1 = \frac{2P}{\pi t D}$$

where:

S_1 = tensile strength, psi,
P = maximum load, pounds,
t = specimen thickness, inches, and
D = specimen diameter, inches.

11.2 If steel loading strips are not used, calculate the tensile strength of a 4-inch (101.6 mm) diameter specimen as follows:

$$S_1 = \frac{S_{10}P}{10{,}000t}$$

where:

S_1 = tensile strength, psi,

S_{10} = maximum tensile stress corresponding to the width of flattened area from Table 1 in AASHTO T 283,
P = maximum load, pounds, and
t = specimen thickness, inches.

11.3 Express the numerical index or resistance of asphalt mixtures to the detrimental effect of water as the ratio of the original strength that is retained after the freeze-warm water conditioning. Calculate as follows:

$$Tensile\ Strength\ Ratio\ (TSR) = \frac{S_2}{S_1}$$

where:

S_1 = average tensile strength of dry subset, and
S_2 = average tensile strength of moisture conditioned subset.

11.4 Calculate the level of saturation as follows:

$$s = \frac{(B_{sat} - A)}{(B - C) * \left[1 - \left(\frac{A}{G * (B - C)}\right)\right]} * 100\%$$

where:

s = level of saturation (%)
A = mass in grams of the dry sample in air
B = mass in grams of the surface-dry sample, in air
B_{sat} = mass in grams of the surface-dry sample, in air, after saturation
C = mass in grams of the sample, in water
G = maximum specific gravity by CPL 5102

11.5 Calculate swell after saturation as follows:

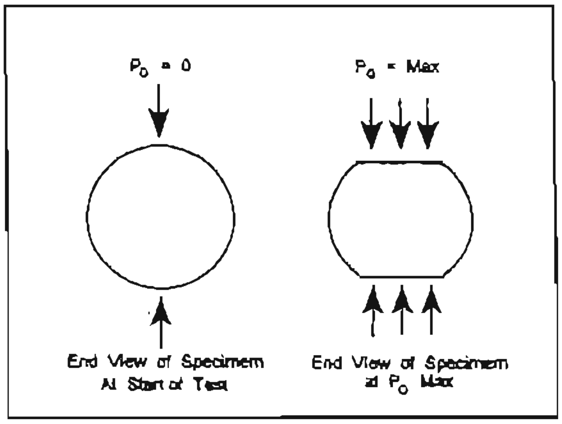
$$swell = \frac{(B_{sat} - C_{sat}) - (B - C)}{(B - C)} * 100\%$$

where:

C_{sat} = same as C except that the sample has been saturated

To calculate the swell after moisture conditioning, Determine B_{sat} and C_{sat} prior to breaking the sample as discussed in section 10.2.

FIGURE 1



Appendix E:

Locations of Various SMA Mixtures for project No. NH 1191-005

Date Paved	Quantity (Tons)	SMA Type	% AC	Sta to Sta	Location	Layer
8/26/94	200	PM-1D	6.0	508+12 - 495+00	SB RT SHLDR	BOT
8/29/94	200	.PM-1D	6.0	495+00 - 481+72	SB RT SHLDR	BOT
	428	PM-1D	5.8	508+00 - 481+72	SB RT LANE	BOT
8/30/94	658	PM-1D	5.8	508+00 - 481+72	SB LT LANE	BOT
	602	PM-1D	5.8	508+00 - 486+00	SB LT LANE	TOP
8/31/94	100	VESTO	5.8	482+50 - 472+00	SB RT SHLDR	BOT
	200	VESTO	5.6	472+00 - 465+00	SB RT SHLDR	BOT
9/1/94	275	VESTO	5.6	465+00 - 455+32	SB RT SHLDR	BOT
	650	VESTO	5.6	481+72 - 455+20	SB RT LANE	BOT
	275	VESTO	5.6	481+72 - 468+25	SB LT LANE	BOT
	100	VESTO	5.4	464+00 - 458+00	SB LT ACCEL LANE	BOT
9/2/94	300	VESTO	5.6	468+22 - 456+00	SB LT LANE	BOT
9/14/94	756	PM-1D	5.8	402+00 - 428+92	NB RT LN & SHLDR	TOP
	398	PM-1D	5.8	508+12 - 486+00	SB RT LANE	TOP
9/15/94	691	PM-1D	5.8	402+52 - 428+92	NB LT LANE	TOP
	337	PM-1D	5.8	508+12 - 485+00	SB RT SHLDR	TOP
	428	VESTO	5.6	482+00 - 458+00	SB RT SHLDR	TOP
	67	VESTO	5.4	458+00 - 451+75	SB RT SHLDR	TOP
9/16/94	245	VESTO	5.5*	486+00 - 469+75	SB RT LANE	TOP
9/23/94	284	VESTO	5.5*	469+75 - 452+50	SB RT LANE	TOP
	228	VESTO	5.5*	473+75 - 456+25	SB LT ACCEL LANE	TOP
	309	VESTO	5.5*	486+00 - 476+00	SB LT LANE	TOP
9/26/94	553	VESTO	5.5*	376+00 - 402+52	NB LT LANE	TOP
	383	VESTO	5.5*	376+00 - 402+52	NB RT LANE	TOP
	345	VESTO	5.5*	476+00 - 453+75	SB LT LANE	TOP
9/27/94	333	VESTO	5.5*	376+00 - 402+25	NB RT SHLDR	TOP
	93	VESTO	5.5*	429+72 - 434+25	NB RT SHLDR	TOP
	292	FIBERS	6.0	434+25 - 455+50	NB RT SHLDR	TOP
9/28/94	453	FIBERS	6.0	428+92 - 454+25	NB RT LANE	TOP
	659	FIBERS	6.0	428+92 - 455+75	NB LT LANE	TOP

* 7% mineral filler in lieu of 5%

Appendix F
SMA Specification for Project No. C0404-030

REVISION OF SECTIONS 401, 403, AND 703
STONE MASTIC ASPHALT PAVEMENT

Sections 401, 403, and 703 of the Standard Specifications and Standard Special Provisions are hereby revised for this project as follows:

Subsection 401.02 shall include the following:

Recycled Asphalt Pavement (RAP) shall not be used in SMA mix.

Table 401-1 shall include the following:

**Stone Mastic Asphalt Pavement - Item 403

Passing 3/8" sieve	± 5%
Passing No. 4 and No. 8 sieves	± 4%
Passing No. 200 sieve	± 2%

In Subsection 401.02, second paragraph, delete items (1) and (2) and replace with the following:

(1) A proposed job-mix gradation for each mixture required by the contract, except stone mastic asphalt (SMA) mix, which shall be wholly within the master range table, Table 703-3 or 703-6, before the tolerances shown in Table 401-1 are applied. Also, a proposed job-mix gradation for SMA mix required by the contract which shall be wholly within the master range table, 703-3, before the tolerances shown in Table 401-1 for stone mastic asphalt pavement - Item 403 are applied.

(2) The aggregate source, percentage of each element used in producing the final mix, and the gradation of each element.

When approved, laboratory test results submitted by the contractor may be used to modify the mixing and compaction temperatures.

Subsection 401.06 shall include the following:

Asphalt Cement shall be (Polymer Modified) (Type I-D).

Subsection 401.07 shall include the following:

Placement of SMA shall be permitted only when minimum air and surface temperatures are 50 F. or above.

Subsection 401.09 shall include the following:

The time between plant mixing and placement of SMA shall not exceed one hour.

REVISION OF SECTIONS 401, 403, AND 703
STONE MASTIC ASPHALT PAVEMENT

Subsection 401.17 shall include the following:

Compaction of SMA shall be accomplished using a minimum of two steel wheel rollers weighing 10 to 12 tons. Additional steel wheel rollers may be required by the Engineer. The initial breakdown roller shall follow the laydown operation as closely as feasible. All rollers must operate within 500 feet of the paver. The Engineer must approve, and may request changes in this distance. In-place density shall comply with Subsection 401.17 except the minimum acceptable level shall be 94 percent of voidless density. Price adjustments shall not apply.

Rollers shall not be used in a vibratory mode unless they are first used successfully in the demonstration control strip. Pneumatic wheel rollers shall not be used on SMA mix. Roller speed shall be between 1 and 3 mph.

Compaction shall be completed before the mix cools down to 275 F.

The method of measuring relative compaction for all SMA mixtures will be in accordance with CP-44 Method B (cores). The contractor shall provide all labor and equipment for the coring operation, and filling the core holes.

In-place density shall be expressed as a percentage of the maximum specific gravity determined for each lot of material.

Subsection 403.01 shall include the following:

This work includes placing a Stone Mastic Asphalt (SMA) pavement as shown on the plans. Before proceeding with the actual work, the contractor shall demonstrate that he can produce and place a satisfactory mix. The actual work may proceed when a full lane width demonstration control strip, having a minimum length of 400 feet, has been successfully placed. The control strip will be used by the Engineer to determine the compactive effort required for density. No other SMA production and placement will be allowed until densities are determined. The Engineer will designate the location of the control strip.

Subsection 403.02 shall include the following:

Mixture design and field control testing shall be performed using the Marshall Method (AASHTO T-245-90).

A minimum of two weeks prior to the proposed use of any stone mastic asphalt pavement on the project, the contractor shall submit to the engineer a mix design meeting the appropriate specification requirements, including the following:

Stability, Marshall Compactor (50 blow)	1400 lbs. minimum
% Voids in total mix	3-4%
VMA (% voids in aggregate)	16
Flow, 0.25 mm (0.01 inch)	8-18
Lottman, CPL 5109, Min.	70
Dry Tensile Strength, PSI, Min. CPL 5109	30

A minimum of one percent hydrated lime by weight of the combined aggregate shall be added to the aggregate for all SMA pavement.

The SMA design must be approved by the Engineer before any pavement is placed on the project. In addition the Contractor will provide field control testing during production of the SMA mix. The following tests will be required for the design mix and their results provided to the Project Engineer during production:

TEST	FREQUENCY
Stability	1/400 ton or fraction thereof
Flow	1/400 ton or fraction thereof
% Voids in total mix	1/400 ton or fraction thereof
VMA, (% voids in mineral aggregate)	1/400 ton or fraction thereof
Lottman, CPL 5109	1/mix design
Dry Tensile Strength, PSI, CPL 5109	1/mix design

The person responsible for the SMA mixture designs and field control tests and the technicians performing them shall be identified at the preconstruction conference. The person responsible must possess one or more of the following qualifications:

1. Registration as a Professional Engineer in the State of Colorado

2. NICET certification at Level II or higher in the subfield of Highway Materials or Asphalt, Concrete and Soils.

3. A minimum of five years testing experience with soils, asphalt pavement and concrete.

Technicians performing the tests shall have previous design experience with the Marshall Method and must possess one or more of the following:

1. A minimum of two years testing in the specialty field.

2. Certification by a nationally recognized organization such as NICET.

3. For the appropriate specialty field, Certification by the American Concrete Institute (ACI), or by the Colorado Asphalt Producers Association (CAPA).

REVISION OF SECTIONS 401, 403, AND 703
STONE MASTIC ASPHALT PAVEMENT

Subsection 403.03 shall include the following:

Tack coat between the existing pavement and SMA shall be placed at a rate between 0.03 and 0.05 gallons per square yard.

Subsection 403.04 shall include the following:

Stone mastic asphalt pavement will be measured by the ton

Subsection 403.05 shall include the following:

Payment for Stone Mastic Asphalt Pavement will be full compensation for, mix design, furnishing, hauling, preparing, and placing all materials, limestone dust, hydrated lime, tack coat, and approved control strip; for labor, equipment, tools, setting of lines and guides where specified, and incidentals necessary to complete the item.

Subsection 703.04 shall include the following:Coarse Aggregate:

Aggregate for Stone Mastic Asphalt Pavement shall conform to the following:

Coarse aggregate for SMA shall meet the requirements of this subsection with the following additions:

1) L.A. Abrasion Loss (AASHTO T96)	30% max
2) Sodium Sulphate Soundness Loss (AASHTO T104)	12% max

100% crushed gravel shall be used in SMA mix. A minimum of 90% of the materials retained on the #4 screen shall have two or more fractured faces. Aggregates used in SMA shall be from a single source.

Fine Aggregate: Fine aggregate shall meet the following requirements:

Sodium Sulphate Soundness Loss (5 cycles, AASHTO T109) 12% max

Fine aggregate shall consist of 100 percent crushed aggregate and shall be nonplastic (AASHTO T-90).

REVISION OF SECTIONS 401, 403, AND 703
STONE MASTIC ASPHALT PAVEMENT

Subsection 703.04, Table 703-3 shall include the following:

Sieve Size	Grading SMA
3/4"	100
1/2"	90-100
3/8	75 (Maximum)
#4	20-30
#8	16-24
#16	
#30	
#50	
#100	
#200	7-11

Subsection 703.06 shall include the following:

Mineral filler for the Stone Mastic Asphalt pavement shall be limestone dust and shall meet the requirements of this subsection and the following:

Plasticity Index (AASHTO T-90)	4% max

The Contractor shall submit hydrometer analysis (AASHTO T88) for mineral filler.

The mineral filler shall be stored in a silo and added automatically in the correct proportion. The mineral filler shall be added at the point the asphalt cement is added.

Appendix G:
Special Handling Recommendations for SMA Mixes.

Appendix , CP-L 5115

Special Handling Recommendations For SMA mixes

Perform the following steps when handling laboratory produced mix sample material:

(1) Set up individual sample without mineral filler.

(2) Stir set-up dry and then mix with 3% water (without mineral filler).

(3) Heat both set-up and mineral filler to required mixing temperature (325°F for PG 76-28).

(4) Mix set-up by hand with enough asphalt cement to accommodate both the set-up and the mineral filler.

(5) Blend proper amount of hot mineral filler to premixed set-up.

(6) Heat for 2 hours at compaction temperature. Excessive heating time or temperature appears to increase drain down.

(7) Stir mortar back into set-up if there is any drain down.

(8) Compact to 100 gyrations.

(9) Set oven temperatures either 1°C or 2°F higher than specified for compaction.(Note : To ensure repeatability, it is very important to compact these samples at the specified temperature). By heating samples 1°C above the specified temperature and transferring the set-up and starting compaction as fast as possible without spilling,(approximately 45 seconds from oven to the start of compaction), the sample is compacted at the proper temperature. Individual labs should check the cooling rate of samples using their mode of sample preparation to ensure the mix is at the proper temperature during compaction.

Perform the following steps when handling project produced mix sample material.

(1) If possible, split out samples to the test size for compaction and Rice specific gravity determination at the mixing plant immediately after sampling. The samples should then be mixed as required to reintroduce drained asphalt cement after heating for the proper time at the compaction temperature.

(2) To prepare a can which has cooled, remove the lid, place upside down on a large pan (24"x 24"), heat for 3 hours at 300°F. This should keep any drain down in the set-up pan, instead of the bottom of the sample can.

(3) In the ignition furnace, heat 2200-gram samples in two cages instead of one to prevent having the mortar drain into the bottom pan where it does not burn totally.

(4) Prior to compaction be sure to scrape the pan bottom and stir mortar back into the mix before loading the mold. Spray all utensils with pam to prevent SMA from sticking to utensils.