Sulphur Enhanced Asphalt Concrete Test Sections

Constructed on the Sea-To-Sky Highway Improvement Project, British Columbia

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ABSTRACT

In the fall of 2008, several test sections of Sulphur Enhanced Asphalt Concrete (Shell Thiopave) were constructed on the Highway 99 "Sea To Sky Highway" improvement project constructed by Peter Kiewit Sons. This paper summarizes the results of the initial research, design, construction practices, production test results and post-construction testing results obtained during the construction of these test sections.

Specifically, this document is intended to provide a brief overview of the Sulphur Enhanced Asphalt Concrete Technology used on this project, as a comparison between the new warm mix asphalt technology and the older liquid sulphur asphalt mixes, a summary of recent preliminary findings with regards to sulphur enhanced mix environmental impacts, a summary of the procedures and information developed during the initial design phase for these test sections, findings and improvements implemented during the construction phase and a summary of the production quality control tests.

Introduction to Sulphur Enhanced Asphalt Concrete

The material used for this project has been categorized as a *Sulphur Extended Asphalt Modifier*, or *SEAM.* This material is used to enhance the stiffness and rut resistance of asphalt paving mixes while maintaining the ductility and resistance to cracking that is critical to pavement performance. Mixtures using this material are produced and placed as a WAM (warm asphalt mix) product consisting of sulphur pellets, a compaction agent, conventional asphalt cement and aggregate mixtures and provides benefits such as reduced fuel costs, reduced aging and reduced emissions during mixture production and handling due to the lower bitumen content and reduced temperatures.

For most conditions, this material is used to replace 20-25 percent of the mass (weight) of the bitumen required by the mixture design with at least the same volume of sulphur-enhanced product. Since sulphur is approximately twice as dense as bitumen, a greater mass of material is required to maintain the same volume of "binder" (combined sulphur enhanced material and bitumen) in the mixture. For example, conventional asphalt paving mixture design that would require 5.0% bitumen (by mass) would use approximately 2.5% Sulphur and 3.8% bitumen to provide the same total binder volume when a 40 percent substitution is used.

Mixtures produced using sulphur-enhanced materials are batched and placed using conventional asphalt mixing plants and paving equipment. These materials are typically added to the asphalt mix toward the end of the mixing process after the addition of the liquid bitumen, after temperatures have equilibrated but allowing for thorough dispersal throughout the mixture before it is discharged for storage or transport.

In terms of positive environmental impacts, reduced mixing temperatures and bitumen content when using Sulphur Enhanced Materials results in less energy needed to produce the mixture. For a properly calibrated mixing plant, the reduced demand for burner fuel, lower temperatures and reduced bitumen content combine to reduce volatile organic compound (VOC) emissions during production, hauling and paving. An additional benefit from this may be realized from reduced greenhouse gas (GHG) emissions, which can be accounted for and perhaps provide an additional economic benefit from using the materials as they become more closely regulated.

Liquid Sulphur "Out", Solid Biochemically Formulated Pellets "In"

Many associate sulphur asphalt mixes with the 1960's and 70's technology which consisted of various methods of introducing hot liquid sulphur into the liquid bitumen prior to completing the mixing process with the heated aggregate.

These processes created many problematic issues related to the improper heating, transfer and mixing of the hot liquid sulphur with the liquid bitumen, which translated to field placement problems, structural inconsistencies and overall mistrust of the reliability of the mixes. Generally, though, when the components were mixed properly there was a favorable outcome with regard to strength and durability.

Other problems with this technology, primarily related to the inability to properly control the heating process, included potential brittleness and the production of potentially harmful SO_2 and H_2S gas during the mixing process, which carried over to the placement location.

The new formulated materials have eliminated all of these problems as well as creating some potential benefits not originally anticipated.

The biochemically formulated sulfur pellets were developed which could be readily added to asphalt paving mixtures via the recycle collar (by using an aggregate feed hopper just as typical aggregate) or in the case of these test sections via an Olds Elevator feeder screw regulated by the plant computer, eliminating the expense and hazard associated with hot, liquid sulfur use and mitigating the fumes and odors emanating from the hot liquid sulphur paving mixture. The new technology is based on the incorporation of a fume adsorbent in the sulfur pellets. The latest improvements in pastillizing and chemistry, which started in 2000 in North America, eliminate many of the problems associated with the use of liquid sulfur. Because of ongoing structural changes in the marketplace, sulfur is again becoming a viable product for the paving industry. Renewed interest in this technology complements current issues of resource conservation and sustainable development and, in particular, the reduction in CO_2 and volatile organic compounds.

In essence, the new sulphur enhancement technology has incorporated the positive strengthening potential of sulphur with a warm mix asphalt (WAM) compaction aid to create a very economical, very workable warm mix asphalt that produces a very durable yet ductile pavement section.

How about the environment?

Don't be fooled by the smell. The truth is as long as the sulphur-enhanced materials are introduced into the mixing process properly, at the correct temperature and at the proper phase of mixing, the levels of potentially harmful SO_2 and H_2S gases are negligible. Additionally, because the Thiopave materials are lacking organic structure and are used at lower temperatures with reduced bitumen contents, the net result is a tangible reduction in volatile organic compound (VOC) emissions during production.

Preliminary results issued by Blue Source Canada confirm these findings and formulate the initial process by which users and/or producers will stand to gain valuable carbon credits when the Carbon Equivalency Program in Canada is established.

"In terms of positive environmental impacts, the use of SEAM (now Thiopave) will yield a benefit via incremental revenue and reduced fuel costs, due to lower mix temperatures and reduced use of bitumen asphalt binder. In addition, project developers should record reduced air emissions during asphalt storage, hot mixing and paving due to the lower asphalt content of the paving mix.

In addition, the potential to capture and commercialize the GHG emission reduction will provide additional economic benefit to the hot mix facility operator. To enable quantification, a protocol is currently being developed for approval in the Alberta Offset System. This system was selected as it is the only compliance based offset system currently operating in North America, however additional systems are also being explored"

Currently there are a number of environmental monitoring programs gathering data that will be used to back up the preliminary results already published.

The Design

During the period of April 1, 2008 through August 11, 2008 Mid Pacific Testing & Inspection Services Inc. performed a series of research trials using the sulphur extended asphalt modifier technology. The laboratory work was primarily performed in the Mid Pacific Testing & Inspection, NW Division laboratory although a small portion of the work was performed in the Mid Pacific Testing Honolulu laboratory in order to cross-verify results. In addition to the testing performed by our firm, fatigue, rut resistance and cold temperature properties testing was performed on our laboratory prepared mix by Dongre Laboratory Services, Inc. in Fairfax Virginia.

The trials consisted of testing both conventional and sulphur enhanced mixes using the Marshall and Superpave mix design procedures as outlined in "The Asphalt Handbook" MS-4, 7th edition by the Asphalt Institute and as modified by the procedures included in this summary.

The aggregate used for these trials was quarried from the Rayonier pit in Squamish, BC and processed using a temporary crusher system operated by Peter Kiewit Sons, Inc. Coast Aggregate products also in Squamish supplied the imported sand. The crushing procedures included a crusher jaw and a high-speed cone. The aggregate was chosen because Mid Pacific Testing had already performed conventional mix designs for both the Marshall and Superpave mixes being used on the Sea To Sky highway project (Olympic Highway) which runs from Vancouver, BC to Whistler, BC and is currently being rehabilitated in order to serve as the main thoroughfare for the 2010 winter Olympic skiing events. Two asphalt cement binder types were used including Strathcona 80/100-penetration and 150/200-penetration bitumen. The 80/100 asphalt cement is the asphalt cement type currently being used for the Sea To Sky project. Using the same aggregate and asphalt cement type for most of the mixes allowed for an accurate, substantiated comparison of the various proportions and mix performances.

The aggregate gradation target values used for these trials were developed using the 2004 edition of the BC-MOT Standard Specifications for Highway Construction, and consisted of the following:

TABLE 1 – MoT Grading Targets

Sieve Size	Sulphur Enhanced & Conventional Class 1 (% Passing)	Sulphur Enhanced & Conventional Superpave (% Passing)
25 mm	100	100
19 mm	100	100
12.5 mm	86	93
9.5 mm	77	80
4.75 mm	59	54
2.36 mm	40	36
1.18 mm	27	24
600 μ	18	16
300 μ	11	11
150 μ	8	8
75 μ	5.0	5.6

In order to provide consistent results, a standardized laboratory procedure was established using the guidelines recommended in the Asphalt Institute Handbook and modified slightly to accommodate the Thiopave product. This procedure is summarized in appendix A.

The asphalt mixes used for these trials were mixed using a Hobart 20 Qt. electric mixer. The Marshall samples were compacted with a Humboldt Manufactured triple automatic compactor with flat compaction heads and a rotating base and received 75 blows per side. The Superpave samples were fabricated using a Pine Instruments gyratory compactor set for traffic loads of 3 to 30 million ESALs. 4% air voids were the target for both mixes.

A total of 13 Class 1 mixes (typical mid range MoT base course or dense graded mix specification) and 3 Superpave (typical MoT surface or wearing course) mixes were prepared during these trials. Additionally, 12 of the 13 class 1 mixes were duplicated using varying target binder contents and mixing & compacting temperatures in order to establish acceptable performance parameters for each mix. A total of four mixes were prepared using the 150/200-penetration binder as a design change option for the Sea To Sky project.

The following table summarizes the performance test results for the Sulphur Enhanced mixes determined to be optimal for the Sea To Sky Project and the corresponding conventional mixes currently being used. These are the mixes that we recommended for use on the project as they exhibited equal or better performance properties than the conventional mix with regard to Marshall stability, flow, fatigue characteristics, modulus and rut resistance.

TABLE 2 – Sea To Sky Mix Design Basics

Mix ID	Asphalt cement Binder Type	% Sulphur Enhanced Product	Gmb	Flow (.25mm)	Stability (N)	Voids	Equiv. Binder	Rut Depth (mm)	# Cycles to 200 mstrain (fatigue)
Conventional Class 1	80/100	0	2.484	10.0	20386	4.1	4.8	5.02	132900
Sulphur Enhanced Class 1 mix #9	80/100	30	2.476	11.0	20173	4.5	5.08	3.25	790000
Conventional Surface	80/100	0	2.470	--	--	4.0	4.9	16.3	--
60/40 Sulphur Enhanced Surface	80/100	40	2.515	--	--	4.0	4.95	2.28	--

The Test Sections

TEST SECTION #1 (CLASS 1 MEDIUM BASE ASPHALT)

On October 26, 2008 a test section of asphalt concrete with Sulphur Enhanced Materials was placed on the Sea To Sky Highway project. This section was approximately 820 metric tons of the base lift of asphalt and was placed on the southbound lanes (both left and right) from station 118+100 to 118+440. The asphalt was produced by BA Blacktop Ltd. from their Squamish Gencor single drum asphalt plant using an Olds Elevator to introduce the Sulphur materials into the RAP chute and a modified air blower system through a Hi-Tech Asphalt Solutions Inc. feeder to introduce the compaction additive (CA) into the asphalt cement flow. The plant was running in the "Volumetric" mode during the enhanced asphalt batching process which forced the pellets and CA to be introduced at a specified rate (in this case based on motor frequencies calibrated to a specified mass of product) without being automatically adjusted by the plant computer system. In most other cases with permanent facilities the sulphur and CA feeders are tied into the automatic batching system.

The initial mixing process began with conventional asphalt at the normal batching temperature (145℃ to 150℃) and once the plant temperatures were normalized and consistent, the mix temperature was systematically reduced until the desired warm mix batching temperature was reached (135℃) at which point the system was switched to the "Volumetric" mode and the sulphur enhanced asphalt mix batching commenced. In all cases the average temperature for the mix leaving the yard was around 137℃.

Initial testing of the binder content was performed on the fourth truck (± 120 tones), which was determined to be the last truck with conventional mix and then again on the sixth truck that was determined to be the first consistent truck with sulphur enhanced mix. Binder contents on the first enhanced mix truck revealed slightly higher than expected asphalt cement and an excess amount of Sulphur. Based on the initial binder test, an adjustment was made to the Olds Elevator motor frequency to reduce the sulphur flow. Subsequent binder testing continued to show slightly high asphalt cement contents and slightly low Sulphur contents throughout the remainder of the batching until the final test which was at approximately 800 tones. This test revealed almost ideal Sulphur content and slightly high asphalt cement content. All testing performed including in place core testing is summarized on the following page.

TABLE 3 - Summary of Test Section #1 Bulk Sample Results

Sample ID & Location	Tones	Total Binder	SULPHUR Content	Stability (N)	Flow (.25mm)	Density	Theoretical Maximum	Lab Voids
61 – 118+380 SB RL	**540**	**6.55**	**2.27**	**21785** **14 day = 22076**	**11**	**2545**	**2598**	**2.04**

62 – 118+500 SB RL	**119**	**5.73**	**1.39**	**17755** **14 day = 19125**	**10**	**2514**	**2602**	**3.38**
74 – 118+115 SB LL	**800**	**5.96**	**1.71**	**20426** **14 day = 21145**	**11**	**2551**	**2604**	**2.04**

TABLE 4 - Summary of Test Section #1 Core Test Results

Core ID & Location	Size	Thickness	Density	Theoretical Maximum	Field Voids
68 – 118+115 SB LL	**6”**	**86.7**	**2509**	**2612**	**3.94**
69 – 118+200 SB RL	**6”**	**72.9**	**2503**	**2616**	**4.32**
70 – 118+290 SB RL	**6”**	**78.7**	**2434**	**2595**	**6.20**
71 – 118+115 SB LL	**4”**	**80**	**2493**	**2612**	**4.56**
72 – 118+200 SB RL	**4”**	**73.8**	**2493**	**2616**	**4.70**
73 – 118+290 SB RL	**4”**	**82.1**	**2450**	**2595**	**5.59**

Theoretical maximum density values for the cores were established using the 6” core samples. These values were also used for the corresponding 4” core calculations. There is some speculation that the sample retrieved at 119 tones contained some Sulphur (as was substantiated using the ignition and nuclear content ovens) and thus was at the transition point between conventional and Sulphur enhanced mix.

Additional stability samples were obtained and tested at 14 days in order to ascertain the strength gain after the Sulphur crystallization process. Additionally, fatigue samples were fabricated and sent to Dongre Laboratories in Fairfax Virginia as required by the agreed upon testing protocol.

TEST SECTION #2 (CLASS 1 MEDIUM BASE ASPHALT)

On November 13, 2008 a second test section of asphalt concrete with Sulphur enhanced materials was placed on the Sea To Sky Highway project. This section was approximately 1000 metric tons of the base lift of asphalt and was placed on the northbound lanes (both left and right) from station 247+580 to 248+400. The asphalt was produced by BA Blacktop Ltd. using the same batch plant and equipment.

The initial mixing process began with approx. 200 tones of conventional asphalt at the normal batching temperature (145°C to 150°C) and once the plant temperatures were normalized and consistent, the mix temperature was systematically reduced until the desired warm mix batching temperature was reached (135°C) at which point the system was switched to the "Volumetric" mode and the sulphur enhanced mix batching commenced. Mix that didn't meet either the conventional mix temperature requirements in the case of the initial mix and the lower temperatures in the case of the Sulphur mix was rejected prior to entering the silo. Temperature readings were recorded from the truck boxes as the mix left the plant and the average temperature for the Sulphur mix leaving the yard was around 135°C.

Testing of the binder content was performed on the ninth truck, which was determined to be the first truck with Sulphur enhanced mix and then every two hundred tones thereafter. Binder content testing throughout the day was consistent with the plant settings and ended up all having slightly higher equivalent binder contents than the target. This higher value can probably be attributed to slightly elevated bitumen contents due to excessive moisture in the aggregate. In most cases, modifications to the plant that allow all materials to be regulated automatically would be completed thereby eliminating this issue.

The Olds elevator and CA feeder systems worked perfectly and responded as expected when slight adjustments in the frequencies were applied.

Field operations were performed just as with conventional paving except compaction was achieved at much lower temperatures. Temperatures behind the screed were 120°C to 125°C and at the finish roller were in the low 60°C range.

Field personnel were issued protective clothing and breathing apparatus, some chose to wear them and others did not. H_2S monitors were worn by the lay down crew and QC inspectors and did not indicate exposure to H_2S.

TABLE 5 - Summary of Test Section #2 Bulk Sample Results

Sample ID & Location	Tones	Total Binder	Sulphur Content	Stability (N)	Flow (.25mm)	Density	Theoretical Maximum	Lab Voids
95 – 200 Sulphur Mix Tones	**200**	**6.23**	**1.94**	**17348** **14 day = 21132**	**10**	**2545**	**2600**	**2.1**
98 – 800 Sulphur Mix Tones	**800**	**5.74**	**1.45**	**17499** **14 day = 20855**	**10**	**2508**	**2595**	**3.4**

TABLE 6 - Summary of Test Section #2 Core Test Results

Core ID & Location	Size	Thickness	Density	Theoretical Maximum	Field Voids
1A – 247+770 NB RL	**6”**	**48.0**	**2471**	**2595**	**4.8**
2A – 248+320 NB RL	**6”**	**52.7**	**2444**	**2589**	**5.6**
3A – 248+157 NB RL	**6”**	**56.1**	**2482**	**2589**	**4.2**

Theoretical maximum density values for the cores were established using the 6” core samples.

Additional stability samples were obtained and tested at 14 days. Samples were also fabricated for fatigue and low temp properties and sent to Dongre Laboratories in Fairfax Virginia.

TEST SECTION #3 (CLASS 1 MEDIUM BASE ASPHALT)

On November 18, 2008 a third test section of asphalt concrete with Sulphur enhanced materials was placed on the Sea To Sky Highway project. This section was approximately 1100 metric tons of the base lift of asphalt and was placed on both the northbound and southbound lanes (all lanes) from station

99+500 to 100+000. As with the other tests, the asphalt was produced by BA Blacktop Ltd. from their Squamish plant using the same procedures and equipment.

The initial mixing process began with approx. 50 tones of conventional asphalt at the normal batching temperature (145°C to 150°C) and once the plant temperatures were normalized and consistent, the mix temperature was systematically reduced until the desired warm mix batching temperature was reached (135°C) at which point the system was switched to the "Volumetric" mode and the Sulphur enhanced mix batching commenced.

Testing of the binder content was performed on the fourth truck, which was determined to be the first truck with Sulphur enhanced mix and then every two hundred tones thereafter. Binder content results throughout the day were very consistent with the plant settings and ended up very close to the production target.

The Olds elevator and CA feeder systems worked perfectly and responded as expected when slight adjustments in the frequencies were applied.

Field operations were performed just as with conventional paving except compaction was achieved at much lower temperatures. Temperatures behind the screed were 120°C to 125°C and at the finish roller were in the low 60°C range.

Final density values revealed a minimum of 97% compaction based on laboratory maximum values and met the project specification.

This third test section received a more vigilant monitoring of the H_2S and SO_2 emissions in the field. As with the previous tests sections, field personnel were issued protective clothing and breathing apparatus, some chose to wear them and others did not. Monitors were worn by the lay down crew and QC inspectors and did not indicate exposure to H_2S or SO_2 although it was said that a couple of them "beeped" on occasion. BA Blacktop had their Health and Safety officer on site performing additional readings of the H_2S levels around the paver and paving personnel. The paver was modified with tarps and ventilation assistance blowers to expel the screed and auger fumes away from the workers. This temporary system improved the working area fume count and will become a permanent system on all pavers placing Thiopave material.

TABLE 7 - Summary of Test Section #3 Bulk Sample

Sample ID & Location	Total Tones	Total Binder	SULPHUR Content	Stability (N)	Flow (.25mm)	Density	Theoretical Maximum	Lab Voids
100 Sulphur Mix Tonnes	**150**	**6.02**	**1.64**					
200 Sulphur Mix Tonnes	**250**	**6.02**	**1.54**	**16873** **14 day = 21145**	**11**	**2515**	**2615**	**3.8**
400 Sulphur Mix Tonnes	**450**	**6.12**	**1.77**					
600 Sulphur Mix Tonnes	**650**	**5.96**	**1.71**					
800 Sulphur Mix Tonnes	**850**	**5.90**	**1.75**	**16952** **14 day = 22331**	**10**	**2525**	**2607**	**3.1**

***Lab specimens compacted at 120℃ to simulate field conditions**

TABLE 8 - Summary of Test Section #3 Core Test Results

Core ID & Location	Size	Thickness	Density	Theoretical Maximum	Field Voids
3A – 99+640 NB LL	**6”**	**80.1**	**2463**	**2599**	**5.2**
3B – 99+750 NB RL	**6”**	**82.1**	**2474**	**2606**	**5.1**
3B – 99+900 NB RL	**6”**	**78.9**	**2483**	**2601**	**4.5**

As with the first two test sections, additional stability samples were obtained and tested at 14 days. Samples were also fabricated for fatigue and low temp properties and sent to Dongre Laboratories in Fairfax Virginia.

Samples fabricated and sent to Dongre Laboratories included TSRST specimens, rut and fatigue specimens and asphalt samples for PG grade analysis. The results of these tests are summarized below.

TABLE 9 -E* Results

Station ID	Air Voids	20°C		40°C		20°C		40°C	
		E*, psi	COV % E*	E*, psi	COV % E*	Delta	COV % delta	Delta	COV % delta
Test section 1 SULPHUR enhanced mix									
Sta118+201	3.9%	175,249	13	30,273	12	34.3	2	36.0	3
Sta118+202	4.1%	202,086	17	36,840	14	26.3	5	41.8	6
Test section 3 SULPHUR enhanced mix									
99+640	5.2%	263,969	8	31,570	18	22.7	7	40.8	3
99+900	4.5%	242,648	57	45,687	73	19.5	18	37.6	13
Conventional Cores									
99+550	5.4%	145,719	12	15,483	18	37.9	7	52.0	6
99+551	5.5%	138,453	7	15,585	12	35.5	4	51.5	4
99+555	5.1%	182,264	10	11,888	21	30.1	2	56.9	7

TABLE 10 - Rut and Fatigue Results

Sample Source	Mix Type	Rut Depth mm	Avg. Rut Depth mm	Rutting Slope mm/cycle	No. of Cycles to Dmg. Ratio = 0.5 (200 μs)
QA/QC	SuperPave I	2.85	2.42	-5.62922E-05	--
		1.99		-5.18435E-05	--

QA/QC	SuperPave I	3.74	4.035	-1.15E-04	--
		4.33		-1.10E-04	--
QA/QC	Class I 09/26/09	--	--	--	< 44,082
		--		--	433,538
QA/QC	Class I 09/29/08	--	--	--	< 75,600
		--		--	379,174
QA/QC	Class I 09/30/08	--	--	--	< 232,242
		--		--	--
QA/QC	Class I 10/18/08	--	--	--	< 220,362
		--		--	< 233,027
QA/QC	Superpave 10/18/08	--	--	--	< 230,889
		--		--	--
QA/QC	Sulphur Mix 10-26-08	--	--	--	26,406,433
		--		--	27,002,450
QA/QC	Sulphur Mix 11-11-08	--	--	--	31,516,486
		--		--	44,791,136
QA/QC	TestSection3_Sulphur	--	--	--	< 27,897,769
		--		--	< 28,034,686
QA/QC	TestSection3_Sulphur 400 μs	--	--	--	452,707,047
		--		--	--
QA/QC	TestSection3_Sulphur 600 μs	--	--	--	21,257,405
		--		--	--

TABLE 11 - TSRST Performance Results

Specimen ID replicate	Fracture Temperature (˚C)	Fracture Strength (MPa)
Sulphur 1	-29.00	4.19
Sulphur 2	-26.97	3.98
Sulphur 3 - 11/08/08	-26.97	5.81
Superpave 1	-20.23	3.66

Superpave 2	-19.30	3.25
Class I 9-26 1	-26.00	4.92
Class I 9-26 2	-27.57	5.07
Class I 9-28 1	-28.60	5.59
Class I 9-28 2		
Class I 9-30 1	-25.77	4.42
Class I 9-30 1 edited	-23.37	4.42
Class I 9-30 2	-21.40	4.22
Class I 10-8 1	-20.17	3.86
Class I 10-8 2	-7.90	1.17
Class I 10-9 1	-17.60	3.59
Class I 10-9 2	-15.17	3.24

*The last 3 specimens ACO5, ACO6, ACO7 were aged for 5 days at 85 C

*Class 1 9-28 2 was broken during the coring. No results for it

*Class 9-30 1 edited due to a microcrack recorded by the LVDT .

TABLE 12 - PG Grading Results

Sample ID	PG Grade	
	Exact	PG
G_10-26-08	PG 65.9-28.8	PG 64-28
Q_11-13-08	PG 66.3-26.0	PG 64-22
Q_11-18-08	PG 66.2-25.8	PG 64-22

APPENDIX A

Procedure for performing Marshall & Superpave mix designs in the Laboratory using the Thiopave technology

1. *Apparatus & Materials*
    a. *Molds, extractor & compaction apparatus in accordance with ASTM D 6925 for Superpave mixes and D 6926 for Marshall mixes.*
    b. *Ovens, heating pans & hot plates in accordance with ASTM D6926.*
    c. *Mixing apparatus – Mechanical mixing is required. Use any type of mechanical mixer capable of producing a well-coated homogeneous mixture while maintaining the proper mixing temperature. A laboratory Drum mixer or Hobart (or similar) mixer is recommended.*
    d. *Balance – a balance or scale readable and accurate to 0.1 g or 0.1% of test load whichever is greater.*
    e. *Calibrated thermometers – Armored-glass or digital type thermometers with metal stems are recommended for determining temperatures of bitumen, infrared thermometers are recommended for determining aggregate and bituminous mixture temperatures. Accuracy shall be ±3℃.*
    f. *Typical mixing vessels, spoons & scoops as mentioned in ASTM D 6926.*
    g. *Ventilation- perform these procedures in a well-ventilated area. The mixing portion of this procedure shall be completed under a fume hood.*
    h. *Cleanup – Do not use heat or open flame to clean equipment. A citrus based biodegradable cleaner or similar is recommended.*

2. *Test Specimens*
    a. *Dry aggregates to a constant weight @ 110℃. After cooling, process the aggregates in accordance with ASTM D 6925 and/or D6926. Two methods can be used to produce the correct proportions of aggregate for the mix.*
        i. *Method 1 – If a well-established traditional asphalt mixture is being duplicated, pile proportions of well mixed and split samples can be combined to re-produce the cold feed mixture. When using this method, an additional mixture of aggregate shall be made and tested in accordance with ASTM C136*

(sieve analysis) in order to confirm the proportions meet the mixture target values.

ii. *Method 2 – the preferred method is to separate the aggregates by dry sieving into the appropriate sizes and then recombine those aggregates into the proper proportions in accordance with the desired target values. Refer to the Asphalt Institute MS-2 or "The Marshall Method" by Dr. Richard W. Smith, PE for proper procedures in proportioning aggregate.*

b. *Determine the estimated target binder content for the design. The asphalt Institute MS-2 and "The Marshall Method" by Dr. Richard W. Smith, PE both contain procedures for estimating target binder content. Select four binder contents for the mix design with two being greater than the estimated target binder content and two being less than the estimated target.*

c. *Convert the four conventional design binder contents to the new Thiopave binder contents using the "Thiopave Binder Content Formula"*

$$\text{Thiopave + Bitumen Wt. \%} = A\left(\frac{100R}{100R - P_s(R - G_{bitumen})}\right)$$

Where: *Thiopave + Bitumen Wt. % = Modified total binder content needed to duplicate the conventional binder target.*

A = Weight % bitumen in conventional mix design

R = Thiopave binder to bitumen substitution ratio

Or $R = G_{THIO} \div G_{BITUMEN}$

P_s *= Weight % of Thiopave binder in total binder*

$G_{bitumen}$ *= Specific Gravity of bitumen*

d. *Once the Thiopave binder content values are established for the four mix design points, carefully determine the mass of bitumen, Thiopave binder & Compaction Additive (CA 100) to be used for the mix using the Asphalt Mix Design Lab Worksheet for Thiopave in the appendix of this procedure. Generally 6000g (aggregate wt.) batches are the most practical individual batches to be mixed. Make sure the final wt. of each batch is sufficient to produce the desired quantities for all required strength and durability tests. Refer to ASTM D6925 for Superpave requirements and ASTM D6926 for Marshall test requirements. Unless otherwise noted, figures should be based on the total weight of mix (TWM) formula.*
e. *The CA 100 shall be introduced directly into the heated bitumen. This can be accomplished by pouring the heated bitumen into a tared container, calculating the total mass of conventional binder to be used, and adding the CA 100 at 1.0% by weight of total bitumen into the heated bitumen stirring rapidly until completely dissolved. Once mixed, the bitumen / CA 100 mixture shall be placed back in the oven and once it returns to the proper temperature is used just as the bitumen in conventional mix design procedures.*
f. *Pre-weigh the required amount of Thiopave pellets for each mixture and retain in an oven at 60℃ until mixing commences.*
g. *Heat the aggregate, bitumen & mixing equipment (bowl, spoon, etc) to the appropriate temperature, established by using the standard temp visc charts issued by the bitumen supplier or to 150℃ whichever is greater. It has been established in lab trials that it is necessary to heat the aggregate and bitumen to slightly higher temperatures than noted in the temp/visc chart in order to achieve the proper mixing temperature at the time of introduction of the materials to the mixing bowl. Factors such as ambient temperature, humidity and other environmental conditions all affect the rate in which the mixing materials cool. A well-established lab should know the ideal oven temperatures at which proper actual mixing temperatures can be maintained.*
h. *All equipment that will be used in the mixing and spooning process shall be pre-conditioned with a bituminous mixture (buttered) so that binder material is not unnecessarily absorbed from the mixture.*
i. *Transfer the heated mixing bowl to the scale. Transfer the heated aggregate to the bowl creating a concave or "dished out" area in*

the center of the aggregate. Tare the scale to zero then add the bitumen/CA100 liquid of appropriate mass to the aggregate. At this point if too much asphalt cement has been added, the asphalt cement will pool in the center of the concave area and allow for bailing the excess from the mixture.

j. *Transfer the bowl to the automatic mixer and begin the mixing process. Once the mixing has begun and the temperature of the aggregate & bitumen mix is between 140℃ and 150℃, pour the Thiopave pellets into the mixing bowl and continue mixing until the mixture is fully coated and homogenous.*
k. *IMPORTANT – once the mixing is complete, retrieve a spoonful of the mix and carefully examine it for un-dissolved Thiopave pellets. If the product has not mixed properly, there will be small bitumen coated perfectly round spheres that look like small aggregate. This is an indication that the mixing temperature was not correct. If this occurs, discard the sample and remix after investigating the procedures for maintaining proper mixing temperature.*
l. *Once the mixing process is complete, follow the procedures set forth in ASTM D 6925 and/or D6926 for compaction assuring that you maintain the proper compaction temperatures noted on the temp/visc chart. Care should be exercised when extracting the compacted specimens from the molds so that damage to the specimen does not occur. A short cooling period prior to extraction of the specimen may be required.*
m. *Report all anomalies with the test results*

**There is a distinct difference in compaction temperatures of the asphalt mixture between design and production QC . In design it has been recognized that the violent nature of asphalt batching is not properly reproduced and therefore the temperatures of the mixture in the laboratory at the design phase for Thiopave material will generally be about 20-25℃ greater than those temperatures used for compacting specimens fabricated from hot mix retrieved from the field during production QC. Generally the design compaction temperatures are 145℃ and QC Production compaction temperatures are 120 to 125℃. Consult the Thiopave Engineers if there is any doubt on the proper compaction temperatures.*