SULFUR EXTENDED ASPHALT AS A MAJOR OUTLET FOR SULFUR THAT OUTPERFORMED OTHER ASPHALT MIXES IN THE GULF

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Abstract

Availability of sulfur has considerably grown in many countries. In the Gulf region, particularly in Saudi Arabia due to the increase in number of oil & gas industries, the production of sulfur as a co-product has also increased. The investigation of new applications for sulfur in construction has become a challenge for civil engineers. Sulfur Extended Asphalt (SEA) used for paving roads is one of the promising applications for sulfur utilization in construction materials. SEA can be used by partial substitution of asphalt with sulfur. Global utilization of 30/70 sulfur/asphalt mix in road construction and maintenance could consume significant amount of sulfur annually making utilization of sulfur in road construction as one of the primary outlets for sulfur.

This paper will outline the result of collaboration between Saudi Aramco, King Fahd University of Petroleum and Minerals, Ministry of Transport and contractors in Saudi Arabia to investigate the feasibility of utilizing elemental sulfur as a partial substitute of asphalt in road construction. The investigation covered different aspects of utilizing sulfur in road construction including field trials and a four-year monitoring program that addressed the different distresses of pavement. The study indicated that workability of sulfur asphalt is similar to conventional asphalt. Fume emissions associated with the use of sulfur asphalt were well below the allowable limits with mixing temperature of sulfur asphalt below 145 degrees Centigrade. The study indicated that 30% replacement of asphalt with sulfur is the optimum replacement. Based on the lab study and four years of monitoring, sulfur asphalt outperformed conventional asphalt and polymer modified asphalt in terms of rutting resistance.

Key words: *Sulfur, Sulfur-asphalt technology, Sulfur modified asphalt mixes.*

1. BACKGROUND

During the last decade in the Gulf region, particularly in Saudi Arabia the availability of sulfur as a by-product has increased considerably. This is mainly due to the implementation of strict environmental restrictions on petroleum and gas refining processes which limit the maximum quantity of sulfur present in oil and gas. The need to investigate the applications for sulfur has thus become fundamental in the region.

Asphalt binder is a thermoplastic material that behaves as an elastic solid at low service temperatures or during rapid loading and behaves as a viscous liquid at high temperatures or slow loading. This double behavior creates a need to improve the performance of an asphalt binder in order to minimize stress cracking, which occurs at low temperatures, and permanent deformation, which occurs at high in-service temperatures. Daily and seasonal temperature variations plus the growth in truck traffic volume, tire pressure and loading have increased stresses on asphalt pavements. Local asphalt pavement temperatures range between –10°C in winter and 73°C in summer (Al-Abdul Wahhab et al. 1997). This has led to an increased demand to modify asphalt binders. Different methods have been used to upgrade the properties of asphalt binders. One of the most commonly used procedures is the modification of asphalt binders by the addition of modifiers.

Sulfur's ability to modify and enhance the properties of construction materials has been extensively researched and exploited over the past four decades. Most of the research work has come to a halt as a result of the historic market demand for sulphur about two decades ago. Since then, the amount of sulfur produced from oil and gas has increased resulting in a drop of market prices. In general, the availability of sulfur has considerably grown in many countries. This is mainly due to the current environmental restrictions regarding the petroleum and gas refining processes, which limit the maximum quantity of sulfur present in fossil fuels. Extremely large quantities of sulfur are thus obtained as a by-product of these processes, together with coal processing. The development of new applications for sulfur becomes fundamental. Sulfur asphalt used for paving roads is one of the prominent among its applications. Using sulfur to enhance or rejuvenate asphalt could consume significant amount of sulfur. Even if sulfur captured only a conservative 5% of the current asphalt market, it would represent a market for nearly one million tons of sulfur annually and can help alleviate the oncoming sulfur surplus. Sulfur-asphalt concrete has a relatively simple composition and manufacturing process, and very interesting characteristics and properties. Its extremely high corrosion resistance, mechanical strength and fast hardening make it a

high performance material suitable for several applications, especially the ones in which other materials may not suffice (Gracia and Vazquez 2003).

In 1978, the Metrology, Standards and Materials Division of the Research Institute at King Fahd University of Petroleum and Minerals (KFUPM/RI) launched an in-house research study on sulfur-asphalt pavement development. Among the various available techniques of substituting asphalt with sulfur, the sulfur-extended asphalt (SEA) paving technology developed by Gulf Canada was considered to be the closest to practical applications. Three SEA test roads were laid in the Eastern Province in cooperation with Gulf Canada and the Ministry of Communications (MOC), Saudi Arabia as part of the ongoing road development program of MOC. A sulfur/asphalt ratio of 30/70 by weight was used in Test Road 1 (Kuwait Diversion) and Test Road 3 (KFUPM), whereas a higher percentage of 45/55 was used in Test Road 2 (Abu-Hadriyah Expressway). Performance of the test roads was monitored from time to time. For Test Road 2, the control section using normal asphalt concrete showed better performance than the SEA sections (Arora et al. 1994). The SEA sections developed mostly longitudinal/transverse cracking in Test Road 1; alligator and block cracking in Test Road 2; and block and longitudinal/transverse cracking in Test Road 3. On the control AC sections, the most predominant distress types were found to be longitudinal/transverse cracking and polishing of aggregate. The inherently stiffer SEA mix of Test Road 2, where the sulfur/asphalt ratio was 45/55, resulted in earlier cracking of SEA pavement, particularly in a thinner section where the thickness was intentionally reduced by 20 percent.

Fatani and Sultan (1982) conducted a study to determine the feasibility of using dune sand in asphalt-concrete pavement in hot, desert like climates through the use of one-size crushed aggregates. Dense-graded aggregate and powdered sulfur were used in the sand-asphalt mixes. Engineering properties, including Marshall design parameters, compressive strength, tensile strength, modulus of rupture, and dynamic modulus of elasticity were evaluated. Results indicated that a mixture of dune sand and asphalt is weak, unstable, easily deformed under light loads, and therefore unacceptable for pavement construction in desert like environment. The use of powdered sulfur and sand-asphalt mixes reduces the optimum asphalt content, increases considerably the qualities of the mix even under severe environmental conditions, and reduces the pavement thickness.

Arora and Abdul-Rahman (1985) have explored the use of sulfur as a rejuvenation agent in recycling reclaimed asphalt pavement from a typical failed segment of Dammam-Abu-Hadriyah Expressway. They indicated that the addition of sulfur, at mixing temperature,

would lower the viscosity of the aged asphalt. Upon cooling, recrystallization of sulfur is known to occur, which improves the strength of the mix. Properties like Marshall stability, resilient modulus and fatigue behavior of sulfur-recycled mix are compared with those of the conventional asphalt-concrete mix. The addition of sulfur results in higher Marshall stability without significant loss in flow values, higher retained strength index, and higher M_R and tensile strength, indicating superior engineering properties of the recycled mixture over the conventional asphalt hot mix. The above properties are particularly advantageous to the hot region of the Arab World since they provide adequate resistance to wheel track rutting otherwise associated with conventional asphalt-concrete mixtures.

Akili (1985) carried out an extensive laboratory testing program designed to measure improvements in engineering properties of sulfur-asphalt-sand (SAS) mixes attributable to the presence of sulfur in the mix, considering locally available sands and prevailing environmental conditions in eastern Saudi Arabia. The laboratory characterization data include Marshall design parameters, resilient moduli, and permanent strain characteristics under repeated triaxial loading. The results, in general, showed improvements in Marshall stability, resilient modulus values and reduced permanent deformation of SAS mixes in comparison to conventional sand-asphalt mixes. From Spring 2001 through February 2002, about 42 lane miles of roads containing sulfur were built in the southwest United States. These projects incorporated a formed, solid sulfur product that was added directly to existing hot mix plant equipment. Following mixing, the sulfur asphalt was hauled to the project location using conventional dump trucks, road paving, and compaction equipment. An additional 104 lane miles of roads containing sulfur are planned in the southwest U.S., and other road projects incorporating sulfur are also being considered in China, Kazakhstan, and Egypt. The use of a formed, solid material and the direct mixing method minimizes hot asphalt mix plant modifications and associated costs. Also, solid sulfur can be shipped freely without regulation; whereas, liquid sulfur requires special shipping considerations (Weber 2002).

The use of sulfur as an additive to extend or replace asphalt has been demonstrated successfully in both laboratory tests and actual construction. The availability and cost of sulfur offer the potential to reduce paving material costs by as much as 21 percent. Binder cost reductions as high as 32 percent are feasible (Weber and McBee 2000).

Sulfur asphalt is enjoying a resurgence of interest worldwide. The Sulphur Institute (TSI) has been actively working with the US Federal Highway Administration and through other channels to promote the utilization of sulfur asphalt.

Although sulfur is a vital raw material to manufacture a myriad of products, its abundance is likely to reduce its regional cost. Other uses such as construction materials should be explored to utilize this abundant resource in a useful, economical, and environmentally friendly way. This research funded by Saudi Aramco was carried out to study the effect of sulfur asphalt mixes and verify their adequacies for safe use locally through laboratory and field studies.

2. RESEARCH APPROACH

2.1 Materials Selection

The locally available aggregate in the Eastern Province was selected for this study. The Saudi Aramco specification for Wearing course (WC) and Base course (BC) gradation was followed in all mix designs. Asphalt cement of grade 60/70 was obtained from Ras Tanurah refinery. The materials obtained were tested for gradation and physical characteristics to assure their conformity to Aramco standards. The elemental sulfur in pellet form, used in the study was obtained from Saudi Aramco.

2.2 Sulfur-Asphalt Asphalt Blends

Blends of modified asphalts were prepared for WC and BC by mixing elemental sulfur with the local asphalt. Blend was prepared using elemental sulfur with a ratio of 30/70 by weight of binder. Each blend was prepared by heating the plain asphalt to 135°C and slowly adding the required amount of sulfur as per the weight ratios using a shear-blender. The mixing was carried out for about 5 minutes in order to obtain a well-homogenized blend.

2.3 Mix Design

Four different asphalt-concrete mixes were designed using the standard Marshall mix design method as per ASTM D 1559 test method with 75 blows, and the optimum asphalt content (OAC) was determined. The mixes were compacted at 140°C, and care has been taken not to exceed 145°C temperature limits for sulfur asphalt mix.

2.4 Test Sections

To evaluate sulfur asphalt technology, three test road sections have been constructed; the first on the Khursaniyah access road, the second on the Shedgum-Hofuf road and a third section on the Dhahran-Jubail expressway for this project. On Khursaniyah access road, a test section of 0.33 km long and two-lane wide, was constructed to include a 30/70 sulfur-asphalt, mix, in addition to one test section of conventional asphalt mix. Base course and wearing course mixes were prepared using the same binder type.

On Shedgum-Hofuf road, a test road section of 0.75 km long and two-lane wide was constructed to include three 0.25 km test sections. Test sections include sulfur WC on sulfur BC, sulfur WC on Conventional Asphalt BC, and Conventional Asphalt WC on Conventional Asphalt BC.

On Dhahran-Jubail expressway, a test road section of 500 m long and one-lane wide, was constructed. It consists of 30/70 sulfur-asphalt mix WC and conventional asphalt-concrete mix base course in addition to one section of conventional asphalt mix.

Test roads were evaluated for performance under local environment and loading conditions. Test sections were monitored for the progress of rutting and fatigue for a period of four years for the Khursaniyah access road and one year for Shedgum-Hofuf road and Dhahran-Jubail expressway.

The collected data were evaluated following relevant standards and as required by the MOT. Statistical analysis was used to analyze the collected data and make an engineering comparison between the effects of different treatments.

The construction quality control, environmental pollution monitoring, traffic analysis and condition surveys were all conducted to evaluate and monitor the test sections performance in comparison to conventional asphalt concrete.

3. RESULTS

3.1 Field Condition Surveys

3.1.1 Khursaniyah Access Road

Khursaniyah access road was opened to traffic in March 2006. Similar to the Dhahran-Jubail expressway, condition surveys were carried out at regular intervals usually after winter and summer to evaluate pavement performance. In particular, pavement surface was evaluated for distresses like cracks, raveling and rutting. The condition survey results are summarized in Table 1.

Traffic counters were installed on all lanes and detailed traffic count was continued for five weeks in 2006 and another five weeks in 2007. The total annual traffic for the test road was 519,395 vehicles in 2006 and 558,815 in 2007. The design lane (outer lane) has been subjected to a total equivalent standard axle load of 9.0 million, which indicates a high volume of loaded trucks.

Condition surveys were carried out in September 2006, June 2007, October 2007, September 2008, January 2009, and June 2009. Pavement condition is generally excellent with pavement condition index of about 95 as shown in Figure 1. No signs of distresses were observed other than minor roughness due to construction process. Up to date, no wheel path depressions or cracking were observed.

3.1.2 Shedgum-Hofuf Road

The Shedgum-Hofuf road test section was opened to traffic in early 2009. Condition survey was carried out on 10th December, 2009 to evaluate the pavement performance. In particular, pavement surface was evaluated for distresses like cracks, raveling and rutting. The condition survey results are summarized in Table 2. Test sections showed excellent performance. No signs of distresses were observed other than minor wheel path densification due to the heavily loaded trucks where wheel path densification of 3-4 mm, as shown in Figure 2, was observed.

Table 1 Summary of the condition of the Khursaniyah access road test sections.

Pavement section	Base course	Wearing course	Length meter	Condition PCI*			Remarks
				October 2007	September 2008	June 2009	excellent
1	Asphalt concrete	Asphalt concrete	Main road	98	98	95	excellent
2	30/70 Sulfur Asphalt	30/70 Sulfur Asphalt	130 m	98	98	95	excellent

* PCI range: Excellent = 85-100; Very Good = 70-85.

Figure 1 Pavement condition of Khursaniyah access road

Figure 2. Very low wheel path densification (3-4 mm).

Table 2 Summary of the condition of the Shedgum-Hofuf road test sections condition.

Pavement section	Base course	Wearing course	Length meter	Condition PCI*, December 2009	Remarks
I-a	7 cm ACM + 28 cm CAB**	5 cm ACM	100 m	98	**Excellent** No signs of cracking, distortion or disintegration very low wheel path densification (3-4 mm)
I-b	7 cm 30/70 Sulfur Asphalt + 28 cm CAB	5 cm 30/70 Sulfur Asphalt	150 m	98	
II-a	7 cm ACM + Old Asphalt	5 cm ACM	100 m	98	
II-b	7 cm 30/70 Sulfur Asphalt + Old Asphalt	5 cm 30/70 Sulfur Asphalt	150 m	98	
III-a	Old Asphalt	5 cm ACM	100 m	98	
III-b	Old Asphalt	5 cm 30/70 Sulfur Asphalt	150 m	98	
Foamed Asphalt	20 cm Recycled Foamed Asphalt Base	4 cm ACM	400+	Variable 80-50	Variable; Very Good to Good with some Fair sections

* PCI range: Excellent = 85-100; Very Good = 70-85; Good = 55-70; Fair = 40-55.

** ACM=Asphalt concrete mix, CAB= Crushed aggregate base.

3.1.3 Dhahran-Jubail Expressway

On Dhahran-Jubail Expressway, two test sections were constructed in the outer lane using conventional asphalt mix and 30/70 sulfur modified asphalt concrete mixes. Sulfur Modified mix was used in the wearing course layer. Regular asphalt mix test section was

limited to 250 m followed by 250 m sulfur modified asphalt test section as shown in Figure 3. Each section consists of 30 cm of subgrade layer, 20 cm granular base course, 7 cm of asphalt base course and 5 cm of asphalt wearing course (WC). Typical pavement cross-section is shown in Figure 4.

Figure 3. Construction of test sections on Dhahran-Jubail Expressway

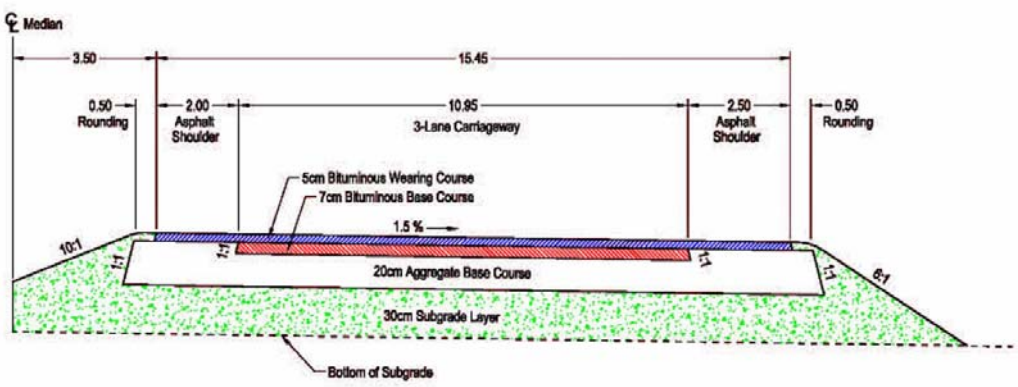

Figure 4 Typical Dhahran-Jubail expressway pavement cross-section

Dhahran-Jubail expressway is the busiest highway in the Eastern Province after Dammam-Riyadh expressway. Traffic counters were installed on all lanes and traffic count was continued for two weeks. The annual traffic for the test road is 2,679,465 vehicles with equivalent standard axle load of 2,945,185.

Dhahran-Jubail expressway test sections were opened to traffic in early 2009. Pavement condition survey, up to date, was carried out and is summarized in Table 3 Condition survey of test sections revealed excellent pavement condition with no apparent surface distresses as shown in Figure 5.

Table 3 Summary of Dhahran-Jubail expressway test sections condition.

Section	Base course	Wearing course	Length, meter	Pavement Condition (PCI) December 2009 PCI#	Average Rut depth, mm*	Cracking, m	**Remarks**
1	Asphalt concrete	Asphalt concrete	250 m	98	1	-	Excellent
2	Old Asphalt concrete	30/70 SACM	250 m	98	1	-	Excellent

#PCI range: Excellent = 85-100; Very Good = 70-85. *Low severity rutting = 6-13 mm.

Figure 5 Surface profiling and rut determination for Sulfur section

3.2 Lab Results

Pavement rutting is the predominant mode of failure of highway in Saudi Arabia. Therefore,

Plain and modified asphalt mixes were evaluated for rutting resistance using the asphalt pavement analyzer (APA) at 64 °C as shown in Figure 6. Wheel load was set to 100 lb, and

wheel pressure was set to 100 psi. 6-in. test samples were compacted using gyratory compactor to the same density of Marshall samples. Test samples were conditioned at test temperature for 4 hrs.

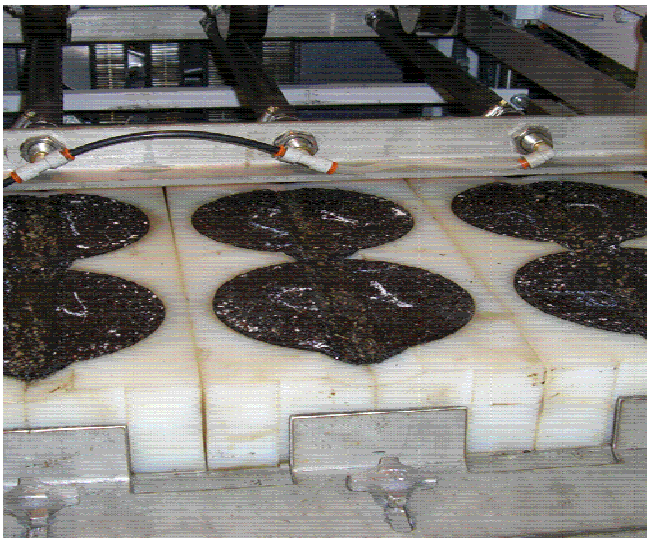

Figure 6. Asphalt samples after rutting test in APA

Test results are presented in Figure 7, which indicate that:

- 40/60 sulfur asphalt concrete mix gave the least rutting (most rut resistant).
- The next best rut resistance is given by 30/70 sulfur asphalt concrete mix and Polybilt modified asphalt mix. Both have similar rutting behavior.
- 20/80 sulfur asphalt concrete mix and plain asphalt mix gave similar rut resistance.
- 10/90 sulfur asphalt concrete mix gave the highest rutting which is greater than the plain asphalt mix.

Figure 8 shows typical profiles of the tested mix samples.

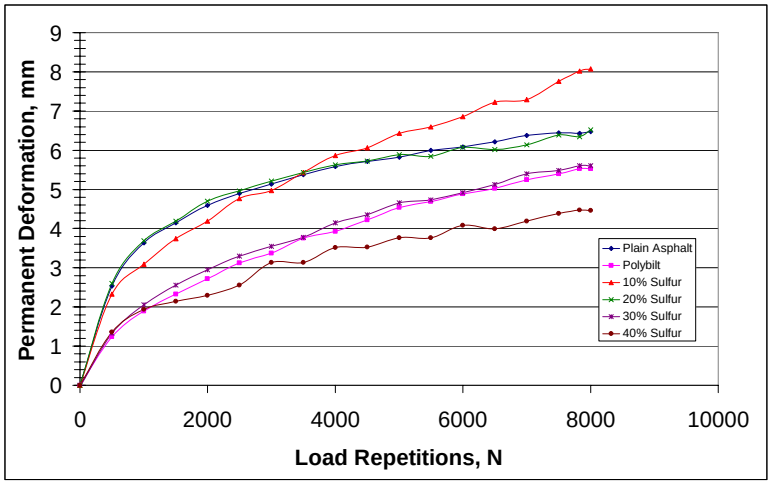

Figure 7. Permanent deformation test results.

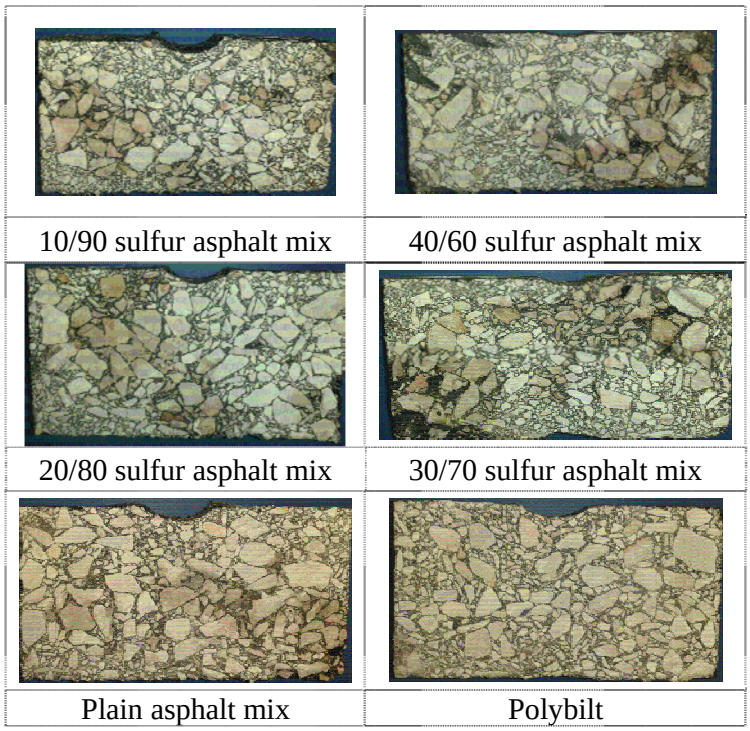

Figure 8. Typical profiles of the tested mix samples.

3.3 AIR QUALITY MONITORING

The investigation was intended to monitor the air quality of a road paved with 30/70 sulfur-asphalt concrete, at Khursaniyah construction site. The specific objective was the

monitoring of gaseous emissions, particularly sulfur dioxide and hydrogen sulfide. Measurements were made at the construction site as shown in Table4.

Table 4 Concentration of gases at construction site

a. Probe at source (20-40 cm over auger)						
SO_2 (ppm)			H_2S (ppm)			Remarks
Maximum	Mean	Minimum	Maximum	Mean	Minimum	
30/70 Asphalt Sulfur Mix						
3.118	0.56	0.156	3.17	2.00	0.26	450C H_2S/SO_2 analyzer
8.0	1.89	0.0	-	-	-	S710 analyzer

b. Probe at elevated levels,		
30/70 Asphalt Sulfur Mix		
SO_2 (ppm)	H_2S (ppm)	Probe Position
0.39	0.47	At Operator (driver) level (2.5 m)
0.404	0.51	At foreman level (1.8 m)

Results indicates that the maximum values of SO_2 concentrations ranged from negligible to 8 ppm when measured close to the source (20-40 cm above the auger). The measured values of SO_2 were found to be within the acceptable limits when measured at the foreman and driver levels ranging from 0.39 to 0.4. The measured values of hydrogen sulfide ranged from negligible to 3.17 ppm close to the source and 0.47 to 0.51 at the foreman and driver levels. It was also noted that the variation of construction temperature (124-147 °C) did not significantly affect the concentration of fumes.

Apart from the measured SO_2 emission close to the source above the auger screw which continuously agitates the asphalt-concrete mix and releases trapped fumes, all measured

gases concentrations are within the acceptable limits. As with asphalt operations, workers should not stand close to the auger; otherwise special safety precautions should be taken.

4. CONCLUSIONS

Based on the monitoring and performance for the three construction sites, the following conclusions can be made:

1. Sulfur asphalt technology can be used successfully with current road construction Equipment and expertise. Use of pelletized sulfur has resulted in convenient handling of sulfur.
2. The same construction equipment and procedures are used for sulfur asphalt and regular asphalt. No equipment modification is required. Minimal modification is needed to the batch plant to allow the addition of Sulfur directly into the pug mill.
3. There are no major safety concerns with regard to careful monitoring of mixing and handling of hot sulfur asphalt mix.
4. Constructed test sections have met the construction quality requirements.
5. Performance of test sections, up to date, is found to be excellent even after almost four years of heavy traffic.

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