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ASSESMENT OF SULFUR CONTAINING AIR POLLUTANTS IN UTILIZING THE SULFUR EXTENDED ASPHALT CONCRETE MIXES IN SAUDI ARABIA

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ABSTRACT

The rapid economic growth witnessed in the Kingdom of Saudi Arabia has brought about an increasing demand for fossil fuels, leading to the substantial release of major airborne pollutants. Acquiring a better knowledge of their distribution and behavior is a prerequisite to further development. In the Gulf region, particularly in Saudi Arabia, because of the increase in number of oil and gas refineries, the production of sulfur as a by-product has increased tremendously from 400 to 6000 tons/day. This alarming situation has developed the urgent need of finding an environmentally risk free ways to utilize sulfur. A study has been conducted at KFUPM on the feasibility of using sulfur as an additive for local asphalt concrete mixtures. The research work covered many aspects of utilizing sulfur modified asphalt in road construction. One of the aspects covered was to evaluate the concerns related to air pollution due to sulfur containing gases. Gaseous emmision at the asphalt plant and field construction site released from sulfur modified asphalt mixes was studied. The results show that, under controlled conditions, hydrogen sulfide concentration generated during mix production and placement was well below the allowable ambient air quality standards. With regard to sulfur dioxide concentration, an exceedance above the standard was observed at mixing temperature of 145°C, which can be safely abated by taking appropriate precautions. An overall assesment of the environmental impact of sulfur-asphalt technology shows that there is no long-term hazard as indicated by the acceptable values of emission of hazardous gases (<1 ppm) even at the high in-service pavement temperature of 76°C.

INTRODUCTION

In the last decades, 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 at combustibles. Extremely large quantities of sulfur are 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 has long been identified as one of the prominent among its applications. Using sulfur to enhance or supplement asphalt could consume significant amount of sulfur, even if sulfur captures 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 (Mohammed Al-Mehthel *et al*., 2010). Currently, there are initiatives to promote market development of sulfur products in the construction material sector. In the transportation industry, sulfur asphalt is a substitute product for road construction binders and could potentially grow big enough to take up a major expected production surplus of sulfur. Sulfur modified asphalt can be a substitute for the normal asphalt binder employed in road construction. In Saudi Arabia, sulfur, a by-product of oil and gas production, is produced currently at a rate of approximately 6,000 tons/day. The rate of production is expected to increase to 10,000 tons/day in a few years. Although sulfur is a vital raw material to manufacture a myriad of products, its abundance has reduced its price worldwide. The storage of the sulfur will also pose an environmental hazard. Other avenues such as the use in local construction industry should be explored to utilize this abundant sulfur in a useful, economical, and environmentally friendly way. The Department of Civil Engineering at King Fahd University of Petroleum and Minerals (KFUPM) has recently completed a major research

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project to explore the possibility of utilizing sulfur as a binder for making sulfur-asphalt and sulfur-concrete materials. The study on sulfur-asphalt concrete consisted of testing sulfur modified asphalt with local asphalt-concrete mixes, and assessing the effect of sulfur and the modified sulfur asphalt mixes by comparing their performance with those of the local plain and sulfur extended asphalt concrete mixes. The work presented here consists of the assessment of sulfur containing gases emitted from sulfur modified asphalt concrete mix at both production plant and field construction site.

Sulfur concrete

Sulfur concrete is not a new material; utilization of molten sulfur as a binder dates back to the 17th century when it was used to fix metal to stone, which was practical for quay-rings used to anchor ships (Gracia and Vazquez, 2004). Such practices are believed to be in use even today in Latin America and most likely elsewhere. In fact, there is evidence of even earlier uses of sulfur, and both archaeological sites and classic literature offer proofs of sulfur knowledge and utilization as a binder. During World War I, there was a very strong demand for sulfur, and several deposits were opened in North America for their exploitation. This operation doubled the annual production of sulfur in the United States and as a consequence, had a surplus stock of sulfur that enhanced the interest in developing new applications for this element (Gracia and Vazquez, 2004). In 1921, Bacon and Davis (1921) published a study about the use of surplus sulfur in the manufacture of construction materials, and performed the first tests on this kind of material. They developed a mortar with 40% sulfur that was highly resistant to acids and had good mechanical properties, and also started to study different additives to modify the properties of sulfur in specific applications. During the 1960’s, there was a remarkable investment in environmental protection against discharge of sulfur into the atmosphere, thus making sulfur a surplus commodity on the market, particularly in the United States and Canada.

This was a crucial point that made the interest to use sulfur as a structural binder to grow further, and initiated extensive research programs which became very active in the 1970’s, focusing on various properties of the material including its durability. The use of sulfur concrete for chemical plants was spread to a certain extent, especially for construction in acidic environments, in which the durability of the material was found to be excellent (Jones, 1990). Research carried out by Jones (1990) to identify the most promising types of asphalt modifiers for reducing permanent deformation (rutting) in flexible airfield pavements indicated the potential of sulfur asphalt. The modifiers evaluated in this study included carbon black, sulfur, styrene-butadiene-styrene, ethyl-vinyl-acetate, and polyolefin. A series of binder and mixture tests were performed in the laboratory to evaluate the modifiers effects on an AR-4000 asphalt cement and an asphalt concrete mixture containing sub rounded river gravel. Binder tests were performed before and after aging in the rolling thin film oven, and included penetration, viscosity, and ductility. Mixture tests included Marshall stability and flow, resilient modulus, creep modulus, and indirect tension. The results were used to estimate the effects of the modifiers on pavement rutting, and it was concluded that all of the modifiers studied has significantly reduced the amount of rutting estimated for thin and thick pavements in a hot climate (Jones, 1990). William *et al*. (1977) conducted research on sulfur asphalt paving, in which sulfur that replaces part of the asphalt binder normally present in conventional asphalt paving, was found by controlled laboratory tests to be superior to the conventional material in terms of its resistance to the solvent action of gasoline, diesel, and jet fuels. Increasing the amount of sulfur in the formulations increased its resistance to attack by these fuels. Two test methods were developed to simulate the solvent action caused by dripping or spillage of fuels onto pavements. In one of these methods, the test samples were immersed in the fuel; in the other method, the fuel was dripped over the sample. The comparative solvent resistant characteristics of asphalt and that of sulfur asphalt paving were evaluated by determining their weight loss and their change with stability. The greater solvent resistance of sulfur asphalt paving to fuels makes its attractive for use as a construction material in areas subjected to fuel spillage. These would include airport service areas and runways, truck stops, and filling stations (William and Sullivan, 1977).

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 collapse about two decades ago. Since then, the amount of sulfur produced from oil and gas has increased resulting in a drop of market prices. For the last five years, world sulfur production has exceeded consumption by one to two million tons per year. Some forecasts have predicted continued overproduction ranging from one to three million tons per year through 2010 (Weber and McBee, 2000). In the last decade, the availability of sulfur has considerably grown in many countries. This is mainly due to the current environmental restrictions regarding petroleum and gas refining processes, which limit the maximum quantity of sulfur present at combustibles. Extremely large quantities of sulfur are thus obtained as a by-product of these processes, together with coal processing and refining of copper in the mining sector. 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 asphalt could consume a significant amount of sulfur.

Even if sulfur captures 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 manufacture, 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 (Weber and McBee, 2000). 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

Transport (MOT) [formerly Ministry of Communications (MOC)], Saudi Arabia as part of the ongoing road development program of MOT. 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 each test road, 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 early 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 were 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 U.S. 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).

Bernard (1987) indicated that various field data have shown that the engineering properties of SEA mixes are comparable to conventional asphalt-concrete mixes except for the stiffening effect that sulfur imparts to SEA when S/A (sulfur/asphalt) ratios are higher than 30/70. SEA mixes with sulfur additions below 20% by weight of the asphalt are the most simple to prepare. Virtually, all the sulfur is readily dissolved in the binder. However, real cost savings and improved material property characteristics are more evident when sulfur additions exceed this level. For most projects, a S/A of 30/70 seems to give the best results. The use of sulfur as an additive to extend or replace asphalt has been demonstrated successfully in both laboratory tests and actual construction. The current availability and low 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 Sulfur Institute (TSI) has been actively working with the US Federal Highway Administration and through other channels to promote the utilization of sulfur asphalt, and at least one world-class oil and gas company is seriously interested in this outlet for its recovered sulfur.

At the same time, Devco Company has already moved to penetrate the market. Using proprietary innovations to produce easily handled forms of pre-blended sulfur asphalt, the company has been constructing roads in Nevada and California for the last two to three years, along with parking lots and other paving projects. King Fahd University of Petroleum and Minerals has conducted major sulfur research in the late 70’s and early 80’s in cooperation with the Ministry of Transport where sulfur was incorporated in the construction of major road sections, some of which are still functioning. Sulfur is added to asphalt to overcome temperature susceptibility (dependency) of local binders, thereby reducing or eliminating the rutting tendency of local mixes. By mid 1980’s, sulfur research had been stopped due to the disadvantages of sulfur mixes. Several agencies such as The Sulfur Institute (TSI), Devco Company and others have continued to improve sulfur mixes to eliminate their disadvantages. Research on development of new construction materials such as sulfur polymer cement concrete, plasticized sulfur and polymer asphalt extender/replacement may be found to be fruitful.

Effect of sulfur

Although the total sulfur content of asphalts may vary considerably (trace to 8 wt %), sulfur does not influence toxicity from exposure to asphalt or asphalt fume because it is largely entrained in the asphalt matrix and released slowly if at all. A significant amount of sulfur is in the form of heterocyclic sulfur compounds with multiple fused rings and large molecular weight due to alkylation, resulting in minimal bioavailability. Some sulfur is released as H_2S and low molecular weight particulates but these compounds are present in very low concentrations in freshly generated asphalt fumes at controlled temperatures (Fraunhofer, 2003; Gamble *et al*., 1999). It has been reported that 80-fold more fume is given off at 250°C than at 160°C, hence appropriate temperature control can considerably reduce emissions from sulfur asphalts (CONCAWE, 1992). Asphalt products are required to be heated to maintain fluidity during mixing, bulk transportation and storage. This work practice can result in the generation of SO_2 and H_2S gases. While the relative concentration of H_2S is related to total particulate matter, benzene soluble matter or polycyclic aromatic hydrocarbons in freshly generated asphalt fume are insignificant. Acute effects among workers exposed to asphalt fumes included eye irritation, and nasal and throat irritation which typically appeared to be of mild severity and transitory in nature (NIOSH, 2000).

Impact on construction industry or contractors

Pavement construction with Sulfur Extended Asphalt (SEA) binders is similar to construction with conventional asphalt binders. Mixing plant modifications are minor and the same placement and compaction equipment and procedures are used. Plant modifications can be made either temporarily or permanently and do not hinder the production of conventional asphalt. The modifications consist of a separate storage tank, pump and circulating system, and/or a means of combining the asphalt and sulfur in the correct proportions. The cost for modifications to an existing batch plant are not significant compared to the benefits and cost savings. Mix design procedures are the same as those used for conventional mixes.

Safety and the environment

In the normal temperature range for handling sulfur/asphalt materials (125°C-148°C), there is little or no evolution of sulfur-containing gases. If the temperature of the sulfur/asphalt binder or mix is allowed to rise above 160^{o}C, evolution of hydrogen sulfide and sulfur dioxide may start to occur. Emission monitoring at mixing plant and construction sites during the construction of several Sulfur Extended Asphalt (SEA) pavements indicates that emissions are controllable and are within acceptable limits.

MATERIALS AND METHODS

To evaluate sulfur asphalt technology, test road section of 0.6 km long and two-lane wide was constructed on Khursaniyah access road in the eastern part of Saudi Arabia. The test section includes 30/70 sulfur-asphalt ratio by weight of binder for both Wearing Course (WC) and Base Course (BC) layer, in addition to one test section of plain/conventional asphalt concrete mix (control mix). Each section consists of 25 cm of granular base course, 8 cm of asphalt base course, and 6 cm of asphalt surface (wearing) course layer. The locally available aggregate in the Eastern Province was selected for this study. The MOT specification for WC and BC gradation was followed in both mix designs. Asphalt cement of grade 60/70 was obtained from Ras Tanurah refinery. The elemental sulfur in pellet form used in the study was obtained from Saudi Aramco. The materials obtained were tested for gradation and physical characteristics to assure their conformity to MOT and Saudi Aramco standards. For both conventional and sulfur asphalt test sections, Marshall mix design method is used to obtain the Optimum Asphalt/Binder Content (OAC) as per ASTM D 1559 test method. Trial mixes were prepared at different asphalt contents. Sulfur modified mixes were compacted at 135°C and care was taken not to exceed the 145°C temperature limit during mixing. OAC that satisfies the MOT specifications for WC and BC mixes was obtained. 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.

Test road sections were constructed under the supervision of KFUPM representatives, and evaluated for performance under local environment and loading conditions. They were monitored for the progress of rutting and fatigue for a period of two years. The results obtained were evaluated following relevant standards as required by MOT and were submitted in the final report by Al-Abdul Wahhaband Baig G.M *et al*. (2008). One of the major concerns of the industry with SEA is the potential hazard created during paving due to the evolution of toxic gases (H_2S and SO_2) and particulate sulfur. In this investigation, a detailed study was carried out to monitor the air quality of sulfur containing air pollutants of a road paved with 30/70 sulfur-asphalt concrete, at both the construction site and asphalt production plant. In addition, the concentration of gases in ambient air in a lab environment and soil contamination, if any, at the construction site was also studied. The specific objective was the monitoring of gaseous emissions, particularly sulfur dioxide SO_2 and hydrogen sulfide H_2S, and to compare the results with the existing air quality standards (Table 1).

Table 1. Industrial hygiene standards

Pollutant	Average Threshold Concentration	Maximum Short-term Limit Value
H_2S	10 ppm (8 hours)	15 ppm
SO_2	2 ppm (8 hours)	5 ppm

In the 1970's and 80's, the methods in use required that the sulfur be mixed with the asphalt cement before the aggregates. The asphalt plant modifications required to manufacture SEA consist of separate sulfur storage facilities, sulfur pumps or augers, a metering system, and in some cases, an in-line blender. The development of the sulfur in pellets form has improved sulfur handling, and the direct feed of solid sulfur to the pug mill has eliminated many safety concerns that relate to the transportation, storage and handling of molten sulfur. In this study, local asphalt batch plants were modified to add a chute allowing manual addition of pre-measured amount of sulfur pellets directly into the pug mill (Figure 1). The operators of the asphalt hot-mix batch plants were able to

Figure 1. Local modified asphalt batch plants

control the temperature of the sulfur mixes (below 145°C) without major problems. The sulfur pellets are added during the period of the batching process when the addition of asphalt cement normally occurs. The temperature of the mix at discharge from the mixer (or mixing temperature) was controlled within the temperature range corresponding to a viscosity of 170 ± 20 cst for the molten sulfur/asphalt cement binder, but less than 145°C. Capital investments related to adapting a plant for production of sulfur-extended asphalt are observed to be minimal. Minimal work is required to install cold feed bin, conveyor belt and weighing scale. Plant modifications can be built to be either temporary or permanent and, to retain flexibility, these changes do not prevent the production of conventional asphalt. Transportation, placement and compaction of SEA hot mix are very similar to conventional asphalt concrete hot mix. The same construction equipment and process are used with no modification for both sulfur asphalt concrete and conventional asphalt concrete mix types. Mix output from the plant must match paver and roller capacity to minimize temperature segregation. Two steel drum rollers must be placed at the front of the mix for maximum compaction while the mix is hot. Rubber-tire rollers can be used on the mix while it is hot only. They must be able to take out their own roller marks. The gaseous concentrations of sulfur dioxide and hydrogen sulfide were measured using the following equipments at the asphalt plant and construction site:

- H_2S/SO_2 analyzer, Model 450C, manufactured by Thermo Electron Corporation, USA was used for ambient level measurement of H_2S and SO_2 gases.
- Multi componenet gas analyzer, Model S710, manufactured by Sick-MaihakGmbh, Germany was used for measurement of high concentration of SO_2 gas.

The principle of operation of the H_2S/SO_2 analyzer used in this work is totally different from that of CMS chip meter. The analyzer is based on the principle that H_2S is converted to SO_2 through a converter. SO_2 molecules absorb UV light and become excited at one wavelength, and then decay to a lower energy state emitting UV light at a different wavelength. If the sample is passed through the converter, H_2S concentration levels can be inferred. If SO_2 readings are required, the sample is not passed through the converter. There is no pre-filtration in this system. The S710 analyzer operates based on a non-dispersive infrared absorption principle. The analyzer module contains the physical analysis unit and basic electronic circuits. The system can analyze all measuring components simultaneously in an interval of 0.5 to 20 seconds. The analyzer has a salient feature of automatic and manual calibration options. It is built-in with a 'MULTOR' analyzer module. When the sample gas flows through the internal measuring system of the gas analyzer, the analyzer module measures the concentrations of more than one gas component simultaneously.

Monitoring at asphalt plant in Jubail

Sulfur extended asphalt concrete mix was prepared at the modified asphalt plant as per the mix design. The mixing temperature was set at 140 ± 3°C for sulfur mix. The monitoring equipments were installed close to the mixing plant near the facility room. Certified calibration gases for H_2S/SO_2 have been used in calibrating the analyzer. The system used consisted of gas analyzer, gas conditioning and sampling system, electrically heated sample line, and electrically heated probe and data acquisition system. The gaseous emissions from the sulfur extended/modified asphalt concrete mixtures produced and dumped immediately in trucks were measured by bringing the truck close to the sampling probe of the instruments as shown in Figure 2. The results obtained are presented in Tables 2 and 3.

Table 2. Measurements using 450C H_2S/SO_2 analyzer (low concentration measuring analyzer)

Measurement Time	SO_2 Concentration (ppm)	H_2S Concentration (ppm)
a) Measurement in ambient air		
11:15	0.062	0.023
11:16	0.107	0.034
11:17	0.107	0.020
11:18	0.107	0.020
11:19	0.107	0.021
11:20	0.124	0.021
Average	0.102	0.023
b) Measurement in ambient air when hot sulfur mix in the truck is emitting gaseous emission and was just close to the monitoring probe of the analyzer		
11:42	0.036	0.745
11:43	0.074	1.344
11:44	0.111	1.136
11:45	0.098	0.994
11:46	0.086	1.233
11:47	0.095	1.443
11:48	0.104	1.467
11:49	0.099	1.509
11:50	0.094	1.099
Average	0.096	1.291
c) Measurements when the truck is moved away		
11:51	0.064	0.722
11:52	0.034	0.489
Average	0.049	0.606

Table 3. Measurements using S710 analyzer (high concentration measuring analyzer)

Measurement Time	SO_2 Concentration (ppm)
a) Measurement in ambient air	
11:15-11:20	0.00
b) Measurement in ambient air when hot sulfur mix in the truck emitting gaseous emission was just close to the monitoring probe of the analyzer	
11:42-11:50	0.00
c) Measurements when the truck is moved away	
11:51-11:52	0.00

Figure 2. Air quality monitoring at the asphalt plant

The average, maximum and minimum emission data of SO_2 and H_2S from the low concentration measuring analyzer are presented in Table 4. From the table, it can be seen that the SO_2 and H_2S concentrations are less than the concentrations defined by the OSHAA Standards for ambient air quality as listed in Table 5, along with local applicable standards.

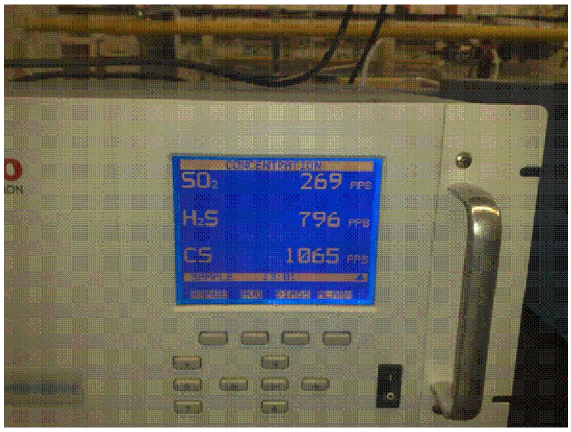

Figure 3. Thermo Electron Corporation 450i H_2S/SO_2 gases analyzer

Workroom Environment as per American Conference of Governmental Industrial Hygienists are as provided in Table 1. It was found that in the plain asphalt concrete blend (control mix) at 140°C, the gaseous emission was not noticeable as indicated in Table 6. In the asphalt concrete mixtures prepared using 30/70 sulfur, it was found that in an open space and at 140°C the average concentration of SO_2 (sulfur dioxide) was in the order of 1.1 to 1.8 ppm, which does not exceed the permissible limit of sulfur dioxide (2.0 ppm) as per Table 1. Similarly, the emission of H_2S gas was in the order of 2.9 to 3.3 ppm, which does not exceed the permissible limit of 10 ppm. It may be noted that although the experiment sample is limited in size compared to the actual field construction, it can still simulate the conditions in actual practice where the mixing will be carried out in an open space with much easy dilution of the emitted gases from the source into nearby environment reducing the concentration of measured gases.

Table 4. Average concentration of gases at asphalt plant in Jubail

SO_2 (ppm)			H_2S (ppm)			Remarks (Analyzer in the downwind direction)
Maximum	Mean	Minimum	Maximum	Mean	Minimum	
			Sulfur 30/70 Mix			
0.111	0.1	0.036	1.509	1.29	0.745	Measurement time: 11:42-11:50

Table 5. Different ambient air quality standards

Pollutant	Averaging Time	MEPA[a]	US-EPA	RCJY[b]	Exceedances allowed by MEPA
SO_2	1 hr	280 ppb	280 ppb	280 ppb	Twice a month
SO_2	24 hr	140 ppb	140 ppb	140 ppb	Once a year
SO_2	Annual mean	30 ppb	30 ppb	30 ppb	None
H_2S	1 hr	140 ppb	30 ppb	140 ppb	Twice a month
	24 hr	30 ppb	-	30 ppb	Once a year

[a]MEPA: Meteorology & Environmental Protection Agency.
[b]RCJY: Royal Commission for Jubail & Yanbu Industrial Cities.

The principal health problem associated with sulfur dust in plant area, is irritation of the eyes. Sulfur is virtually non-toxic but it can irritate the inner surfaces of the eyelids and, most probably, the nasal passages. For workers, these problems can be minimized by wearing goggles and using a fine breathing apparatus.

Monitoring in the laboratory

Two samples of sulfur extended asphalt concrete mix, one prepared at the lab and the other taken from the asphalt production plant, were tested in the laboratory to determine the ambient gases concentration in open lab space. The sulfur blended asphalt concrete mixes about 4 kg each at 140°C were placed in containers whose interiors are lined with a cardboard of 5 mm thickness at the bottom and sides to prevent immediate temperature loss. The mix was stirred with a spoon and the meter probe was placed 5-10 mm below, from the mix surface. The gaseous concentrations of sulfur dioxide and hydrogen sulfide were measured using H_2S/SO_2 analyzer, Model 450i. It was used for ambient level measurement of H_2S and SO_2 gases as shown in Figure 3. The results of the gaseous measurements are tabulated in Table 6. The threshold limit values of chemical substances and physical agents in the

Table 6. Summary of test results of gas emission in laboratory environment

Blend Type	Temperature °C	Ambient Gas Emission in ppm	
		H_2S	SO_2
	minimum	0.02	0.05
Control mix	average	0.11	0.03
	maximum	0.23	0.1
	minimum	0.490	0.14
30/70 sulfur	average	1.780	0.71
	maximum	2.940	1.1

Monitoring at the construction site at Khursaniyah

The monitoring equipment was installed in a mobile car parked on the shoulder of the road section under study (Figure 4). The mobile car was kept in the downwind direction of the paver. Readings were taken close to the source 20-40 cm above the auger level. This was done in order to measure the strength of the fume emission. In addition, measurements were taken at probe level of 1.8 m and 2.5 m (i.e. at the level of the foreman and paver operator). It should be noted that hot aggregate bins were kept to at least one quarter full at any time. The mixing temperature was set at 135-143°C for sulfur mix. The maximum hauling time was about 40 min (±). Sulfur mix was delivered to the site at temperature of about 125°C. At each point/level, a continous emission measurement of upto 5 minutes was done.

Figure 4. Fumes released from behind the paver

Table 7 shows the maximum values of SO_2 concentrations ranging from 0.0 to 12 ppm when measured close to the source (20-40 cm above the auger). The maximum measured value is 8 ppm for 30/70 sulfur mix. The measured values of SO_2 were found to be within the acceptable limits when measured at the foreman and driver levels ranging from 0.3 to 0.4. The measured values of hydrogen sulfide H_2S ranged from 0.0 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 temperature (124-147°C) did not significantly affect the concentration of fumes.

It has been established that 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 gas concentrations are within the acceptable limits. Workers should not stand in the downwind direction of the paver close to the auger; otherwise special safety precautions should be taken. Paver can be modified by adding fume extraction duct above the auger and stack fume dispersion. Adjustable plastic windshield to help keep asphalt fumes and hot air off from the paver operator can be added for the operator's comfort as shown in Figure 5.

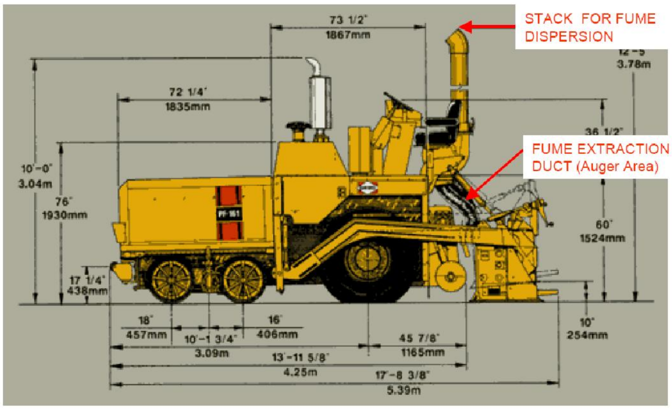

Figure 5. Paver recommended modifications

Soil contamination at the construction site

X-ray Fluorescence Spectroscopy (XRF) method was used to test soil samples obtained from the field after 33 months of construction, next to the plain and elemental sulfur extended test sections on Khursaniyah road. Three sets of soil samples were obtained from the shoulder next to the pavement from the elemental sulfur test section and two from plain asphalt section. Samples were analyzed using XRF method to determine total elements content including sulfur. Three trial or replicates for each sample were tested. Results are summarized in Table 8, which clearly indicate that there is no difference in sulfur content between sets of samples obtained from both locations. Use of sulfur asphalt in Khursaniyah road did not result in soil contamination over an exposure cycle of 33 months.

Table 7. 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)

Table 8. Sulfur fraction in the soil samples

Sample Source	Sample No.	% Sulfur by weight of total elements			Mean	Standard Deviation
		Trial 1	Trial 2	Trial 3		
Conventional asphalt	M1	1.1351	0.1039	2.5764	1.2718	1.241905
section (Control mix)	M2	0	2.2504	0.9663	1.072233	1.128934
Elemental sulfur asphalt	S1	0.0355	0	2.6361	0.890533	1.511809
section	S2	0	0.1384	1.507	0.548467	0.832994
	S3	1.1579	0	2.4865	1.2148	1.244226

Environmental effect

Once laid, evolution of hydrogen sulfide and sulfur dioxide from SEA will be very slow such that levels will never exceed their respective maximum allowable concentrations under normal use of the sulfur-asphalt pavements (i.e. temperature below 100°C). Some odor is possible immediately after the material is compacted to form the roadbed. Compacted specimens put into direct contact with flame resulted in significant sulfur conversion to H_2S and SO_2. However, the fire stopped as soon as the external flame was removed, suggesting that SEA roads present no flammability hazard. It has been found that the upper temperature limit during blending should stay below 145°C to avoid copious production and emission of sulfur containing gases.

Economics

The present cost of sulfur may vary depending on logistics involving hauling or transportation costs. Where it is readily available, sulfur costs will be less. Where transportation is a factor, its costs may be a little higher. By comparing the current average cost of asphalt per ton (the price of asphalt may continue to rise) to the average per ton cost of sulfur (it is anticipated that the future price of sulfur will be much lower because supply will exceed demand), the use of sulfur asphalt concrete will provide huge savings. Use of sulfur in asphaltic concrete pavements typically saves between 16% and 30% of the asphalt bitumen in the mix. This asphalt is replaced with a similar volume of sulfur resulting in lower overall cost of the asphalt mix. The increased demand for asphalt resulted in the shortage of asphalt supply and increase in the asphalt prices. On the contrary, increased sulfur production lowers the cost of sulfur. The addition of sulfur to the paving mix requires reduction of the mix temperature by at least 10°C, resulting in lower energy consumption and, therefore, reducing the operating cost of the hot mix plant. Viscosities of SEA at temperatures above the melting point of sulfur are always lower than that of asphalt cement and much lower than that of filler extended asphalt. This feature of SEA shows the advantage of improving the workability of the paving mix. Thus, sulfur asphalt mix can be compacted at temperatures lower than that of the conventional asphalt mixes.

Conclusions

Based on the measurement results obtained and the observations at both the asphalt plant and construction site, the following conclusions can be made:

- Sulfur asphalt technology can be used successfully with current road construction technology and expertise. Use of pelletized sulfur has resulted in convenient handling of sulfur.
- Required modifications to batch plants are minimal.
- The same construction equipment and procedures are used for sulfur asphalt and regular asphalt. No major equipment modification is required.
- There are no major safety concerns with regard to mixing and handling of hot sulfur asphalt mix, if carefully monitored.
- The emission of SO_2 and H_2S gases from sulfur extended asphalt concrete mixes are within acceptable limits if the temperature of the mix is controlled below 145°C.
- Constructed test sections have met the construction quality requirements, and the performance of sulfur test sections, up to date, is superior to that of the regular conventional asphalt section which has developed rutting.
- The use of elemental sulfur pellets as an additive for road construction can be attractive and cost effective when compared with other expensive additives. It can also alleviate the sulfur surplus.

Recommendations

- Sulfur extended asphalt concrete should be given more consideration in the construction and maintenance of roads, as it can provide a relatively safe utilization of ongoing huge sulfur surplus in the Kingdom.
- Sulfur can be used in both wearing course and base course layers with strict quality control to avoid undesirable performance due to layer stiffness compatibility.

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