Sulfur-Asphalt Site Construction Trial in Kuwait

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***Abstract*—A full scale trial into the use of sulfur-extended hot mix asphalt was carried out on a full depth 2 lane access road South of Kuwait City in June 2015. The road is composed of wearing, binder and base course hot mix asphalt layers all in compliance with Ministry of Public Works mix gradation specifications. Four binder types were assessed; 60/70pen grade Kuwaiti bitumen, 2% EVA polymer modified binder, 60/70pen modified with locally produced sulfur and 60/70pen modified with Shell Thiopave pellets. The trial road was divided into six longitudinal sections to facilitate direct comparison of the performance of the various binders types. Full depth cores were extracted for testing from each of the six sections soon after the completion of construction and after 1 year of opening to traffic. The paper includes details of the site layout, granular subbase and asphalt compaction, variation in asphalt mix density and voids, indirect tensile stiffness determinations, moisture conditioning and wheel tracking tests. Overall, both sulfur extended asphalt mixes performed better than the conventional 60/70pen mix, in particular with respect to stiffness and creep performance. Significantly, compared to the 60/70pen mix, the sulfur-extended mixes ageing with time could not be explained entirely by environmental exposure related oxidative hardening mechanisms.**

***Index Terms*—hot mix asphalt, sulfur-extender, thiopave, full scale site construction**

I. An Overview of Sulfur-Extended Hot Mix Asphalts

A. Background to Sulfur-Extended Asphalt

In the early 1970s, due to concern over asphalt cement (bitumen) supply issues and an anticipated overabundance of elemental sulfur, several organizations in the U.S. and Canada, began to evaluate the potential for sulfur to substitute for bitumen as binder extender, this became known as Sulfur Extended Asphalt.

In the late 1980s, a sharp rise in the price of sulfur in addition to the fact that the use of hot liquid sulfur during production generated a significant amount of noxious fumes brought its use in road paving to an end. However, more recent rises in bitumen prices coupled with the production of low sulfur fuels has once again made sulfur a marketable product in the asphalt industry.

To overcome the problems with hot liquid sulfur used in bituminous mixes, Sulfur Extended Asphalt Modifier in solid pellet form (patented process) was developed and is currently being marketed as an additive for hot mix asphalt under the brand name Shell Thiopave™ [1], [2].

Thiopave pellets are in a solid, non-sticky, non-melting form at ambient temperatures, which eases handling, storage and transportation. The pellets have melting point in the range 93 to 104°C, which has been specifically designed to melt when in contact with Hot Mix Asphalt (HMA). Thiopave is intended to act both as a bitumen extender and as an asphalt mixture modifier.

The key to the composition of Thiopave is that liquid sulfur is plasticized by the addition of carbon black (0.4 to 0.8%) and the plasticized sulfur is further treated with amyl acetate (0.2 to 0.4%) to produce an even more manageable plasticized sulfur additive. Amyl acetate helps to reduce unwanted odours from the product and thereby improve its overall handling [3].

B. Manufacturing and Laying Sulfur Extended Asphalts

Sulfur may be used in asphalt mixes made with conventional bitumen in weight ratios from 20%/80% to 50%/50% Sulfur/Bitumen. Stiffness and Marshall stability are expected to increase with increased amounts of sulfur [4]. Once a Sulfur/Bitumen ratio is selected, the equivalent volume replacement of binder (by % weight) can be determined. Since sulfur is about twice as dense as bitumen, a given weight of sulfur has about half the volume of the same weight of bitumen [5].

The sulfur pellets at ambient temperature are added to the pre-heated aggregate and bitumen during the HMA production process. The addition can be achieved via a feeder in an asphalt batch plant or via the reclaimed asphalt collar in a continuous mixing plant.

For health and safety reasons, the manufactures stress that when incorporating sulfur additive, the asphalt mix discharge temperatures must be carefully controlled to never exceed the recommended range 135-146°C. At this temperature, the pellets melt quickly and the shear conditions in the mixer are high enough to disperse the sulfur into the HMA mix in a very short time that is compatible with asphalt mix production.

It is recommended that Sulfur-Extended HMA storage time be kept to a minimum in order to minimize mix odor and fume emissions at the paving site. Delayed delivery trucks arriving at the paving site with Sulfur Extended HMA below approximately 115 °C shall be rejected [6].

C. Dissolution and Reactions between Sulfur & Bitumen

When sufur and bitumen are heated and combined, three distinct types of reactions may occur [5], [7]:

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a) The sulfur can react chemically with the bitumen and result in dehydrogenation (sulfurization through attack of the double bonds in the bitumen). This becomes important at temperatures above about 152 ℃. Dehydrogenation occurs and hydrogen sulphide gas is formed, which results in significant changes in the rheological properties of the bitumen.

b) The sulfur can be dissolved in the bitumen, in a different mechanism from the chemical dehydrogenation reactions.

c) Sulfur in the crystalline form can remain in suspension in the bitumen.

In one study, Differential Scanning Calorimetry analysis of Sulfur-bitumen blends containing 35% sulfur (by mass of bitumen) showed that 70% of the sulfur in the blend remained in immiscible crystalline form, with the remainder 30% being amorphous. Visual monitoring of the same bitumen/sulfur blends stored at room temperature for up to 1 month showed the emergence of a solid phase segregated on the surface of the samples which was also confirmed to be crystalline sulfur [6].

The larger the amount of added sulfur to a bitumen, the larger the amount of sulfur that ends up not in solution and hence existing in a crystalline state. The result is large amounts of crystalline sulfur existing in the paving mixture generally as ‘needle-like’ structures most prevalent in the mix voids. The driving force for nucleation and growth of the sulfur needles is believed to be provided by the solubility differences at mixing and ambient temperatures [5].

D. General Findings from Full Scale Trials

As early as 1989, a large full scale investigation was conducted by the California Department of Transportation to determine whether the incorporation of sulfur with a soft grade of bitumen could change the temperature-viscosity relationship of the resulting binder, thereby making it more useful in cold and hot climates [4]. The two trial sections (a hot and a cold climate test sections) utilized the same sulfur/bitumen blends, i.e. 20% and 40% sulfur by weight of total binder, and each project used the same blending AR 2000 bitumen (i.e. RTFOT Residue with viscosity of 2000 Poise at 60 ℃). Overall, based on the findings of this full scale study, sulfur-extended binders were a viable alternative to conventional bitumens. Results of physical tests (Hveem system) on compacted briquettes and field cores revealed no significant differences in stability, cohesion and surface abrasion between sulfur-extended and conventional asphalt mixes. The findings of this study raised one major concern, in that it appeared that sulfur-extended blends with over 20% sulfur by weight (e.g. at a 40%/60% sulfur/bitumen ratio) should not be utilized in overlays in colder climate areas due to an early thermal cracking potential. This was not an issue for the hotter climate test section [4].

The U.S. Federal Highway Administration also completed a field study in 1990 to compare the performance of sulfur-extended asphalt pavements to conventional asphalt control pavements. A representative set of pavements from 18 States was chosen to provide a comprehensive evaluation. The sulfur/bitumen ratios investigated were (10/90, 20/80, 25/75, 30/70, 35/65, 40/60) including surface and binder courses. The primary conclusion was that there was no difference in overall performance between the sulfur-extended and control sections. A laboratory study complemented the field study, and cores were obtained from many of the pavements for testing. In general, the laboratory test results supported the results of the field study. Overall, sulfur did not increase or decrease most test properties, and often it had no effect on a given test property of a mixture. However, sulfur did decrease the resistance to moisture susceptibility in the laboratory. There were also minor trends indicating that with some mixtures, sulfur reduces the susceptibility to rutting. Additionally stress-controlled repeated load indirect tensile fatigue tests were carried out on cores obtained from the trial sections and when considering all projects there was an indication that sulfur decreased the fatigue life [8].

Nicholls [9] summarised key findings from selected full scale trials covering the period 2004 to 2008 from a number of countries including; Canada, U.S.A., Saudi Arabia, Qatar [10] and China. Cores taken from a wide range of sites have shown that the incorporation of Thiopave does not result in any impairment of the compaction, with the bulk density being marginally greater than the control in most cases. The marginal difference was attributed to the higher density of the pellets in comparison to the bitumen. In general, Marshall stability of the sulfur-extended mixtures were similar to the control mixtures on day 1, however the stability values were observed to increase with time. Overall, the results were very positive, with rut depth values of sulfur-modified mixes being 20 to 55% less than the corresponding control mixes.

Al-Mehthel [11] also presented excellent performance results from four full scale trials (using 30/70 sulfur/bitumen blends) laid in 2006 at various locations across Saudi Arabia that were monitored for signs of rutting and fatigue cracking for a period of up to four years. Nazarbeygi [12] also reported excellent pavement condition index and no wheel path depressions or cracking of a full scale trial monitored for 3 years composed of a 35/65 (Sulfur/bitumen) HMA.

E. Moisture Susceptibility of Sulfur Extended Mixtures

In one large laboratory investigations carried out by the Washington State DoT, it was found that mixture moisture susceptibility (assessed using the Lottman moisture conditioning test) increased when greater amounts of sulfur were added to the binder [5].

In a large scale US Federal Highway Administration investigation conducted in 1990, the susceptibility to damage by moisture of sulfur-extended asphalt pavements was evaluated on cores obtained from a number of trial pavements (representing 18 States). The testing procedure was in accordance with ASTM D 4867 (minor variation on the Lottman procedure) with resilient modulus and tensile strength values being determined before and following moisture conditioning. It was concluded that when considering all the projects, the effect of sulfur was to reduce both the tensile strength ratios (TSR) and the resilient modulus ratios, but not the visual percent stripping. It was hypothesised that the lower ratios were related to a loss of cohesion rather than a loss of adhesion. Overall the results indicated that the sulfur-extended binders were weakened by the moisture conditioning processes [8].

In another recent investigation [2], moisture susceptibility testing was performed on four different sulfur-extended mixes in comparison to two control HMAs. Conditioning was conducted in accordance with ALDOT 361-88 (vacuum saturation of 55-80% of air voids with water) and AASHTO T 283-07 (vacuum saturation of 70-80% of voids with water followed by 16 hours freezing and thawing in 60°C water for 24 hours) test procedures.

Test results showed that the Thiopave modified mixes had lower tensile strength ratios (TSR) than the control mixtures conditioned using both the ALDOT and AASHTO methods. In this study, the TSR values of the 4 Thiopave mixtures were all found to be lower than the commonly accepted failure threshold of 0.8, in contrast to the control mixes with TSR values exceeding 0.8 [2].

In yet another more recent laboratory investigation [13], asphalt mixtures composed of 40/60pen grade bitumen modified with 30% Thiopave sulfur pellets by mass of total binder were slab compacted and cored. Indirect tensile stiffness modulus test results on dry and moisture conditioned (immersed in water at 85℃) sulfur modified specimens showed that after 9 days of water immersion approximately 50% of the initial dry modulus was retained. Interestingly, further tests revealed that following water immersion tests, long term dry recovery periods (minimum 2 weeks) caused the specimens to partially recover their stiffness values with time.

The National Center for Asphalt Technology (NCAT) has successfully constructed two structural Thiopave modified HMA trial sections built for the 2009 NCAT Pavement Test Track. In these trials, Thiopave HMA mixes exhibited excellent performance, both in the laboratory and on the track [14]. Encouraged by the positive results, a Thiopave warm mix asphalt (WMA) was produced along with a control HMA and paved as two adjacent test sections at the NCAT Pavement Test Track in May of 2010. No significant problems were encountered whilst manufacturing either mix. High densities were measured in both experimental pavements. In the laboratory, loaded wheel testing and flow number testing indicated that both mixes would provide acceptable rutting performance. Dynamic modulus testing on the plant-produced mixes showed the Thiopave WMA would be stiffer than the HMA at warmer temperatures and slower loading frequencies. Tensile strength ratio, Hamburg Wheel-Track, and Boiling Water Testing on the plant-produced HMA and Thiopave WMA indicated both mixes should be resistant to moisture damage [15].

In another more recent study by the Louisiana Transportation Research Center, a PG 64-22 HMA was compared to an SBS (PG 70-22 base binder) HMA and a WMA incorporating a sulfur based mix additive (PG 64-22 base binder) [16]. A suite of tests were performed to evaluate the rutting performance, moisture resistance, fatigue endurance, fracture resistance, and thermal cracking resistance of the three mixtures. Experimental results showed that the rutting performance of sulfur-modified WMA was comparable or superior to conventional mixes prepared with polymer-modified and unmodified bitumens. Results of the modified Lottman test showed that the moisture resistance of the sulfur-modified mixture was comparable to conventional HMAs. Additionally, fracture and fatigue properties, as measured by the semi-circular bend and beam fatigue tests, showed that the sulfur-modified WMA mixture possessed stiffer properties than that of a conventional polymer-modified mixture [16].

II. Kuwiat Sulfur Extended Hot Mix Asphalt Trial

A. *Site Location and Sub-base Construction*

The site selected for this investigation was a 2 lane access road (approx. 850m in length) at Wafra Industrial Waste Water Treatment Plant (Long., Lat. = 47.92019, 28.80035). Each lane should receive the same number of trucks as it functions solely as an access road. The site was located about a 45 minute drive away from Hot Mix Asphalt plant hired for this trial.

A 300mm layer of granular sub base material, known locally as ‘gatch’, was compacted above the prepared subgrade. Monitoring included dynamic cone penetrometer (DCP) testing of the sub grade and sub base layers at an agreed 20 locations. The DCP penetration rate (PR) data were next converted to California bearing ratio (CBR) values using a well established relationship developed by the U.S. Army Corps of Engineers (USACE) [17] as follows:

$$\text{Log (CBR)} = 2.465 - 1.12\ \text{Log(PR)} \tag{1}$$

A summary of the DCP results and the CBR conversions is shown in Table I below. As an approximate guide, the compacted gatch used on site is equivalent to a UK Type 1 granular sub-base material with a modulus in the range ~ 157 to 185 MPa.

TABLE I. Summary of DCP Penetration Rate Results and CBR Conversions

	Dynamic Cone Penetrometer Results (PR) (mm/blow)	CBR calculations using USACE equation (%)
Number of locations tested	42	42
Maximum value (mm/blow)	13.8	38.5
Minimum value (mm/blow)	6.10	15.4
Mean value (mm/blow)	9.09	25.5
Range	7.7	23.1
Standard Deviation	1.57	4.95

B. Site Layout, Asphalt Mix Design and Production

In this road trial, the wearing course for all trial sections was composed of a Type III mix gradation, whereas the binder and base course layers were both composed of Type II asphalt mix gradation. All mix gradations were in compliance with Kuwait Ministry of Public Works (MPW) hot mix asphalt (HMA) specifications as shown in Table II.

TABLE II. GRADATION OF HMA, % PASSING BY WEIGHT

Sieve Size (mm)	Type II Binder or Leveling Course	Type III Wearing Course
25	100	-
19	82 - 100	100
12.5	60 - 84	66 - 95
9.5	49 - 74	54 - 88
4.75	32 - 58	37 - 70
2.36	23 - 45	26 - 52
1.18	16 - 34	18 - 40
0.60	12 - 25	13 - 30
0.30	8 - 20	8 - 23
0.15	5 - 13	6 - 16
0.075	4 - 7	4 - 10

Four binder types were investigated as follows;

- Conventional 60/70pen grade Kuwaiti bitumen,
- Proprietary locally blended polymer modified bitumen (60/70pen + 2% EVA Dupont Elvaloy),
- 60/70pen grade Kuwaiti bitumen modified with locally produced sulfur, a by-product from Kuwait Oil Company (KOC).
- 60/70pen grade Kuwaiti bitumen modified with Shell Thiopave pellets

Based on the Marshall method of mix design, the optimum binder contents (o.b.c.) was determined (by mass of mix) for each mix type as shown in Table III.

TABLE III. OPTIMUM BINDER CONTENT OF THE VARIOUS HMA TYPES INVESTIGATED

	Wearing course, Type III gradation	Binder / Base course, Type II gradation
60/70pen.	3.9	3.8
PMB	3.9	3.8
Local Sulfur	5.0	4.4
Thiopave	5.0	4.4

The process of designing the sulfurized binders consisted of simply substituting 30% of the 60/70pen bitumen by volume with either Thiopave or Local Sulfur (both being in easy to handle solid pellet form).

The site was split into six sections as shown in Table IV Site Layout. Sections 1 to 5 were 150m in length each whilst section 6 was 190m. As mentioned earlier, the trial road consisted of 2 lanes (8m total width).

TABLE IV. SUMMARY OF TRIAL SITE LAYOUT

Material Type	Design Layer thick-ness	Sect-ion 1	Sect-ion 2	Sect-ion 3	Sect-ion 4	Sect-ion 5	Sect-ion 6
Type III Wearing course	40 mm	60/70 pen	PMB	60/70 pen	60/70 pen	Local S	Thio-pave
Type II Binder Course	60 mm	60/70 pen	PMB	Thio-pave	Local S	Local S	Thio-pave
Type II Binder Course	80 mm	60/70 pen	PMB	Thio-pave	Local S	Local S	Thio-pave

Small modifications to the hot mix asphalt batch plant were necessary to allow for safe introduction of Thiopave and local Sulfur pellets to the HMA. After careful consideration by KISR, the local contractor and taking into consideration advice from the Thiopave pellet supplier (Shell), it was decided that for this trial, the Sulfur pellets would be manually added into a hoper via a chute with three slide valves, for explosion isolation (ensured by having at least one product plug formed during loading).

Asphalt production and laying of the trial sections commenced on 31st May 2015 and progressed up to 7th June 2015. The temperature of each load was recorded on leaving the HMA plant to ensure that no sulfur-asphalt mix exceeds the upper safe working temperature of 145°C.

Soon after completion of the pilot road trial construction, extracted cores from the various asphalt sections were shipped to the UK for volumetric and mechanical testing to be carried out by Transport Research Laboratory (TRL-UK).

C. Coring and Assessment of Layer Thickness

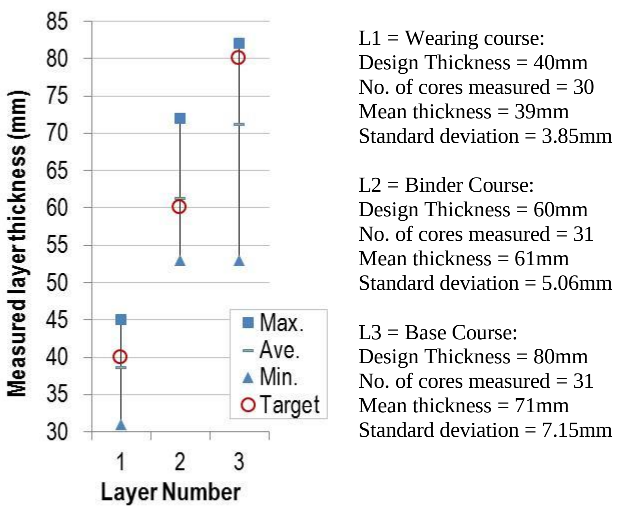

Figure 1. Variation in layer thicknesses across the Pilot Road determined from actual core thickness measurements.

A number of full depth cores were extracted from the various trial sections and sliced into wearing/binder/base-course layers. It was thus possible to verify the as constructed thicknesses of the asphalt layers in comparison to the design values.

Fig. 1 shows the variation in measured layer thicknesses obtained from a minimum of 30 extracted (150mm diameter) cores. The circle symbols in Fig. 1 represent the target layer thickness for the wearing, binder and base courses (Layers 1,2,3 respectively). In general the variation in thickness was high, in particular for the base course layers. Next to Fig. 1, the number of cores extracted, the mean and standard deviation of the thickness results are shown for each layer type.

D. Comparison of Compacted Density Measurements

Nuclear Density Gauge readings of the various trials sections measured immediately after the completion of the compaction process, were compared to the laboratory measured density values of the cores extracted from the various sections prior to opening the site to normal traffic. The laboratory density values (foil sealed testing in accordance with BS EN 12697-6:2003 Procedure C) and nuclear density values thus represented HMA surfacing densities on a non-trafficked road.

Fig. 2 shows a comparison of the compacted density values obtained using the Nuclear Gauge (dashed lines represent the min. & max. values) versus actual laboratory determined density values (mean values shown as crosses and range shown as thick vertical bars).

The range of density values was clearly much tighter for the laboratory measured results compared to the nuclear density readings, which cast serious doubt on the accuracy of the onsite nuclear density measurements (operator, procedural or equipment calibration error).

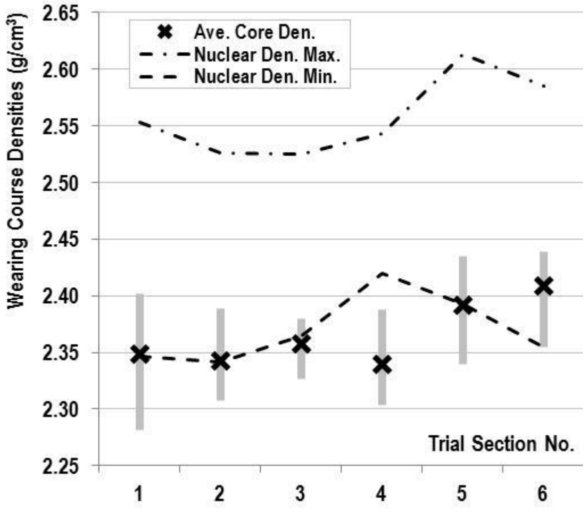

Figure 2. Nuclear density gauge readings taken immediately following construction phase (a total of 152 measurements across the entire trial length), compared to bulk density (sealed) values obtained from extracted cores (6 cores were extracted from each trial section).

E. Observations on Measured Air Void Values

In Fig. 3, the thick vertical bars show the range of air voids content obtained from the cores extracted from the various trial sections immediately following construction, while the crosses indicate the mean void content for each mix type. Since the binder and base course layers (L2 & L3 respectively) were composed of the same Type II gradations having identical volumetric properties, the results from both layers were thus combined.

The hollow circle symbols shown in Fig. 3 represent the average air void results obtained from a 2nd set of cores extracted 1 year after construction.

The first general observation that can be made is that for every HMA type, the voids in the wearing courses were on average significantly higher that the binder or base course layers, even though the bitumen content of the wearing courses were higher than those of the binder/base courses. This can be attributed to two potential factors, a- lack of adequate compaction on site, b- errors in gradations and/or binder contents during asphalt mix production. To verify which of the factors was more likely in this project, the binder was recovered from a number of asphalt cores using solvent and the binder content and gradation assessed. It was clear that the binder content and gradation were both in compliance with the mix design and that the most probable cause of increased air voids in the wearing courses was lack of on-site compaction.

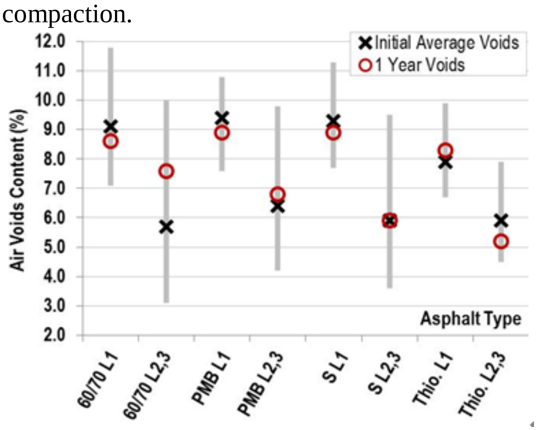

Figure 3. Range and Mean of air void contents obtained from extracted cores soon after completion of construction phase. The hollow circles indicate the results obtained from cores extracted after 1 year. L1 = wearing course, L2 = binder course, L3 = base course.

F. Observations on Binder Recovery and Gradation

The binder was recovered from a number of extracted cores, soon after the completion of the compaction stage, using dichloromethane as solvent (BSEN 1427:2015 & BSEN 1426:2015, Rotary Evaporator). Penetration and Softening Point tests were carried out on the recovered binder and the results are shown in Table V below.

TABLE V. RESULTS OF PEN. AND SOFTENING POINT TESTS ON RECOVERED BINDERS

	Recovered Penetration at 25°C (dmm)	Softening Point (℃)
60/70pen	32	58
PMB	31	57.8
Local Sulfur	81	48.2
Thiopave	83	48.2

Several interesting observations can be noted from Table V. Kuwaiti MPW 60/70pen specifications stipulate that the virgin bitumen shall have a penetration value in the range of 60 to 70pen and that following Thin Film Oven Ageing (3.2mm, 163℃, 5 hours), that the bitumen shall retain a minimum of 54% of its original penetration. The recovered penetration value (32pen) of the unmodified 60/70pen bitumen shown in Table V only just satisfies this short term ageing requirement.

It is interesting to note that the recovered penetration of the PMB binder is slightly lower than the unmodified 60/70pen., even though the EVA polymer modification would have been carried out by the contractor on the same source of 60/70pen grade base bitumen.

Of greatest concern were the results of the Local Sulfur and Thiopave modified bitumens. In both cases the penetration values were higher than the original penetration of the virgin bitumen. This is clear indication that the crystalline structure of the sulfur have been altered / damaged by the use of Dichloromethane (DCM) solvent. Since the penetration value was not re-measured after a prolonged resting / recovery period, it was not possible to ascertain whether this damage is reversible or not. Thus the traditional penetration and softening point tests are not suitable for non-conventional sulfur modified binders, which is in agreement with findings from earlier investigations [8].

Cores recovered from the trial site 1 year after opening to traffic were also subjected to binder content analysis using binder ignition oven (BS EN 12697-39:2012, test temperature 520℃). Unfortunately, despite the best efforts of the testing laboratory, the binder content results were entirely out of the expected range with correction values that were excessively high. The binder ignition oven test was thus deemed unsuitable for the Gabbro aggregates used in Kuwait. Additional samples (from sections 1 & 5) were therefore re-analyzed using conventional DCM solvent. The results of recovered binder contents are shown in Table VI below and in this case the results were far more in line with expectations.

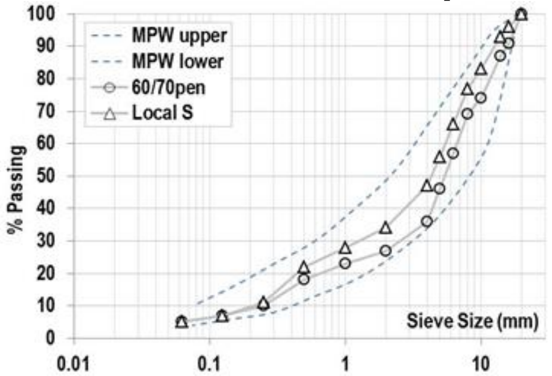

Figure 4. Comparison of MPW Type III specification limits with gradation of extracted wearing course cores from 60/70pen and Local Sulfur-modified trial sections.

TABLE VI. BINDER CONTENTS OBTAINED FROM EXTRACTED CORES (SOLVENT EXTRACTION)

	Section 1 Type III, 60/70pen	Section 5 Type III, Local Sulfur
DCM solvent recovered b.c. (%)	4.0	5.0
Design b.c. (%)	3.9	5.0

Fig. 4 below shows the aggregate gradation obtained from the samples in Table VI following binder recovery. In both cases the gradation was found to be well within the MPW specification limits.

Thus from a binder content and gradation perspective, we had some confidence that the contractor was able to adhere to the mix design requirements. Nonetheless, there was some evidence that the compaction effort on site was problematic resulting in significant variation in air voids content across the various trial sections.

G. Observations on Stiffness Modulus Results

Indirect Tensile Stiffness Modulus (ITSM) data were obtained from cores extracted soon after the completion of the Pilot road construction phase. All ITSM tests were carried out by TRL-UK at a standard temperature of 20℃ in accordance with BS EN 12697-26:2004.

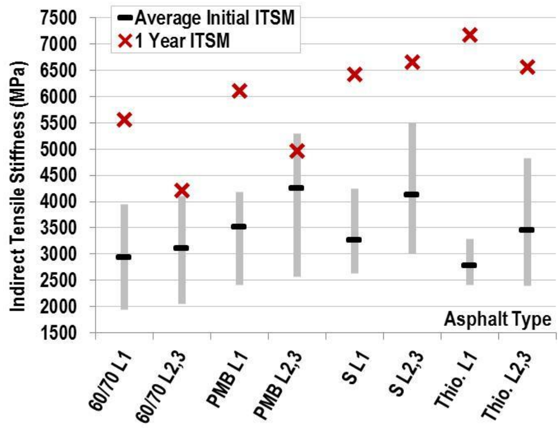

Figure 5. Range and mean of ITSM values determined on cores extracted soon after completion of construction. Cross symbols represent average ITSM results obtained from cores extracted after 1 year. L1= wearing course, L2 = binder course, L3 = base course.

Fig. 5 shows the ITSM data obtained from cores extracted soon after the completion of the Pilot road construction phase (thick vertical bars in Fig. 5 represent ITSM range), and average results 1 year after opening to traffic (crosses). For each mix type, the ITSM results from binder course (L2) & base course (L3) mixes were combined since the binder and base courses in this trial have identical gradations and bitumen contents.

The ITSM data show considerable scatter, but it is still possible to generalize that, irrespective of mix type, Type II binder/base course mixes have on average slightly higher stiffness values than their equivalent Type III wearing course mixes, which may be attributed to a combination of lower bitumen content and larger aggregate sizes.

To put the results in context, the stiffness targets specified in UK Specification for Highway Works is a minimum of 1800 MPa for materials with 40/60 pen bitumen and a minimum of 2800 MPa for 30/45 pen bitumen when tested at 20℃.

When examining the 1 year old ITSM results (crosses in Fig. 5), more interesting observations can be made. Considering the 60/70pen and PMB mixes on their own, the wearing course of both mix types show considerable increase in ITSM compared to the binder & base courses. Such behavior is expected as the binder & base courses in all sections are well protected from direct exposure to weathering and ageing by the wearing course layer. Thus the difference is primarily caused by asphalt mix oxidation.

On the other hand, when observing the behavior of the sulfur mixes (both local Sulfur and Thiopave) the wearing and binder/base course mixes have all significantly increased ITSM values following a duration of 1 year trafficking and environmental exposure. Furthermore, on average, all the sulfur mixes displayed higher ITSM results compared to the 60/70 or PMB data. This is a clear indication that partial bitumen replacement with sulfur has a considerable long term stiffening (reinforcing) effect independent of oxidative ageing, i.e. irrespective of environmental exposure. This may be attributed to continuous slow re-crystallization of the sulfur component in the binder phase and the gradual transformation from monoclinic to more thermodynamically stable orthorhombic crystalline phase.

Overall, the findings from this full scale trial with respect to stiffness modulus are in broad agreement with earlier research findings [2], [13].

H. Observations on Temperature and Water Sensitivity

Cores extracted soon after completion of the trial sections were sliced and each mix type tested for its Indirect Tensile Stiffness Modulus (ITSM) values at 20 ℃ and 40 ℃. The data points (circle symbols) in Fig. 6 indicate the percentage retained stiffness at 40 ℃ compared to the results obtained at the standard 20 ℃. The data highlight the very high temperature susceptibility of all the mix types, since none of the mixes were able to retain even close to 20% of their stiffness at 20 ℃. This behavior is not very surprising and is primarily a function of the high temperature susceptibility of the 60/70pen base bitumen which has a typical penetration value of 69 dmm and a softening point of 50 °C. The ITSM test is a non-destructive test, but at such low ITSM values, the test operator has to take extra precautions to ensure the test specimens are not being permanently damaged during the test (i.e. accumulation of irrecoverable deformations).

Fig. 6 also shows the average ITSM results following 24 hour immersion in a water bath at 60 ℃ (water conditioning). The hashed bars show the average % retained ITSM (measured at 20°C) for the first set of cores (Set 1) extracted soon after the completion of the construction phase, whilst the solid bars indicate the average % retained stiffness (also measured at 20°C) for the cores extracted 1 year after opening to traffic (Set 2). Except for one set of results (60/70pen Layers 2/3) which appears to be an outlier, it is difficult to identify one or more mix types that clearly perform very well with respect to moisture resistance.

There was a slight trend indicating that the 1 year old samples perform on average better than fresh samples, which may be attributed to the reduction in voids (densification, as shown earlier in Fig. 3) which is expected as a result of trial section trafficking. Nonetheless, examining the 1 year old sample results, almost none of the mixes achieved 70% retained stiffness.

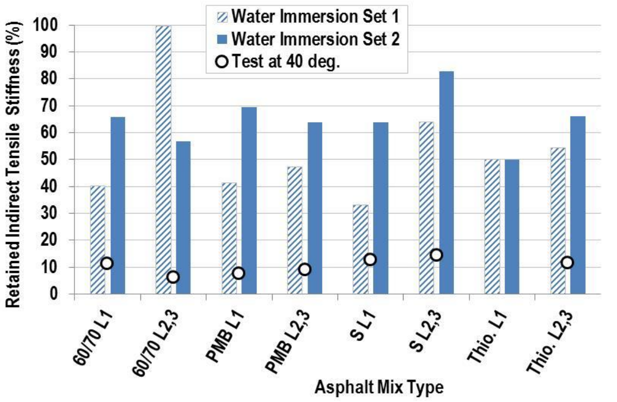

Figure 6. Bars show % retained indirect tensile stiffness results following moisture conditioning on all mix types. Set 1 relates to cores extracted soon after construction and set 2 relates to cores extracted after 1 year of opening to traffic. The circle symbols show the retained stiffness at 40 ℃ test temperature for the early age cores.

I. Observations on Wheel Tracking Test Results

Wheel tracking test (BS EN 12697-22:2003) was carried out using small scale wheel tracker (60 ℃) on extracted 200mm diameter core samples from all 4 wearing course mix types. Fig. 7 shows wheel tracking results in terms of; Proportional Rut Depth at 10,000 cycles (rut depth as a % of original sample thickness), and in terms of Individual Rut depth at 10,000 cycles (i.e. actual measured deformation in mm). To assess the influence of mix volumetrics on rutting, the results are plotted versus the air voids content for each individual sample. The Proportional rut depth (diamond shaped symbols) refer to the left y axis, whilst the Individual Rut Depth (square shaped symbols) refer to the right side y axis. A dashed line has been drawn around results from the same mix type to ease identification.

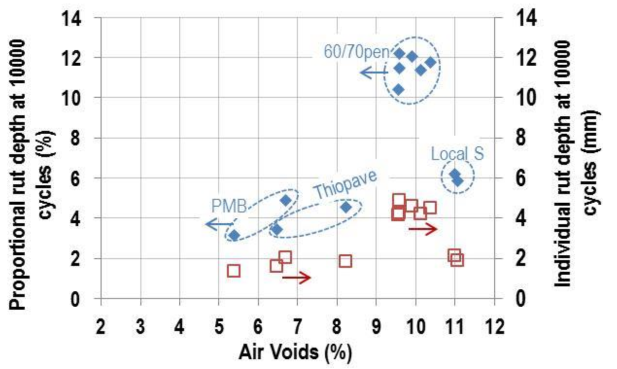

Figure 7. Wheel tracking results at 60 ℃. The diamond shaped data points show the proportional rut depth values (%) at 10,000 cycles, whilst the square shaped data points show the individual rut depth values (mm) at 10,000 cycles.

It is interesting to note that the rutting performance can be divided into two main classes, the 60/70pen badly performing HMA versus all other mixes. Unfortunately the picture is further complicated by the fact that the

60/70pen samples all had higher air void contents. It is also difficult to differentiate between the rut performance of the PMB and Thiopave mixes as they both perform very well in comparison to the 60/70pen mix.

But most interestingly, the local Sulfur modified mix performed very well, despite suffering from high air voids content (attributed to inadequate site compaction). Based on the results of recovered binder content and mix gradation, we are able to argue that together with binder type, the air voids content was a major factor influencing the rutting performance of our trial mixes.

III. Conclusions

Taking all factors into consideration, overall the sulfur-extended hot mix asphalt trial can be viewed as successful. Both the Thiopave and Local Sulfur additives performed equally well. Based on analysis of key aspects of the trial, the following main points may be highlighted:

- Only Minor modifications are needed to the asphalt plant to allow the safe addition of sulfur pellets. The asphalt mix temperature control that must be exercised when dealing with sulfur was readily achievable.
- The use of sulfur additives does not eliminate or reduce the need for tight control on compaction of the asphalt mixes on site. Any deficiency in compaction will result in excessive air voids regardless of mix type.
- Indirect Tensile Stiffness Modulus (ITSM) test results show that in general, irrespective of mix type, binder/base course mixes have on average slightly higher stiffness values than their equivalent wearing course mixes, which may be attributed to a combination of lower bitumen content and larger aggregate sizes.
- Considering the 60/70pen and PMB mixes on their own, the wearing course of both mix types show considerable increase in ITSM 1 year after construction compared to the binder & base courses, primarily as a result of asphalt mix oxidation. Alternatively, when considering the sulfur mixes (both local Sulfur & Thiopave) all layers had significantly increased ITSM values following 1 year of trafficking and environmental exposure. On average, all the sulfur mixes displayed higher ITSM results compared to the 60/70 pen or PMB data. There is evidence that partial bitumen replacement with sulfur has a considerable long term stiffening effect which may be attributed to slow re-crystallization of sulfur in the bitumen phase.
- All the mix types (including sulfur-extended) tested in this investigation displayed high temperature susceptibilities as reflected by the significant reduction in stiffness when tested at 40 ℃.
- Stiffness results obtained following moisture conditioning were borderline. There was no clear improvement in water resistance by introducing sulfur.
- It was difficult to differentiate between the 60 ℃ rutting performance of PMB and Thiopave mixes as they both performed very well in comparison to the 60/70pen mix. Most interestingly, the local Sulfur mix performed very well despite suffering from high air voids content.

A. Future Work

The Pilot trial will be monitored at set intervals for an additional duration of 4 years in order to compare the in situ performance of the various asphalt sections. Measurements of rut depths using a straight edge will also be carried out at set intervals.

The end of life recyclability of sulfur-bitumen mixes (whether Thiopave or Local Sulfur) also requires a more detailed investigation, in particular the use of warm and low temperature asphalt mix production technology.

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