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Improvement of Mechanical Properties of Asphalt Concrete Surface Course Mixtures Using Yellow Sulfur

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Abstract— Specific requirements are needed to control the quality of pavement's materials by means of mechanical and durability properties. Accordingly, many studies have been conducted to improve these properties. This study represents laboratory studies to characterize asphalt cement-yellow sulfur and the produced asphalt concrete by conducting classical test procedures. Yellow sulfur has been added as a replacement to the asphalt cement with nine contents which were 0, 5, 10, 15, 20, 25, 30, 35, and 40 by total weight of asphalt cement. The yellow sulfur modified mixtures were designed according to Marshall method and their engineering properties i.e. stability, flow, bulk density, percent of voids in total mix, and percent of voids filled with asphalt were determined. Marshal stability of the modified mixtures is higher than those of control mixture. Also, the test results show that the engineering properties of hot mixtures treated with yellow sulfur comply with SORB specifications for surface course mixtures.

Index Terms— Marshall Stability, Hot mix asphalt, yellow sulfur, and Asphalt concrete.

1 Introduction

SPECIFIC requirements are needed to control the quality of highway pavement materials to improve its durability especially for the roads suffer from heavy trafficked, high temperatures and water damages. It is worthy to say that in Iraq, the main deterioration in roads happens because of very high temperatures and extreme lack of solar isolation during summer.[1]

Generally, Sulfur is added to asphalt cement as a replacement of the weight of the later to generate the new binder which is called asphalt cement-sulfur. The aim of this study is to investigate the performance of asphalt concrete mixtures produced by using asphalt cement-sulfur binder.

Asphalt cement is a widely used binding material for roads construction. Many materials such as polymers, carbon black and sulfur used to be blended with asphalt cement to improve certain properties of the pure asphalt cement as well as the produced asphalt concrete mixture. One of the main challenge when adopting asphalt cement-sulfur binder is the increment of the total cost of the final product, therefore an economic analysis is required before commercial use becomes a reality. Block styrene-butadiene elastomer, known as block SB rubber and block SBS rubber as well, is utilized to improve the properties of asphalt cement and asphalt concrete treated mixtures. The treated mixtures generally display better physical properties in comparison with untreated mixtures. The main restriction to use the block SB elastomer in paving applications is the high cost. Therefore, sulfur is recommended to modify asphalt cement as an economic option which is traditionally prepared from a comparatively inexpensive sulfur.[2]

2 Materials

The aggregate, asphalt cement, Portland cement (as mineral filler) used in current study were conventionally used in roads paving materials in Iraq. Furthermore, yellow sulfur is utilized as replacement of asphalt cement with different percentages by weight of asphalt cement.

2.1 Aggregate

The aggregate used in this study was crushed aggregate. The aggregate was divided into coarse aggregate ranges from (25.4mm) to (4.75mm) while fine aggregate ranges between (4.75mm) to (0.075mm) according to S.O.R.B specification [R9]. Table (1) shows the physical properties of aggregate while Table (2) presents the gradation of the aggregate which is corresponding to the limits of grading requirements for asphalt mixtures that is used in the surface coarse construction according to S.O.R.B. specification.

2.2 Mineral filler

Portland cement was used in this study as filler. Table (3) shows the physical properties of the Portland cement.

2.3 Asphalt cement

The asphalt cement used in this study was of grade (40-50) Penetration brought from Al-Nasiriya refinery. Table (4) presents the physical properties and the tests of the asphalt cement.

2.4 Yellow sulfur (YS)

Sulfur forms polyatomic molecules with different chemical formulas, with the best-known allotrope being octasulfur, cy-

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clo-S8. Octasulfur is a soft, bright-yellow solid with only a faint odor, similar to that of matches. It is melting point and boiling point are 115.21 °C and 444.6 °C, respectively and sublimes easily. Between its melting and boiling temperatures, octasulfur changes its allotrope again, turning from β-octasulfur to γ-sulfur, again accompanied by a lower density but increased viscosity because of the formation of polymers. At even higher temperatures, however, the viscosity decreases as de-polymerization occurs. Molten sulfur assumes a dark red color above 200 °C. The density of sulfur is about 2 g.cm^{-3}, depending on the allotrope; all of its stable allotropes are excellent electrical insulators.[3] Eight percentages were used in preparing modified binder as a replacement of the asphalt cement i.e. 5, 10, 15, 20, 25, 30, 35 and 40% by weight of asphalt cement.

3 Preparation of Asphalt Concrete Mixtures

The amount of sulfur was determined by multiplying it's percent by the total weight of asphalt cement. As mentioned previously, eight percentages of sulfur were added to prepare the hot mixtures. The asphalt cement with the required weight was heated in an oven at 150 ^{o}C, then the required amount of sulfur was added as quickly as possible i.e. 10 sec. then, they were mixed thoroughly keeping the temperature constant at 150 ^{o}C. After that the required amount of modified asphalt cement was added to the preheated aggregate and filler in the mixing bowl. The materials were mixed comprehensively within the required limits i.e. 145-155 ^{o}C until all aggregates and filler particles were completely coated with modified binder. Each asphalt mixture was placed in the preheated mold and then spaded vigorously with the preheated spatula 15 times around the perimeter and 10 times in the interior. Then 75 blows on the top and bottom of the specimen were applied with the standard compaction hammer. The specimens were left in mold to be cooled at room temperature for 24 hours and then it was extruded from the mold. Three Marshall specimens were prepared at each asphalt content. Therefore, 15 specimens were prepared for each control and modified mixtures.

4 Determinitaion of Marshall and Volumetric Properties

Marshall Specimens were prepared with various asphalt cement content i.e. 4-6% and tested to determine Marshall and volumetric Properties. The procedure used for determining these properties are as follows:

4.1 Marshall stability and flow

Marshall Stability and flow test is performed on each specimen in accordance with the procedure described by ASTM D 1559[8]. Marshall Stability represents the resistance to the plastic flow of bituminous mixture using Marshall apparatus with Electronic recording system. The specimen is placed in water bath at 60 °C for (30-40) min. The Marshall Stability value is the maximum load in (KN), while the Marshall flow is the total displacement or strain corresponding's to the maximum load during the stability test.

4.2 The volumetric properties

4.2.1 Bulk density

The bulk density is determined in accordance with the method described in ASTM D2726 [8] . The weight of the specimen is measured in air, in water at 25°^{o}C and in condition of saturated surface dry condition (SSD). The bulk density in (g/cm3) is the calculated as follows:

$$Gmb = \frac{W_A}{W_B - W_C} \qquad \text{..............(1)}$$

where:
Gmb = Bulk density of the compacted specimen.
WA = Weight of specimen in air (gm).
WB = Weight of saturated surface dry (SSD) specimen (gm).
WC = Weight of specimen in water (gm).

4.2.2 Percentage of air voids and maximum specific gravity

The percentage of Air voids and maximum specific gravity were performed in accordance with standard test method of ASTM D204[8]. The maximum specific gravity and air voids can be calculated as follows:

$$\text{Max. } S.G. \text{ at } 25°\text{C} = \frac{W_A}{W_A - W_C} \qquad \text{..............(2)}$$

$$VTM\,(\%) = \frac{S.G. - Gmb}{S.G.} * 100 \qquad \text{..............(3)}$$

where:
Gmb = Bulk density of the compacted specimen (gm/cm3).
WA = Weight of specimen in air (gm).
WC = Weight of specimen in water at 25^{o}C (gm).
S.G. = Maximum specific gravity.
VTM = Voids in total mix.

4.2.3 Percentage of voids filled with asphalts VFA (%)

The percentage of the Voids Filled with Asphalt VFA characterizes the effective asphalt cement in compacted mixtures as percent of the Voids in Mineral Aggregate VMA. It can be calculated as below:

$$VFA(\%) = \frac{VMA(\%) - VTM\,(\%)}{VMA(\%)} * 100 \qquad \text{..................(4)}$$

where:
VTM = voids in total mix.
VMA = voids in meniral aggregate.

4.3 Optimum asphalt content for control and modified mixtures

The optimum asphalt content of the various mixtures was determined from Marshall property curves (stability, bulk density, and air voids in total mix). It represents the numerical average of the percentages of binder content corresponding to the maximum Marshall stability, maximum bulk density, and medium range of voids in total mix. The Asphalt Institute [9] recommends this procedure

5 Results and Discussion

5.1 Marshall Stability and flow

Marshall stability (MS) of control and modified mixtures with different percentages of sulfur and different asphalt cement contents are shown in Figure (1). It is clearly shown that the stability values for different mixtures are following the typical trend in their relation with different asphalt cement content i.e. MS values increase with asphalt cement content increment until reaching a maximum value then MS trends to decrease.

On the other hand, MS for the same asphalt cement content and with different modified binder is higher than those prepared with untreated binder. In addition, it can be indicated that MS values increased with sulfur content increased until 30% after this point MS values decreased slightly. The largest MS value was occurred for mixtures with 5% binder content and 30% sulfur (12.85 KN) which represents almost 52% more than those for untreated mixtures (8.5 KN).

Generally, MS of a mixture depends on internal friction and cohesion. Inter particle friction i.e. internal friction among the aggregate particles based on the characteristics of aggregate such as surface texture and shape. While cohesion is related to the bending ability of the binder[10]. Therefore MS increase for the modified asphalt concrete mixtures can be contributed to improve the workability of the mixture with sulfur particles addition as well as increase the cohesion between the aggregate and the modified binder. Kam [3] reported that MS of the comparative paving mix compounds had almost 10,000 KN when 6% by weight of asphalt cement was added in the mix. Accordingly and depending on the improvement in MS value due to yellow sulfur addition it can be reported that adopting the modified binder should provide paving compositions having a reduced tendency to become rutted.

Figure (2) shows the influence of addition of sulfur on Marshall flow with different asphalt cement contents. It is clearly shown that Marshall flow for the control and modified mixtures increased with asphalt cement content increment. Furthermore, modified mixtures i.e. asphalt mixtures prepared with asphalt cement sulfur binder, exhibited lower Marshall flow values in comparison with control mixtures. Finally, Marshall flow decreased when sulfur content increased.

5.2 Volumetric properties

The relationship between the bulk density values of different asphalt concrete mixtures i.e. control and modified mixtures and binder content is shown in Figure (3). It is clearly shown that the trend of the modified mixtures is similar to those of the control mixtures as the bulk density increased with binder content increment until reached the maximum value, 5%, after which the bulk density decreased. On the other hand and for the same binder content, the bulk density for the control mixtures is higher than those for the modified mixtures. This reduction of the bulk density of the modified mixtures can be contributed to the low specific gravity of the yellow sulfur.

The relationship between voids in total mix and binder content for treated and control mixtures is presented in figure (4). The VTM percentage decreased with binder content increase which is common in asphalt concrete mixtures. In addition, it can be reported that the VTM percentage for modified mixtures is lower than those of untreated mixtures for different asphalt cement content. Generally, mixtures' workability and compaction efficiency increased due to addition of sulfur for modified mixtures, therefore the VTM percentages increased.

Figure (5) illustrates the relationship between voids filled with asphalt (VFA) percentage and binder content for control and modified mixtures. Generally, it can be reported that VFA percentage increased with the increase of binder content. For the same asphalt cement content, VFA percentage of modified mixtures is more than those of control mixtures. The high VFA percentage can be explained as the modified mixtures have high VTM percentage in comparison with untreated mixtures. As for the same asphalt cement content, VTM percentage decrease leads to increase of VFA percentage.

5.3 Matshall stability and flow of modified and control mixtures at optimum binder content

The optimum binder content for control mixtures is 5.0% while for the modified mixtures are 5.15, 5.12, 5.11, 5.08, 5.06, 5.04, 5.01 and 5.0% for asphalt concrete mixtures with 5, 10, 15, 20, 25, 30, 35 and 40% sulfur (by weight of asphalt cement), respectively. There is a small difference in the optimum binder content between untreated and treated mixtures. This difference is within S.O.R.B tolerance (±0.15%). Therefore, it can be considered that the optimums binder content for modified mixtures is 5.0%.

Figure (6) shows the effect of sulfur content percent on Marshall stability at optimum binder content for control and modified mixtures. MS values increased with sulfur content increase until 30% addition of sulfur then MS values decreased. From this Figure, it can be reported that Marshall stability for different mixtures are above the requirement adopted by S.O.R.B specification for asphalt concrete mixtures for surface course (8.4 KN).

On the other hand, Figure (7) illustrates the influence of addition of sulfur on Marshall flow at optimum binder content for treated and untreated mixtures. It can be stated that Marshall flow values for different mixtures are within the range specified by S.O.R.B. specification for the asphalt concrete mixtures suitable for surface course (2-4mm). In addition, all treated mixtures exhibit low values of Marshall flow when compared with untreated mixtures.

5.4 Volumetric properties of control and modified mix-

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tures at optimum binder content

Firstly, Figure (8) illustrates the influence of sulfur content on VTM at the optimum binder content i.e. 5%. Generally, it can state that VTM values for all mixtures are within the requirement that specified by S.O.R.B. for surface course asphalt concrete mixtures (3-6%). In addition, it is clearly shown that VTM percentage decreased with sulfur content increase that can be contributed to the role of sulfur to fill the voids in the mixtures.

Secondly, the effect of sulfur addition on the VFA at optimum binder content is shown in Figure (9). From this Figure, VFA percentage for the modified mixtures increased with increasing of sulfur content and all the results of modified mixtures are within the specification adopted by S.O.R.B for surface course mixtures (65-85%).

6 CONCLUSIONS

The main conclusions from these laboratory studies can be listed as below:

- Addition of yellow sulfur to the asphalt cement increase mixture workability and compaction efficiency for modified mixtures.
- The same behavior of Marshal properties for modified mixtures in comparison with untreated mixtures is revealed.
- There is no significant difference in optimum binder content between control and modified mixtures.
- Marshall properties i.e. MS, Marshall flow, and volumetric properties i.e. bulk density, VTM and VFA for modified mixtures comply with the S.O.R.B requirements for surface course mixtures.
- By means of MS, adding 30% of sulfur leads to maximum improvement in MS values. While, Marshall flow and VTM decrease with increasing yellow sulfur percentage.

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TABLE 1

PHYSICAL PROPERTIES OF AGGREGATE

Property	Coarse aggregate	Fine aggregate
Bulk specific gravity (ASTM C127&C128)	2.646	2.63
Apparent specific gravity(ASTM C127&C128)	2.656	2.667
Percent water absorption (ASTM C127&C128)	0.14	0.523

TABLE 2

AGGREGATE GRADATION FOR SURFACE LAYER ACCORDING TO S.O.R.B [7]

Sieve size(mm)	Passing%
19.0 (3/4 in)	100
12.5 (1/2 in)	90 - 100
9.5 (3/8 in)	76 - 90
4.75 (No. 4)	44 - 74
2.36 (No. 8)	28 - 58
0.3 (No. 50)	5 - 21
0.075 (No. 200)	4 - 10

TABLE 3

PHYSICAL PROPERTIES OF FILLERS

Property	Portland Cement
Passing sieve No. 200, (%)	94.76
Specific gravity (ASTMC188-95)	3.05

TABLE 4

PHYSICAL PROPERTIES OF THE SELECTED ASPHALT CEMENT

Property	Test	Units	value	S.O.R.B Specification
Penetration (25°C 100 gm, 5 Sec)	ASTM D5-1997	1/10 mm	42	40-50
Softening point (R+B)	ASTM D36-2000	°C	59	50-60
Ductility (25°C, 5 cm/min)	ASTM D113-1999	Cm	>100	>100
Flash Point (Cleveland and open cup)	ASTM D92-02B-2005	°C	323	>240
Specific gravity at 25°C.	ASTM D70-03-2005		1.04	1.03-1.06

TABLE 5

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PHYSICAL PROPERTIES OF YELLOW SULFUR

<table>
<tr><th colspan="2">Property</th><th colspan="6">Yellow sulfur</th></tr>
<tr><td colspan="2">Phase</td><td colspan="6">Solid, powder</td></tr>
<tr><td colspan="2">Density</td><td colspan="6">Alpha 2.07 gm/cm3</td></tr>
<tr><td colspan="2">Density</td><td colspan="6">Beta 1.96 gm/cm3</td></tr>
<tr><td colspan="2">Density</td><td colspan="6">Gamma 1.92 gm/cm3</td></tr>
<tr><td colspan="2">Liquid density</td><td colspan="6">1.819 gm/cm3</td></tr>
<tr><td colspan="2">Melting point</td><td colspan="6">388.36 K, 115.21 Co, 239.38 oF</td></tr>
<tr><td colspan="2">Boiling point</td><td colspan="6">717.8 K, 444.6 Co, 832.3 oF</td></tr>
<tr><td colspan="2">Critical point</td><td colspan="6">1314 K, 20.7 MPa</td></tr>
<tr><td colspan="2">Heat of fusion</td><td colspan="6">(mono) 1.727 kJ/mol</td></tr>
<tr><td colspan="2">Heat of vaporization</td><td colspan="6">(mono) 45 kJ/mol</td></tr>
<tr><td colspan="2">Molar heat capacity</td><td colspan="6">22.75 J/mol.K</td></tr>
<tr><td rowspan="2">Vapor pressure</td><td>P (Pa)</td><td>1</td><td>10</td><td>100</td><td>1 k</td><td>10 k</td><td>100 k</td></tr>
<tr><td>At T (^oC)</td><td>101.8</td><td>134.8</td><td>175.8</td><td>234.8</td><td>317.8</td><td>443.8</td></tr>
<tr><td colspan="2">Bulk modulus</td><td colspan="6">7.7 GPa</td></tr>
</table>

Fig. 1. Marshal Stability curves for control mixes and modified mixes

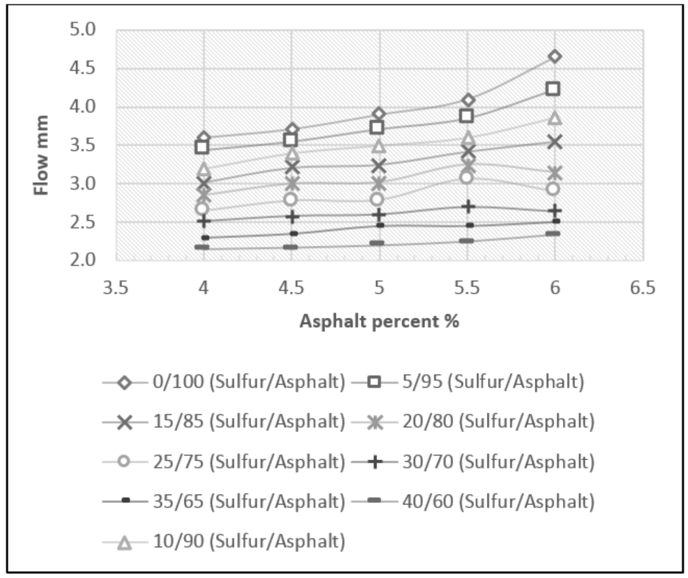

Fig. 2. Marshal Flow curves for control mixes and modified mixes

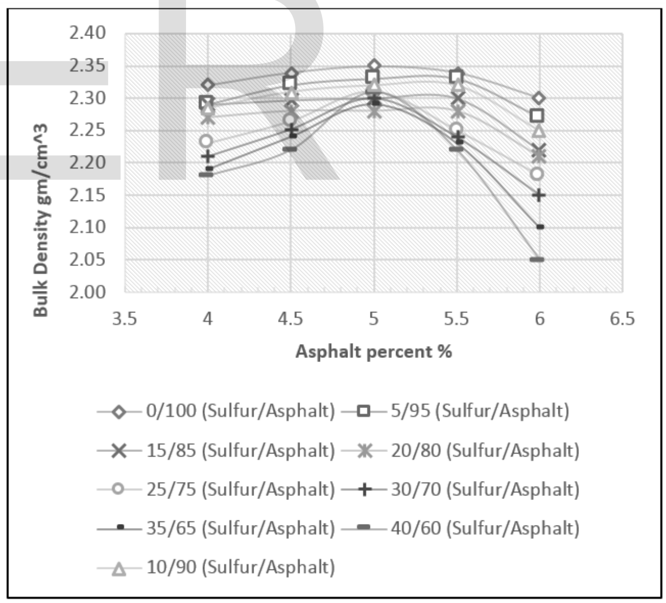

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Fig. 3. Bulk Density curves for control mixes and modified mixes

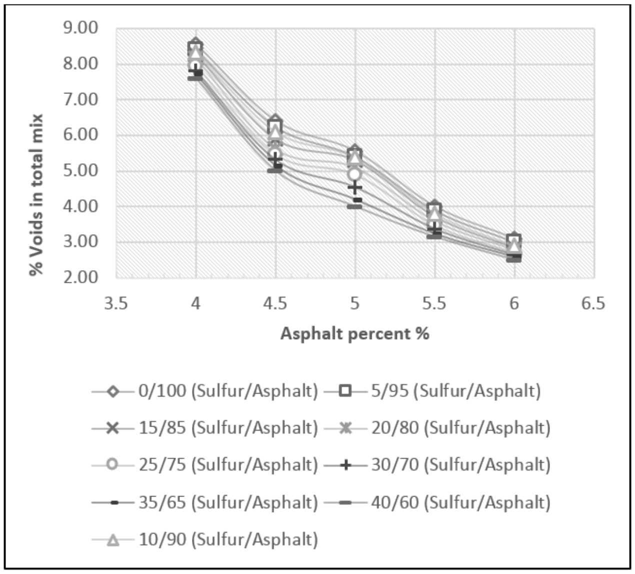

Fig. 4. Voids in total mix curves for control mixes and modified mixes

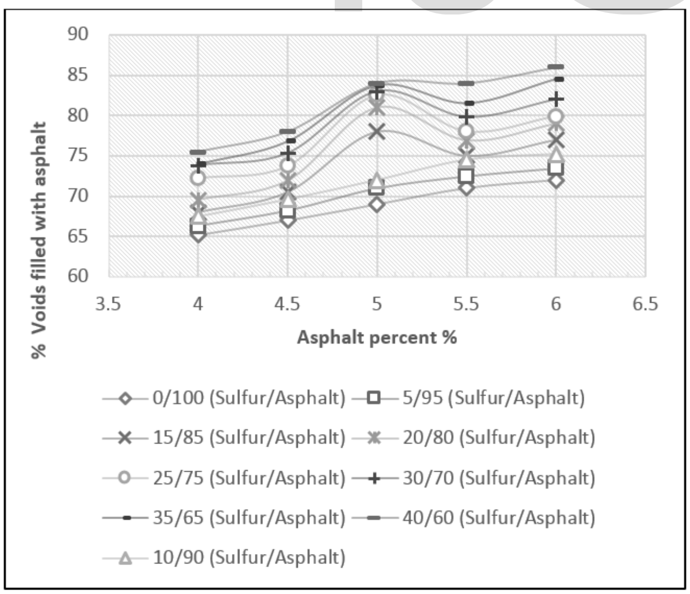

Fig. 5. Voids Filled with asphalt curves for control mixes and modified mixes

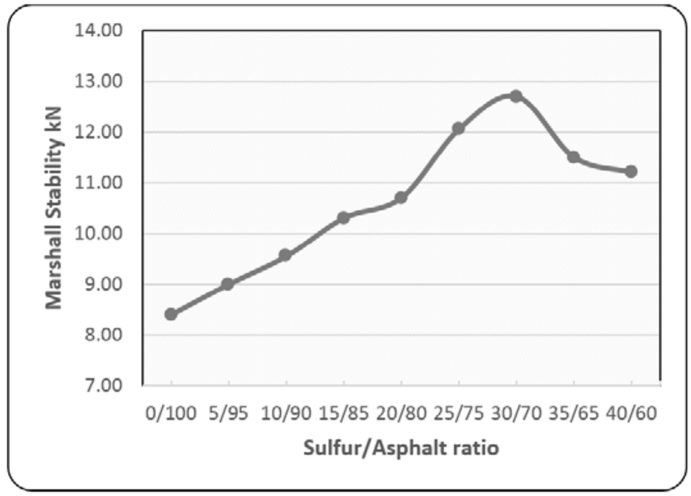

Fig. 6. The relationship between Stability and yellow sulfur percent

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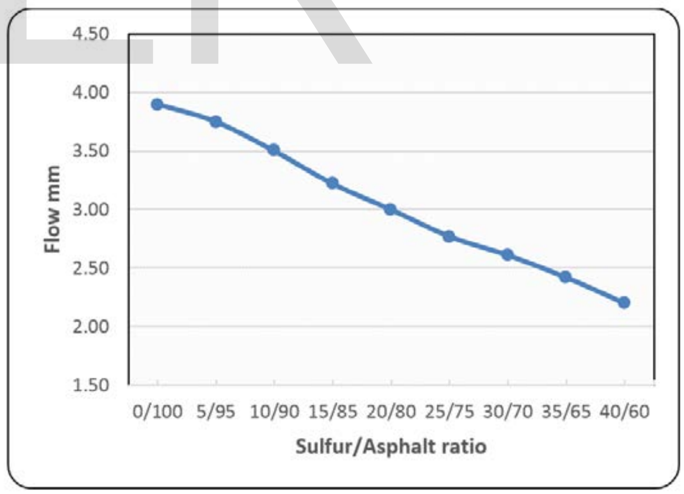

Fig. 7. The relationship between Flow and yellow

sulfur percent

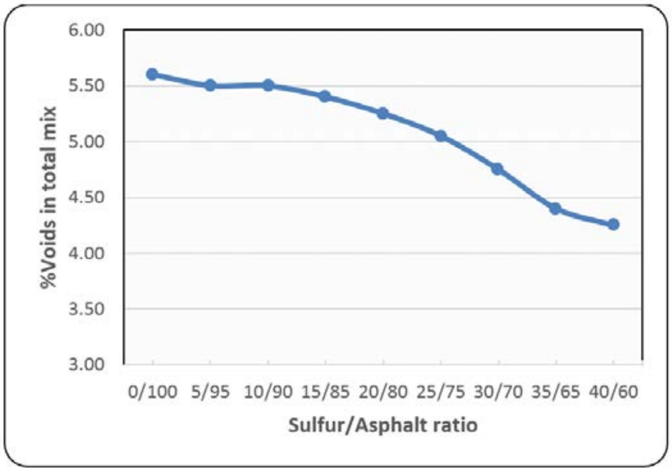

Fig. 8. The relationship between %voids in total mix and yellow sulfur percent

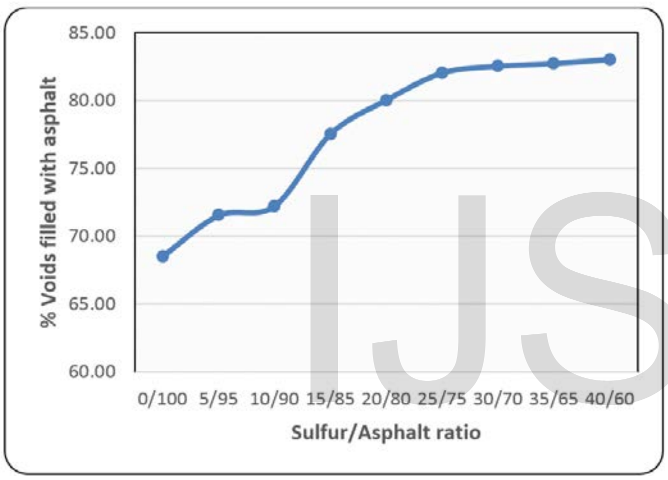

Fig. 9. The relationship between %voids filled with asphalt and yellow sulfur percent

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