Study of the Mechanical and Physical Properties of Self-healing Asphalt

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Abstract— Asphalt Pavement needs continuous maintenance to fulfill the required level of performance. This research aims to study the effect of adding steel wool (SW) on the property of the self-healing of the wearing layer in the asphalt mix. Several Tests have been conducted on aggregates, SW and bitumen to evaluate their properties. Asphalt mixes have been prepared in accordance with standard specifications followed by testing asphalt samples to obtain values of the stability, flow and specific gravity. Marshall Method has been used for the design of the asphalt mix to determine the optimum content of SW as well as to obtain the characteristics of SW modified asphalt mixture. 20 samples were prepared to determine the optimum SW content and to investigate the self-healing property through various tests. Asphalt samples with SW content of 5% showed the best thermal and electrical conductivity. The results showed also that it is possible to use SW in the preparation of asphalt wearing layers to enhance the self-healing property by heat induction. Asphalt samples with SW content of 3 and 5 % presented the strongest bonding among the different percentages. Accordingly, Marshall samples test results showed that the optimal content of SW is 4.33% (by volume of optimum bitumen content).

Index Terms— Self-Healing Asphalt, Steel Wool, Heat Induction.

1 INTRODUCTION

Asphalt pavement consists of several layers: asphalt layers (mainly binder and wearing courses) and base layers (mainly base and sub base courses) constructed on a subgrade with a suitable bearing capacity. An asphalt layer consists of mineral aggregates, asphalt binder (bitumen) and air voids. The pavement behavior under traffic and climatic loads depends on many mechanisms that are strongly related to the load transfer between layers and aggregate particles in each layer. The increase of dynamic load (traffic) in combination with neglecting preventive maintenance cause an accelerated and continuous deterioration of the road network. To overcome this problem, a pavement management system is effective and strongly needed to control the pavement condition during its analysis or performance period.

Asphalt pavement performance is affected by several factors, e.g., the properties of the components (binder, aggregate and additive) and the proportion of these components in the mix. The performance of asphalt mixtures can be improved with the utilization of various types of additives, these additives include: polymers, latex, steel wool and many other additives [1].

Induction heating of asphalt concrete is a technique that consists of heating electrically conductive particles, for example, steel wool fibers, previously mixed into the asphalt concrete mixture. Then, with the help of an induction heating device, it is possible to heat the particles locally and, through heat diffusion, heat the binder and heal the cracks. It was illustrated in [2] that a very small volume of fibers, more than 0%, serves to increase the temperature via induction heating.

The first prerequisite of induction heating is that the heated material must be conductive. The second prerequisite is that these fillers and fibers are connected in closed-loop circuits. First a micro crack appears in the bitumen. If enough volume of conductive fibers or fillers is added they will form closed-loops circuits all around the micro crack. If this magnetically susceptible and electrically conductive material is placed in the vicinity of a coil, eddy currents are induced in the closed-loops circuits, with the same frequency of the magnetic field. Heat is generated through the energy lost when eddy currents meet with the resistance of the material and, finally, bitumen is melted and the crack is closed [3].

In this research the possibility of using conductive materials, such as steel wool (SW), to produce self-healing asphalt is investigated. The principle objectives of this research are to:

- Study the effect of adding different percentages of local SW on the self-healing mechanism of asphalt mix.
- Compare it with conventional mix properties.
- Identify the optimum percent of SW to be added in the HMAs.

2 MATERIALS and Test Procedures

2.1 Materials and Laboratory Tests

Bitumen: The laboratory tests performed to evaluate the bitumen properties are: specific gravity, ductility, flash point, penetration and softening point. The properties of asphalt binder are presented in Table (1) and compared with ASTM specification limits.

Steel Wool material: Steel Wool was obtained from a local market (kitchen wash steel wool) then chopped manually. Properties of used steel wool material are shown in Table (2).

In order to define the properties of used aggregates, number of laboratory tests have been conducted, these tests are:

a. Sieve Analysis(ASTM C 136)
b. Specific gravity test (ASTM C127).
c. Water absorption (ASTM C128)
d. Los Angles abrasion (ASTM C131)

Table 1: Summary of bitumen properties

Test	Specification	Results	ASTM Specification Limits
Penetration (0.01 mm)	ASTM D5-06	65	60-70
Ductility (cm)	ASTM D113-86	146	Min 100
Softening point (^oC)	ASTM D36-2002	50	(48 – 56)
Flash point (^oC) Open Cup ©	ASTM D92-02	308	Min 230^o C
Solubility (%)	ASTM D2042		
Specific gravity (g/cm^3)	ASTMD D70	1.05	1.01-1.06

Table 2: Steel Wool properties

Property	Detail
Diameter (µm)	97.54
Length (mm)	3.0 - 7.0
Density (g/cm^3)	6.61

Aggregates: The coarse and fine aggregates used were crushed rocks imported from Egypt. Aggregates used in asphalt mix can be divided as shown in Table (3).

Table 3: Aggregates types

Type of aggregate	Particle size (Gradation) (mm)
Adasia	0/ 12.5
Simsimia	0/ 9.50
Trabiah	0/4.75

Table (4) presents the gradation of proposed mix and Table (5) presents the results of aggregates tests

2.2 Methods

2.2.1 Obtaining the Optimum Bitumen Content (OBC)

Marshall Method for designing hot asphalt mixtures is used to determine the OBC. A previously prepared gradation and obtained OBC are used from reference [2]. However in this research, 20 samples of a weight of 1230 g were prepared with four different steel wool content (SWC: 0, 3, 5 and 7%).and compacted with 75 blows according to standard Marshal design method designated in ASTM D 1559 [4]. Five samples were prepared from each SW percentage; three samples from each SWC were used to perform Marshal Stability [5], bulk density [6] and Theoretical Maximum Specific Gravity tests [7].

Table 4: Gradation of proposed mix with ASTM Specifications limits

Sieve size (mm)	% Passing
19.5	100
12.5	90
9.5	75
4.75	55
2.36	37
1.18	23
0.60	13
0.30	8
0.15	6
0.075	4

Table 5: Results of aggregates tests

Test	Eff. Specific Gravity (g/cm^3)	Absorption (%)
Adasia 0/ 12.5	2.67	1.8
Simsimia 0/ 9.50	2.595	3.39
Trabia 0/4.75	2.59	3.36
Designation Number	ASTM : C127	ASTM : C128
Specification limits	--	< 5

2.2.2 Preparation of asphalt mix with different steel wool content

There was no specific procedure for mixing the SW with the aggregate and bitumen therefore initial experimental trials were conducted to achieve the most applicable process of addition. In this study; the aim of adding SW to asphalt mix is to investigate the ability of self-healing in asphalt and not to enhance the strength of asphalt mix. After blending the aggregate with the previously obtained OBC (5.6%), the 20 samples were prepared to evaluate the effect of adding SW to asphalt mixture samples by considering four proportions of SW (0.0, 3.0, 5.0 and 7.0% by the volume of bitumen).

The procedure of incorporating SW in asphalt mix can be summarized as follows:

a) SW have to be chopped by scissors to achieve the required length range (2.0 – 7.0) mm.

b) Aggregates (Adasia (0/12.5), Simsimia (0/9.5), Tirabeya (0/4.75) are heated for 24 hours at 150^{o}C to obtain completely dry condition.

c) Requisite amount of bitumen is heated for 4 hours at a temperature of 150^{o}C.

d) Aggregates are mixed together followed by addition of hot bitumen at OBC.

e) Requisite amount of chopped SW is thrown gently on the mix and over several batches with continuous mixing. It should be taken in consideration to mix uniformly in order to prevent forming clusters of SW.

f) All ingredients are mixed vigorously to form a homogeneous asphalt mixture.

g) After preparing modified asphalt mix, specimens are prepared, compacted with 75 blows, and tested according to standard Marshal Method (ASTM D 1559 [6]).

2.2.3 Evaluation of self-healing mechanism in asphalt

To perform these tests properly, the compacted specimen's samples were cut into thinner cylindrical samples with thickness of 20 mm and a diameter of 101.6 mm, this is done to obtain flat surfaces which allow good contact between different elements of the test instruments and the surface of the sample. After cutting, the samples were placed in an oven at 40 ºC for 2 hours to remove the moisture which was coated during the cutting process and prevent the SW from corroding on the surface of the samples. Inside the sample, the SW do not corrode, because they are completely coated with bitumen [8].

Electrical resistivity measurements test

To study the electrical conductivity of asphalt mixes, their electrical resistance was measured in experiments at a room temperature of 22.4 ºC. A Fluke digital multimeter was used to measure the resistance below 36×106Ω. Accordingly, two aluminum plates electrodes connected with the multimeter were placed at both ends of the sample to measure its resistance. A small pressure was applied to the copper electrodes to obtain a good contact with the surface of the sample.

After measuring the resistance, the electrical resistivity of each sample was obtained from the second Ohm-law equation as follows:

$$\rho = \frac{RS}{L} \quad \text{...} \quad (1)$$

Whereas,

ρ = The electrical resistivity, [Ω m].

R= the measured resistance, [Ω].

S= the electrode conductive area, [m^2].

L = the thickness of the cylinder, [m].

Heat transmission measurements test

Hot plate was used to study heat transmission through a 20 mm thick asphalt samples with different SWC (0.0, 3.0, 5.0 and 7.0%). Temperature of hot plate was set to 70□ c and a laser thermometer was used to measure the temperature at the top and bottom surface of the samples at a five minutes interval for 30 minutes. Room temperature was recorded to be 22.4□ C (the asphalt samples initial temperature).

Healing of full cracked asphalt samples using microwave

Asphalt samples with different SW contents (0.0, 3.0, 5.0 and 7.0%) were cut to a thickness of 20mm and frozen at a temperature of -17.5□ C for 48 hours in order to ensure homogenous hardening of the sample that facilitates the breaking process. Then a spontaneous full crack was introduced to the sample by a hammer in order to investigate the healing tendency of each sample. Samples were then put in a microwave with a power of 700 Watt for two stages. Firstly, samples were heated in the microwave for 60 seconds and then their temperatures were measured using a digital thermometer. Secondly, samples were put in the microwave for 90 seconds and their temperatures were also recorded, after that, the samples were immediately put back in their molds until they cool down. Twenty-four hours later, they were extracted from the molds and visually inspected to determine which samples have a better healing tendency.

3 RESULT ANALYSIS

The effect of adding different SW percentages on the properties of asphalt mix are analyzed and compared with the conventional asphalt mix (No additive) properties, which acts as the control group. These properties include Marshal Stability, flow, bulk density, Air voids (V_a) and Voids in mineral aggregates (VMA) in addition to other tests to evaluate the self-healing property of asphalt.

3.1 Mechanical Tests

3.1.1 Stability – SW content relationship

The stability of modified asphalt mixes oscillates. First, the addition of SW more than 0% (by volume of bitumen) reduces the stability by approximately 27% at a SWC of 3%, then it starts increasing until it reaches a maximum of 1950.10 kg at a SWC of 5% which is very close to the stability of conventional asphalt mix. The curve then start falling again until a SWC of 7%. Figure (1) shows the oscillation of the stability of modified asphalt mix with a maximum stability at a SWC of 5%.

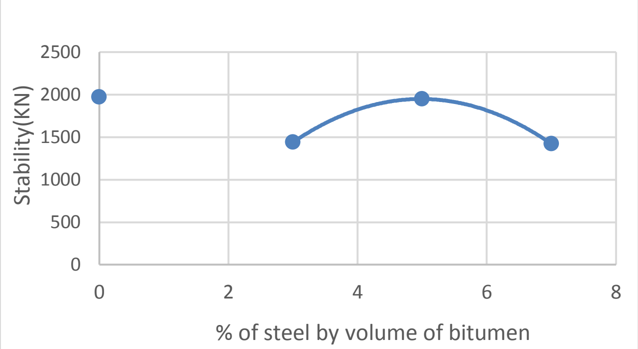

Figure 1: Asphalt mix Stability – SW content relationship.

The noticeable drop in stability at first is attributable to the replacement of aggregate with a small amount of SW until it reaches a minimum stability of 1441.30 at 3% volume of SW. After that any additional replacement of aggregate increase the stability of the mix until it reaches a maximum value at 5% SW volume. Again the stability starts decreasing due to large amount of aggregate being replaced by SW that does not provide the same stability aggregate does. The decrease in stability can also be explained by the nesting of SW around the aggregate that occurred during mixing which led to slight loss of bonding between the contents of the mixture.

3.1.2 Flow – SW content relationship

Generally, the flow of modified asphalt mix is higher than the conventional asphalt mix (2.47 mm). Figure (2) shows that the flow increases continuously as the SWC increases. The flow value extends until it reaches (3.88mm) at SWC of 7%.

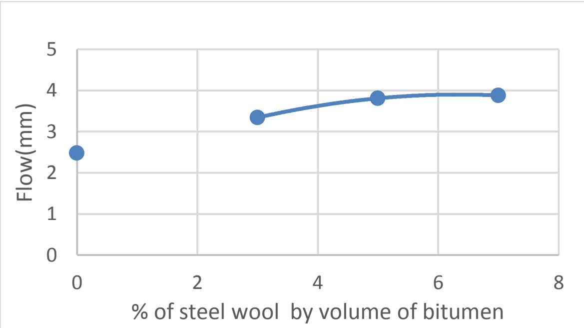

Figure 2: Asphalt mix flow – SW content relationship.

3.1 Bulk density – SW content relationship

The bulk density of compacted SW modified asphalt mixture is lower than the conventional asphalt mix (2.367 g/cm^3). The general trend shows that the bulk density decreases as the SWC increases. The maximum bulk density is (2.30 g/cm^3) at SWC (3.0 and 5.0%) and the minimum bulk density is (2.27 g/cm^3) at SW (7%). This decrease of bulk density can be explained to be as a result of increasing percentage of void as the SWC increases.

Figure (3) shows asphalt mix bulk density – SWC relationship

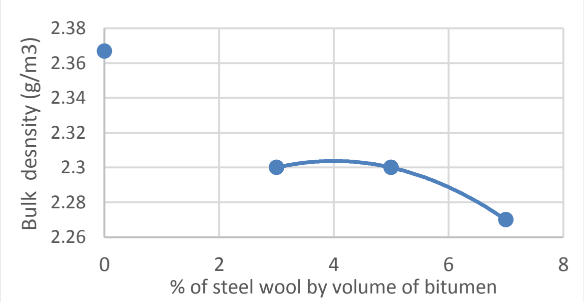

Figure 3: Asphalt mix bulk density – SW content relationship.

3.2 Air voids (Va) – SW content relationship

In general, the air voids proportion of modified asphalt mixes is higher than conventional asphalt mix (3.82 %). V_a % of modified asphalt mixes increases gradually as the SW content increase till it reaches the highest V_a% value at 7% SWC. Generally modified asphalt mixes have Va% content exceeding the specifications range due to the mentioned nesting problem that indicates a higher compaction energy is required for modified asphalt mixes with SW. Figure (4) shows the curve which represents asphalt mix air voids – SWC relationship.

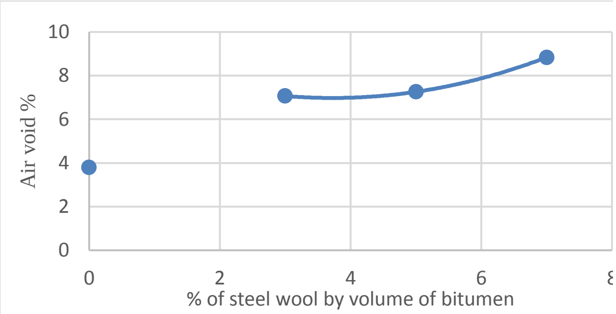

Figure 4: Asphalt mix air voids (Va %) – SW content relationship.

3.3 Voids in mineral aggregates (VMA) – SW content relationship

The voids in mineral aggregates percentage VMA% for asphalt mix is affected by air voids in asphalt mix Va and voids filled with bitumen Vb. VMA% of modified asphalt mixes is generally higher than conventional asphalt mix (16.44%). VMA % of modified asphalt mixes is approximately constant (20.94% at 7% of SW content). Even though Va % increases as the SW content increases, VMA remains the same due to decrease of bulk density which decreases Vb as well .Figure (5) shows the curve which represents asphalt mix VMA% – SWC relationship.

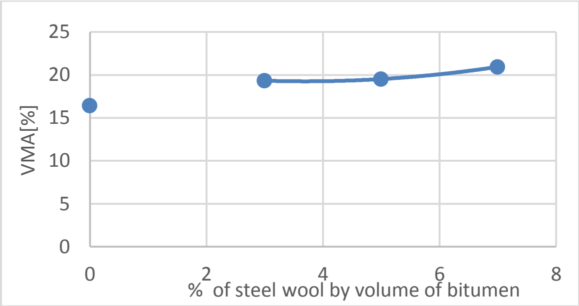

Figure 5: Asphalt mix voids of mineral aggregates (VMA) – SW content relationship.

3.4 Optimum steel wool (modifier) content

A set of controls is recommended in order to obtain the optimum modifier (SW) content that produces an asphalt mix with the best mechanical properties [9, 10]. Asphalt mix with optimum modifier content satisfies the following:

- Maximum stability
- Maximum bulk density
- Va % within the allowed range of specifications.

Figures (1, 3 and 4) are utilized to find SW percentages which satisfy these three controls. The SW percentages which satisfy controls are summarized in Table (6).

- The Optimum SW content is the average of the previous three SW contents.
- Optimum SW content (By OBC weight) = 4.33 %.

Table 6: Summary of controls to obtain optimum modifier content

Property	SW (By OBC volume)
Maximum stability	5 %
Maximum bulk density	5 %
Va % within the allowed range of specifications	3 %

3.5 Comparison of control mix with SW modified mix

A comparison of the mechanical properties of SW modified asphalt mix at the optimum SWC (4.33 % by OBC volume) and properties of the conventional (control) asphalt mix is shown in Table (7). Minimum and maximum allowed limits are also presented according to Municipality of Gaza specifications in Table (8) [11].

Table 7: Comparison of SW modified asphalt mix and conventional (control) mix properties

Property	**Conventional asphalt mix**	**(4.33%) SW modified asphalt mix (By OBC volume)**	**Change amount**
OBC (%)	5.60	5.60	-
Stability (kg)	1973.49	1811.67	- 8.20 %
Flow (mm)	2.47	3.65	+ 47.77%
Stiffness (kg/mm)	798.98	492.60	- 37.22%
VMA %	16.42	19.43	+18.33 %
Va%	3.80	7.17	+ 88.68 %
Bulk density (gm/cm3)	2.367	2.30	- 2.83 %

Table 8: Properties of SW modified asphalt mix with specifications range

It is clearly shown that asphalt mix modified with (4.33% SWC by OBC volume) has a slightly lower stability and stiffness compared to the conventional asphalt mix, but still higher than the specified minimum range. While for the other properties of modified mix are within the range except for air void that is slightly out of the allowed range of the specifications. This can be improved by performing a special mixing procedure that guarantees a better homogeneity of the mixture.

3.6 Self-healing mechanism tests

Several tests were conducted to obtain the phenomena of self-healing of asphalt samples with different SWC (0.0, 3.0, 5.0 and 7.0% by OBC volume). These tests include: electrical resistivity measurements, heat transmission measurements and healing of cracked asphalt samples using microwave.

3.6.1 Electrical resistivity measurement test

The resistivity of conventional and modified asphalt mix samples were measured using fluke digital multimeter, Figure (6) shows the relationship between electrical resistivity and

Property	(4.33%) SW modified asphalt mix (By OBC volume)	Local Spec. (MOG, 1998) [11]	
		Min.	Max.
Stability (kg)	1811.67	900	*
Flow (mm)	3.65	2.0	4.0
VMA%	19.43	13.5	*
Va%	7.17	3.0	7.0
Bulk density (g/cm3)	2.30	2.30	*

SWC in asphalt mix.

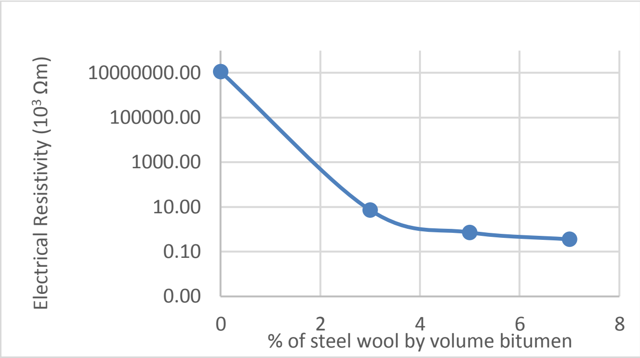

Figure (6): Asphalt mix electrical resistivity – SWC relationship.

The Figure shows that an amount of SW=0, the electrical resistivity is very high, it is exhibiting the case of insulating behavior. The addition of more SW to the mix decreases the electrical resistivity. The SWC (3 – 5%) can be considered as the optimal content for conductivity purpose, because adding more steel wool above this content to the mixture improve its electrical conductivity weakly.

3.4.2 Heat transmission measurement test

The test was performed to investigate heat transmission through the samples using hot plate. Figure (7) shows for example the temperature change in asphalt sample at SWC of 5% with time at top and bottom surface.

Figures (8) and (9) illustrate how the temperature changes over a period of time of 30 minutes on top and bottom surfaces for asphalt samples with different SWC. Samples with SWC of 3% and 5% exhibits the highest heat transmission between top and bottom surfaces of samples among the four percentages of SWCs. Although asphalt samples with SWC of 7% has the highest electrical conductivity, it exhibits the lowest heat transmission. Figure (10) summarizes the heat transmission rate for asphalt samples with different SWC at bottom surfaces after five minutes.

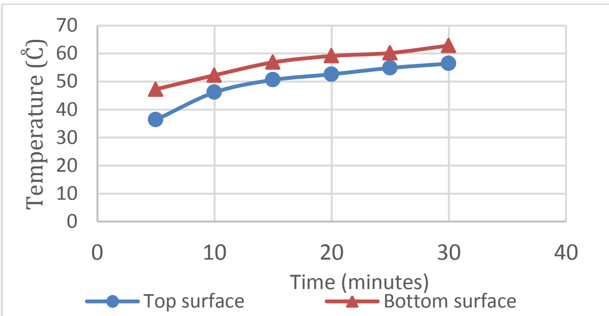

Figure (7): Relationship between top and bottom surface temperatures with time at SWC of 5% (by OBC volume).

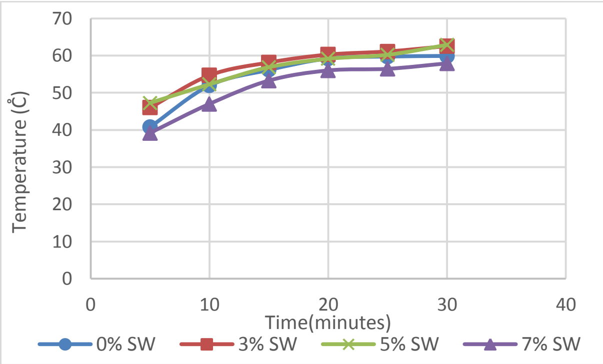

Figure (8) Relationship between bottom surface temperatures with time and different SWC.

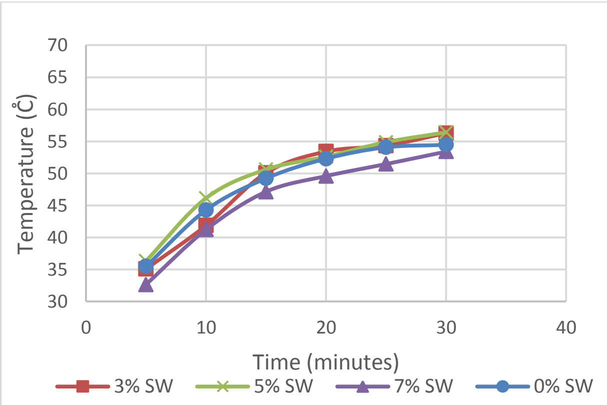

Figure (9) Comparison between top surface temperatures with time and different SWC.

Careful consideration to Figure (10) shows a significant results of heat transmission for asphalt samples with different SWC. For example, considering the heat transmission after five minutes indicates a higher heat transmission rate for asphalt samples with SWC of 3% and 5% (105% and 111% respectively) and a slow rate for conventional asphalt samples (SWC = 0%) which integrates with the previously mentioned concept of electrical resistivity of asphalt samples with different SWC.

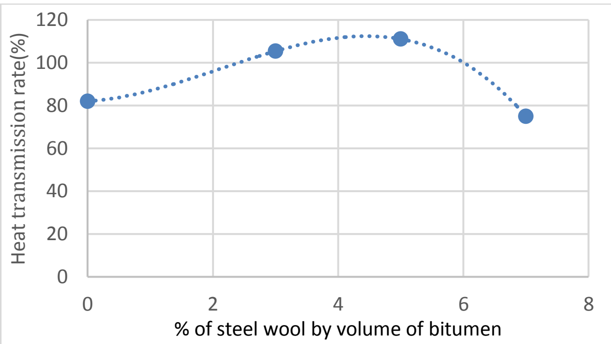

Figure (10) Heat transmission rate after five minutes at the bottom surface of asphalt samples.

The specified optimum SWC (4.33% by OBC volume) lies within the range of SWC that provides the highest heat transmission rate. Further analysis of the figure shows that an increase in SWC greater than the optimum SWC range doesn't provide a higher heat transmission rate. On the contrary, asphalt samples with SWC of 7% has a reduced efficacy by 5% compared to asphalt samples with 0% SW content which is referred to the inhomogeneity of mix that forms clusters which do not provide a homogenous distribution of heat through its surface instead it provides a local heating where clusters occur.

3.4.3 Healing of cracked asphalt samples using microwave

Testing procedures were performed and results were recorded. Table (9) shows the temperature of asphalt samples with different SWC after 60 and 90 second of being heated at the microwave.

Table (9): Temperature of asphalt samples after 60 and 90 seconds in microwave.

SW content (% by OBC volume)	Measured temperature (C□)	
	for 60 seconds	for 90 seconds
0	24	31.5
3	60	80
5	55	75
7	50	70

In reference to the table, heating samples with different SWC exhibits different behavior of microwave heat absorption for each time interval. It was observed that the same pattern of heat and electrical resistivity is followed for microwave heating. Samples with 3% SWC has the highest temperature after being heated in the microwave for 60 and 90 seconds, while temperature of samples with SWC = 0% was around room temperature after 60 seconds which clearly shows the inefficacy of conventional asphalt mix when introducing heat for self-healing purposes. Whereas, samples with SWC of 7% exhibits a good microwave heat absorption but a partial damage to the sample was observed after heating to 90 seconds due to low stability and inhomogeneity of the sample. Visual inspection of samples after 24 hours of being left to cool down to room temperature in molds where it was originally casted. Samples with SW content of 3 and 5% were seen to have an excellent bonding between the fractured surfaces, whereas the 7% SW sample did not have an efficient healing.

Figure (11) shows the relationship between SWC and the dramatic decrease in electrical resistivity while air void percentage increases gradually.

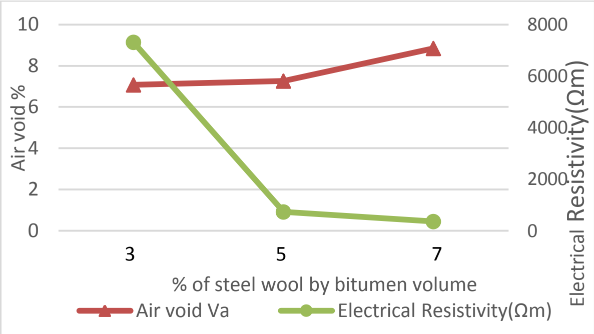

Figure (11): Relationships between SWC, electrical resistivity and air void ratio.

4 CONCLUSIONS

Based on experimental work results for SW modified asphalt mixtures compared with conventional asphalt mixtures, the following conclusions can be drawn:

a) The optimum amount of SW to be added as a modifier of asphalt mix was found to be (4.33%) by volume of OBC of the asphalt mix.

b) higher compaction energy is required for modified asphalt mixes with SW to obtain higher values of bulk density and reduce air void percentage to be within the specified range

c) Asphalt mix with SW needs more time in mixing compared with the conventional asphalt concrete mix due to its special mixing process whereas SW is added to the mixture of aggregate and bitumen by throwing chopped SW into the mix gently over several batches during continuous mixing.

d) Asphalt mix modified with SW exhibits higher flow values as the SW percentage increased.

e) Asphalt samples with SW content of 3 and 5% represent the best healing behavior compared with samples with 7% SW content.

f) Adding SW to the asphalt mix greater than the optimal content causes nesting (clusters) in the mixture, which reduces the stability of mix due to the higher air void percentage.

g) Adding steel wool to asphalt mix makes it electrically conductive. The electrical resistance of asphalt concrete depends on the content of SW. There is an optimal content of SW to obtain the highest conductivity. Greater than this optimal content, addition of more steel SW does not increase the conductivity anymore. Excess SW can make the mixture difficult to mix.

h) Asphalt concrete with steel wool can be heated with induction energy. Content of the SW are important for the heating speed of asphalt concrete. There is an optimal content of steel wool. Addition of SW above the optimum does not increase the induction heating speed anymore.

i) The durability of asphalt concrete roads will be improved with induction heating due to the improvements in the healing capacity.

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