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Improving Life Cycle of Asphalt Pavement Mixture Using Self-Healing Technique

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- Microwave Heating (MH).

A B S T R A C T

Self-healing technology is a new field in material technology. It is causing a transformation in materials engineering and revolutionizing the behavior of various materials which can make a new generation of asphaltic materials artificially healed while in-service which c4 extend the service life of asphalt pavement. This article provides an overview of investigations concerning the self-healing characterization and enhancement in the modified control mix (MCM) and modified Recycled Asphalt Pavement RAP mix (MRM) by applying a microwave heating field at the surface of the mixtures while working by embedding steel wool fibers in the asphaltic mixtures. Marshall mix design was used for the design of HMA and SH-HMA mixtures for testing of Physical properties and compared with the control mixes. For MCM, the used percentage was 5% of S.W.F. which got healing percentages (93.2%, 77%, 63.9%) respectively, while the control mixtures healing percentages were (51.5%, 41.8%, 31.8%) respectively. For MRM, the used percentage was 3% which got healing percentages (83.6%, 73.4%, 62. 5%) respectively, while the control mixtures healing percentages were (44.7%, 33%, 24.2%) respectively. The results of the experiment showed that the addition of steel wool can improve the self-healing behavior of HMA and the overall performance.

1. INTRODUCTION

Asphalt is a highly adaptable construction material widely employed in various paving projects. Comprised of aggregates, sand, additives, and asphalt, asphalt pavement is utilized for the creation of driveways, parking lots, roadways, and more. Based on the variations in asphalt used in pavement design, there are several types of asphalt pavements [1]. The five most common types of asphalt pavements used in construction are:

- Hot mix asphalt pavement
- Warm mix asphalt pavement
- Cold mix asphalt pavement
- Porous asphalt pavement
- Dense-graded asphalt pavement

Roadways are the most widely used transportation method across the globe right now, and one of the main contributors to accidents on them is road distresses [2]. Various types of distresses can occur as a result of high contact stresses on wheels, repeated traffic loads, the properties of the materials involved, construction methods, and climatic changes can be effect on pavement.

Moreover, damaged pavements require costly maintenance and repair which in turn cause restrictions in traffic flow, and consequently results in undesirable traffic congestion. One of the major distresses that directly affect the serviceability and quality of flexible pavements is cracking [3].

1.1 Cracks

There are many different factors that can contribute to asphalt erosion and make surface or deep cracks as shown in Fig. 1. It can be the result of seasonal changes, poorly compaction base, water leakage in asphalt layers, tree roots underneath the asphalt or the weight of vehicles and heavy traffic [4].

Keeping a well-maintained highway network requires the detection and measurement of pavement distresses. This allows highway authorities to take prompt action when these distresses are in their early stages, ensuring that quick measures are initiated. [5], [6].

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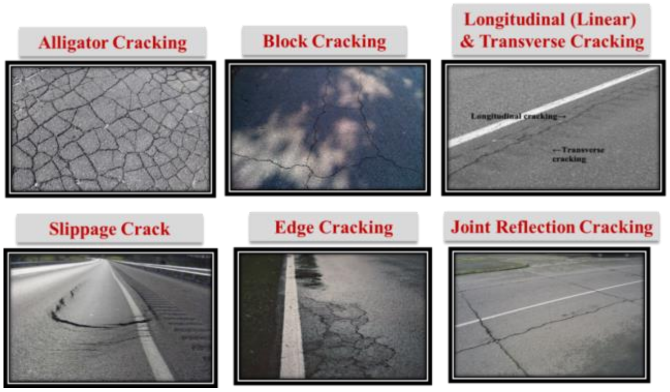

Figure (1) Types of cracks

1.2. Asphalt Additives to Control Cracking

Additives are often used to produce asphalt mixtures with better physical properties over a wide temperature range. This modified asphalt mix leads to pavement and roofing materials that increase pavement life [7]. In this study, steel wool fibers were used to improve asphalt mixes, for both MCM and MRM mixes.

1.3. Self-healing

In order to enhance the implementation of new technologies, researchers evaluate the properties of healing materials such as "self-healing asphalt" [8].

The primary goal of self-healing technology is to facilitate and support the ability of material systems to self-repair following any form of damage. Its objective is to minimize the extent of damage and enhance or restore the functionality and lifespan of the affected part [9].

The process of asphalt aging, caused by the combined effects of weather and traffic, leads to the development of micro cracks within the mortar component. By adding a conductive material in the asphalt production, such as steel wool fibers the possibility arises of heating up the mortar of the asphalt by microwave device [10, 11].

Microwave heating (MH) has attracted great interest from the industry and academia thanks to its advantages of high uniformity, energy saving, selective heating and environmental friendliness [12].

A short "heat shot" through the steel fibers, causes melting of the bituminous binder and because of that, hairline cracks in the asphalt layer are closed [13].

The pavement material can experience a range of damaging failures in both hot and cold conditions, such as cracking, fatigue cracking, or permanent deformation, ultimately leading to a decrease in quality and performance [14] [15].

Recycling asphalt pavement creates a cycle of reusing materials that optimizes the use of natural resources [16].

Reclaimed asphalt pavement (RAP) is a valuable substitute for virgin materials as it reduces the requirement for utilizing virgin aggregate which that make a positive impact on the environment [17], [18].

Extending the service life of an asphalt surface layer is always a continuing desire. This can be achieved by enhancing the quality of the product during installation. Another option is to upgrade the quality throughout the service life. This approach is known as Self-Healing Asphalt [19], [20].

This paper investigates the use of steel wool fibers of various lengths and contents added to asphalt during mixing, which, after being subjected to microwave heating, can help heal the micro-cracks in asphalt pavement specimens.

Numerous laboratory tests have been developed to assess and compare the mechanical and engineering characteristics of asphalt mixes under various loadings and environmental conditions [21]. The three-point test is a valuable tool used to forecast and assess the long-term durability of asphalt mixes, ensuring their performance over time. This test plays a crucial role in determining the maintenance needs of these mixes

2. RESEARCH PROBLEM

Cracking is one of the primary issues causing distress in flexible pavements. The last studies found out that any change in the percentage of the ingredients of hot mix asphalt mixture will have an effect on the characteristics of the HMA mixture. It's very important to find some alternatives for these high cost materials by using the available products so we can increase the performance of the asphalt and save the environment from the incremental increase of these products. So, one of these solid wastes is the steel wool fibers which could be used in the asphalt industry to decrease the cracks and deformation by enhancing the self-healing properties in the asphalt mixture. This study was conducted as a result of the growing expenses associated with repairing roads in Egypt. The presence of cracks and distress on the roads has become a major concern, as they occur shortly after construction. These cracks not only affect road performance but also contribute to an increase in accidents at various locations. As a result, the government is forced to spend a substantial amount of money to restore road performance and allocate significant resources from landfills.

3. RESEARCH OBJECTIVES

The main objectives of this study to evaluate the feasibility of using steel wool fibers in investigating fatigue behavior and recovery:

1- Investigate the self-healing efficiency of asphalt mixtures containing steel wool fibers (for modified control mix (MCM) and modified RAP mix (MRM)).
2- Evaluate the capability of steel wool fibers to enhance the performance of the hot mix asphalt specimens.
3- Understand the self- healing phenomenon through numerical modelling.

4- Decreasing maintenance coast.
5- Increasing life-time of pavement.

4. MATERIALS, TEST EQUIPMENTS, AND METHOD

4.1. *Materials*

4.1.1. Bitumen

In this study the type of bitumen that was used for producing all the specimens that tested later was 60/70 penetration grade and sourced from Suez, the physical properties of this asphalt were conducted in Laboratory.

Table (1): Physical characteristics of bitumen

Properties	Values	Specifications
Penetration at 25 °C (0.1mm)	67	60/70
Kinematic Viscosity at 135 °C	369	320
Softening Point	53	45/55

Figure (2): The bitumen used

4.1.2. Aggregate

The aggregate that used in this study was commonly crushed aggregate that sourced from Atta's mountain. Experiments and tests have been applied to find out the physical properties of the aggregate and gradation tests were conducted to find out the distribution of aggregate size. The tests were carried out to evaluate the physical properties of the aggregate in Figure (2) and all these results were summarized together with limits in Table (2).

Table (2): Physical characteristics of the aggregate

1320	Total weight of mixture (gm)
1259	Weight of solid materials (gm)
8	Weight of Ash (gm)
4.18	Asphalt percentage (%)

Figure (3): The aggregate used in fresh HMA

4.1.2.1. Sieve analysis of aggregates

For modified control mix (MCM): The gradation test was carried out according to the specification (ASTM C 136) on a sample of used aggregate for each type of aggregate in a Laboratory and the results are presented in Fig. 4.

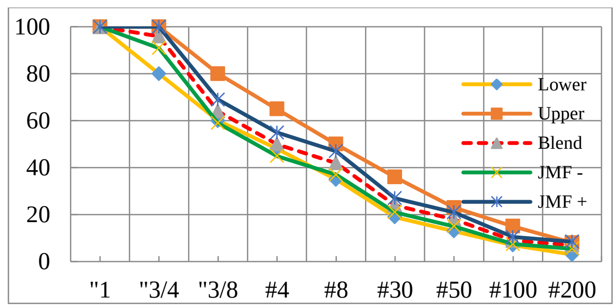

Figure (4): Aggregate Gradation

For Modified RAP mix (MRM),

the gradation test was carried out according to the specification (ASTM C136) on a sample of used RAP in Laboratory and the results are presented below in Table (3), and Figure (4) Aggregate Gradation.

Table (3): Extraction test result for MRM

Mix Components	Percentage of Components (%)	Mix Components (gm)
BIN(25 -13mm)	20%	240
BIN(13 -9mm)	30%	360
Sand(6-0mm)	15%	180
C.Sand(6-0mm)	33%	396
Filler (powder)	2%	24
Bitumen	5%	60
Total weight of specimen	1200 gm	

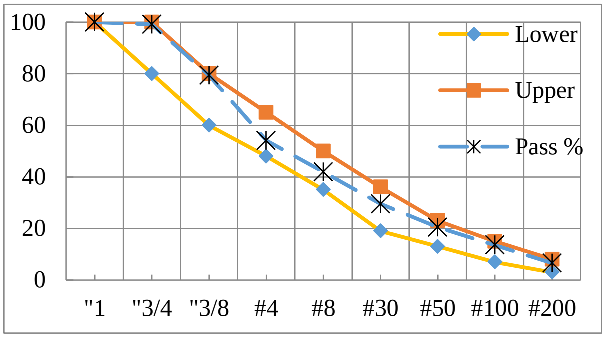

Figure (5): Aggregate Gradation

4.1.3. Steel Wool Fiber

Steel wool fiber was selected as the microwave heating material. Steel wool that was used in this research was (3 - 6) mm in lengths which was collected and embedded in the mixture of fresh or Rap.

Figure (6): Steel Wool Fiber

4.1.4. Oil

The waste engine oil (WEO) was mainly used with recycled asphalt as a rejuvenator for enhancing and restoring the basic performance by adding optimum oil content [22].

Figure (7): Waste Engine Oil

4.2. *Equipment*

4.2.1. Marshall Stability test

Marshall Stability test is used in this study for both determining the optimum binder content (OBC) and evaluation the specimens.

Figure (8): Marshall test Device

4.2.2. Three Point Bending Test device

The mission of this test device develop micro cracks in the specimen. Form 3-point test with (Rate = 0.5mm/min – Stop load =1%) we recorded the max load.

Figure (9): Three points test device

4.2.3. The Microwave

The microwave oven used in this study had an output of 1150W and a 230V, 50Hz power supply which used to fill micro cracks in specimens by melting bitumen at a certain temperature.

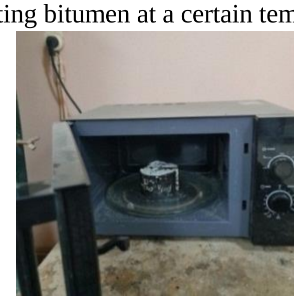

Figure (10): Specimen in the microwave

4.2.4. *Infrared Thermometer*

Infrared thermometer or laser thermometer used to measure the temperature and thermal distribution of the objects by non-contact way with aim of laser.

Figure (11): Infrared thermometer measure the temperature of specimen

5. METHODOLOGY

According to the EGYPTIAN CODE specifications, aggregates are banded together in order to get a proper gradation. The percentage of each type of aggregate is computed and compared to specification limits.

5.1. *Marshall Test Method*

To prepare Marshall specimens, aggregates were heated at a temperature of 150°C for 2h, while bitumen and steel fibers were heated at the same temperature and time.
Therefore, the materials were added into metallic bowl in the following order: first, coarse aggregate; second, fine aggregate and filler (stone dust) and finally, bitumen and steel wool fibers.
Specimens were prepared according to physical properties values which were:

All materials were mixed during approximately 3.5min into the bowl by mixer at a constant rate of 100 rpm. After the mixing process, the mixture were manually added into a metallic bowl and back to the oven with a same temperature for 1h with Marshall molds. One hour later, mixture were put into a Marshall molds and then compacted applying 75 blows on each side of the specimen with a Marshall Hammer. After compaction and cooling specimens to ambient temperature, Marshall specimens were mechanically extracted from the mould. Finally, Marshall Specimens of asphalt mixture type were manufactured. Asphalt concrete was prepared specifically, three replicated of each percentage, with the addition of three control mixes of both types (MCM and MRM), for a total of 12 samples. Steel wool fibers that was used in this research in two ways:
Firstly, for modified control mix (MCM), the substitution plan for the specimens was done by three percentages for each content type (3, 5,7%) were used to obtain the characteristics of HMA and to characterize the effect of S.W.F in HMA for each percentage, which is steel wool fibers was included by the weight of the bitumen.

Secondly For modified RAP mix (MRM), Steel wool fibers were mixed to RAP with percentages (3,4,5%) from the weight of bitumen which were in RAP, and the percentage of oil which were put on RAP were calculated from the total weight of specimen and weight of bitumen after the extraction test.

The used specimens are the ones that gets the highest performance in Marshall test which checked the stability and flow. So, for fresh mix the used percentage was (5%) , which equal (9 grams), Table (4), for the 3 moulds of marshall, and for RAP the used percentage was (3%) ,which equal (13.53 grams) for the 3 moulds of Marshall Table (5).

Table (4): Fresh mix, the used percentage was 5%

Mix Components	Content percentage of mix (gm)	
	Control Mix	**5%** Steel Fibers
Aggregates (6-25mm)	750	750
Filler (0-6mm)	390	390
Bitumen	60	57
Steel Wool Fibers	-	3

Table (5): Moulds of marshall, and RAP the used percentage was (3%)

Mix Components	Content percentage of mix (gm)	
	Control Mix	**3%** Steel Fibers
RAP	1165.37	1160.86
Oil (23%)	34.63	34.63
Steel Wool Fibers	-	4.51
Total weight of specimen	1200 gm	

Figure (12): Healed Specimen

6. DATA ANALYSIS AND RESULTS

The Control specimens, which did not contain any steel fibers, and the Self-healed specimen, which contained steel wool fiber, were subjected to testing for volumetric and physical properties in the Marshall Stability unit. These tests were conducted to determine the stability and flow values. [23].

6.1. *Marshall Test*

6.1.1. *For Modified Control Mix (MCM)*

Table (6) shows the stability and flow results for control mix and different S.W.F percentages, while Figure (13) shows physical properties for all types of mixtures

Table (6): Stability and flow results for control mix and different S.W.F percentages

S.W.F. percentage (%)	Stability (kg)	Flow (mm)	Rigidity (kg/mm)
0%	1303	2.6	501
3%	1271	3.5	363
5%	1457	2.7	540
7%	1740	2.6	669

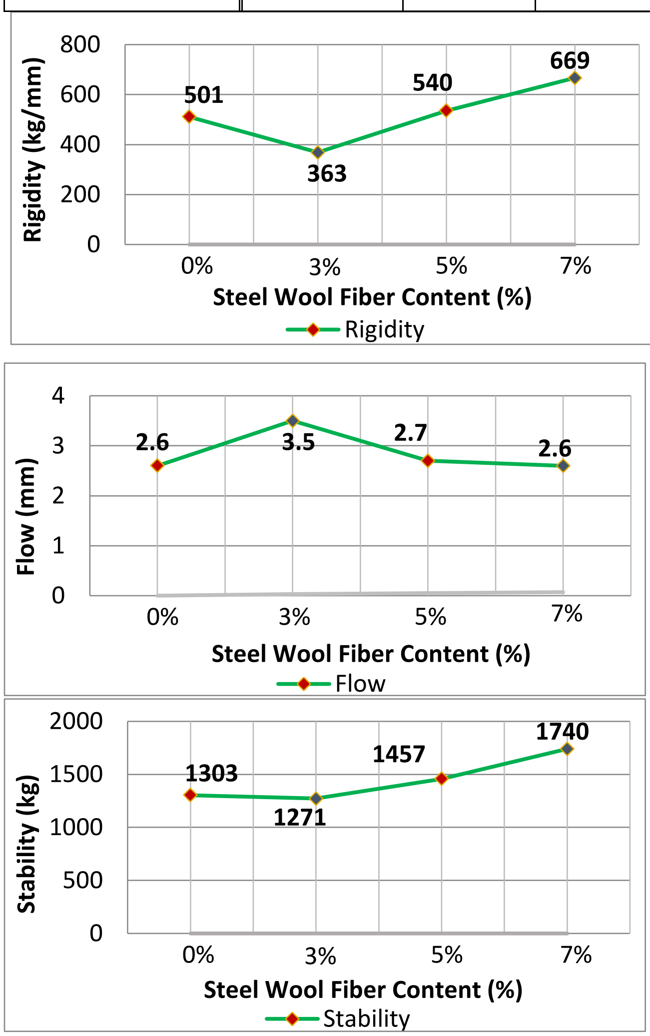

Figure (13): Physical properties for all type mixtures

From the above table and figure it was noticed that the suitable stability, flow and rigidity of asphalt mix is at 5 % S.W.F content.

6.1.2. *For Modified RAP MIX (MRM)*

The following table (7) presents Stability and flow results for control mix and different S.W.F percentages.

Table (7): Stability and flow results for control mix and different S.W.F percentages

S.W.F. percentage (%)	Stability (kg)	Flow (mm)	Rigidity (kg/mm)
0%	1240	2.7	459
3%	1499	3	500
4%	1638	3.3	496
5%	1779	3.2	556

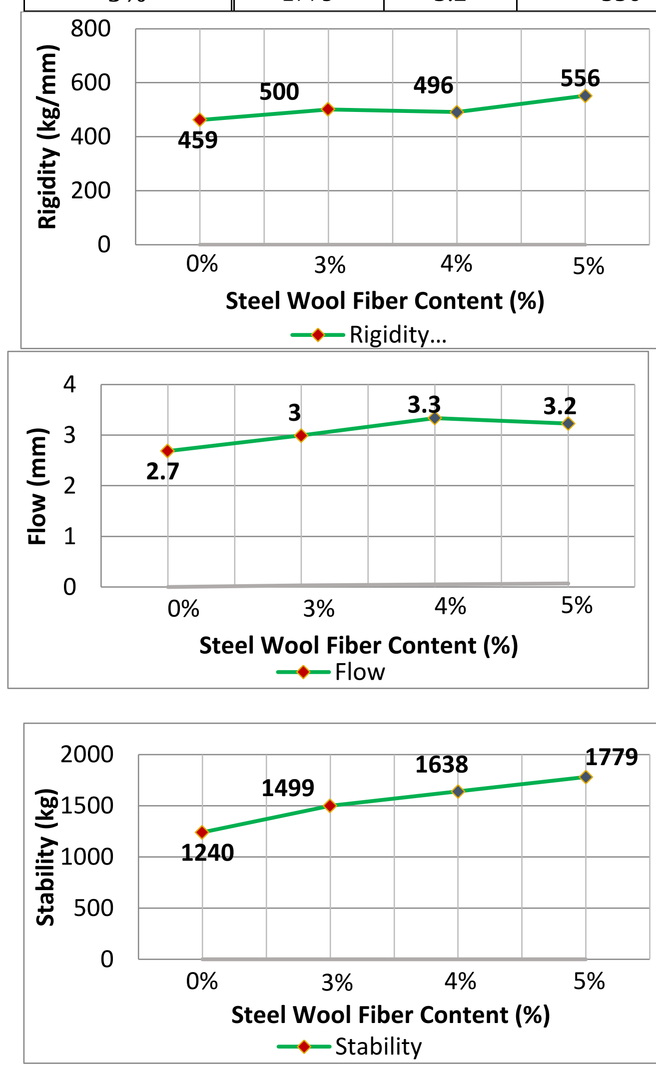

Figure (14): Physical properties for all type mixtures

From the above table and figure it was noticed that the suitable stability, flow and rigidity of asphalt mix is at 3 % S.W.F content as shown in Table (7), Figure (14).

6.2. *Self-Healing*

6.2.1. *For Modified Control Mix (MCM)*

Table (8): Three point test results for control specimens

SWF percentage (%)	Mould no.	Max.load (KN) Cycle (1)	Cycle (2)	Healing percentage (%)	Total Percentage (%)	Tempe. (°C)
0%	Control (1)	3.9	2.1	53.8%	51.1%	53
		3.8	1.9	50.0%		48
	Control (2)	3.6	1.9	52.8%		45
		4.8	2.2	45.8%		52
	Control (3)	4.2	2.1	50.0%		59
		3.9	2.1	53.8%		56
		Cycle (2)	Cycle (3)			
	Control (1)	2.1	0.94	44.8%	42.4%	50
		1.9	0.8	42.1%		51
	Control (2)	1.9	0.8	42.1%		52
		2.2	0.9	40.9%		47
	Control (3)	2.1	0.86	41.0%		54
		2.1	0.92	43.8%		55
		Cycle (3)	Cycle (4)			
	Control (1)	0.94	0.32	34.0%	32.0%	51
		0.8	0.25	31.3%		47
	Control (2)	0.8	0.28	35.0%		48
		0.9	0.25	27.8%		49
	Control (3)	0.86	0.27	31.4%		50
		0.92	0.3	32.6%		51

Table (9) Three point test results for (5%) S.W.F.

S.W.F. percentage (%)	Mould no.	Max.load (KN) Cycle (1)	Cycle (2)	Healing percentage (%)	Total Percentage (%)	Tempe. (°C)
5%	1,2,3	4.2	3.9	92.9%	92.9%	93
		4.3	4	93.0%		88
		Cycle (2)	Cycle (3)			
		3.9	3.04	77.9%	76.7%	86
		4	3.02	75.5%		90
		Cycle (3)	Cycle (4)			
		3	2	66.7%	65.0%	84
		3	1.9	63.3%		86

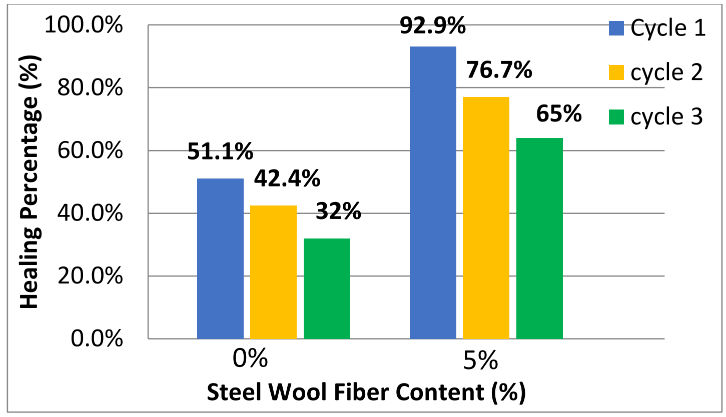

Figure (15): Comparative graph between healing percentages and S.W.F. content

The comparative relationship shows that, the control specimens and healed specimens which blended by using 5% S.W.F which equals (9.38 grams), the results shown that as the temperature rise up the self-healing process goes up and reach its maximum results (93.2%). .

6.2.2. *For Modified RAP Mix (MRM)*

Table (10): Three point test results for control specimens

S.W.F. percentage (%)	Mould no.	Max.load (KN) Cycle (1)	Cycle (2)	Healing percentage (%)	Total Percentage (%)	Temp. (°C)
0%	Control (1)	2.3	0.9	39.1%	45.1%	54
		2.9	1.4	48.3%		48
	Control (2)	2.6	1.1	42.3%		56
		2.5	1.2	48.0%		50
	Control (3)	2.9	1.3	44.8%		52
		2.3	1.1	47.8%		49
		Cycle (2)	Cycle (3)			
	Control (1)	0.9	0.3	33.3%	32.8%	56
		1.4	0.5	35.7%		47
	Control (2)	1.1	0.3	27.3%		53
		1.2	0.4	33.3%		54
		1.3	0.4	30.8%		51
		1.1	0.4	36.4%		52
		Cycle (3)	Cycle (4)			
	Control (2)	0.3	0.1	33.3%	26.9%	54
		0.5	0.1	20.0%		48
	Control (3)	0.3	0.1	33.3%		52
		0.4	0.1	25.0%		47
	Control (1)	0.4	0.1	25.0%		51
		0.4	0.1	25.0%		48

Table (11): Three point test results for (3%) S.W.F.

S.W.F. percentage (%)	Mould no.	Max.load (KN) Cycle (1)	Max.load (KN) Cycle (2)	Healing percentage (%)	Total Percentage (%)	Tem. (°C)
3%	**1,2,3**	2.2	1.8	81.8%	83.0%	93
		1.9	1.6	84.2%		88
		Cycle (2)	Cycle (3)			
		1.8	1.3	72.2%	70.5%	90
		1.6	1.1	68.8%		84
		Cycle (3)	Cycle (4)			
		1.3	0.9	69.2%	63.8%	84
		1.2	0.7	58.3%		90

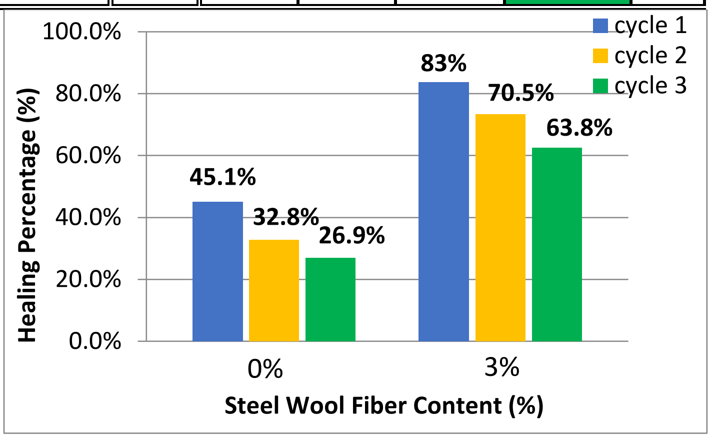

Figure (16): Comparative graph between healing percentages and S.W.F. content

The comparative relationship shows that, the control specimens and healed specimens which blended by using 3% S.W.F which equals (3.01 grams), the results shown that as the temperature rise up the self-healing process goes up and reach its maximum results **(83.6%).**

6.3. *Regression Model Analysis*

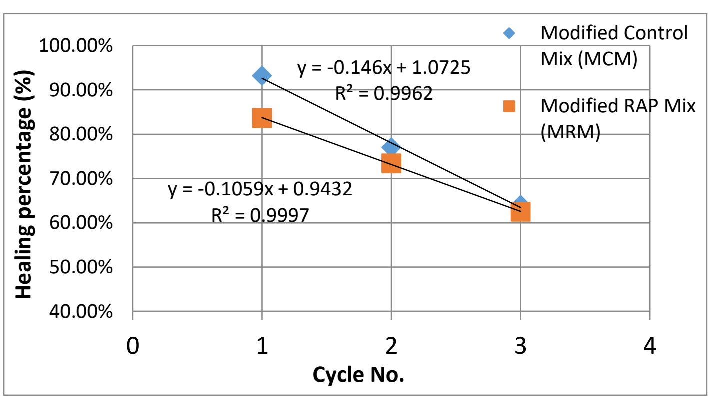

Figure (17): Regression model for modified control mix (MCM) and modified RAP mix (MRM)

The regression line is a trend line we use to model a linear trend that we see in a scatterplot. In equation of the regression line,

X = number of cycles of healing which made before.

The data shows a **strong linear relationship because** data is clustered tightly around its regression line, the regression line of the data has a negative slope, the data has a **negative linear relationship**.

7. CONCLUSION

The addition of steel wool fibers is crucial for improving the performance of asphalt concrete due to their conductive characteristics. These fibers play a vital role in enhancing the dynamic modulus, resistance, and thaw resistance properties of the asphalt. conclusions from the experiment results are presented below:

1. The mix prepared with steel wool fibers and the control mix were both designed to meet the limits set by the Marshall Mix design method. The goal was to achieve an optimal mix that would maximize performance and durability.
2. The Marshall test results, which measure stability and flow, align with the specified range for various steel fiber contents.
3. Marshall Stability achieves the maximum results for modified control specimens at the 7% of S.W.F. in the asphalt binder (1740.4 kg) , and at the 5% for RAP specimens (1779.7 kg).
4. The Rigidity For fresh specimens were (368.5, 535.6, 666.8 kg/mm) at 3%, 5%, 7% of S.W.F. respectively which the control specimen was (510.9 kg/mm), and For modified RAP specimens were (501.1, 491.1, 551.5 kg/mm) at 3%, 4%, 5% of S.W.F. respectively which the control specimen was (461.9 kg/mm).
5. After conducting trials, it was observed in microwave heating experiments that the samples containing steel fibers achieved higher temperatures compared to the control mixture without any steel wool fibers. This indicates that the healing process for specimens with a lower percentage of fibers took a longer time to recover and had a less effective outcome when compared to the modified specimens.
6. It was observed that, the control mixtures with less steel wool fibers were poor in terms of properties when compared with modified mixtures (MCM and MRM).
7. For modified control specimens, the control mixtures result of cycles of healing were (51.5%, 41.8%, 31.8%) respectively, which were results of 5% S.W.F. were (93.2%, 77%, 63.9%) respectively.
8. For modified RAP specimens, the control mixtures result of cycles of healing were (44.7%, 33%, 24.2%) respectively, which were results of 3% S.W.F. were (83.6%, 73.4%, 62.5%) respectively.
9. Microwave heating exhibits a consistent and even distribution along its length.
10. The process of microwave heating leaded to a more consistent and even repair of cracks in an asphalt mixture.

8. RECOMMENDATION

1. Further studies are needed using different percentages of steel wool fibers content .

2. It is recommended for the local authorities to permit using recycled materials in construction fields.

3. In addition, by incorporating various categories of steel and aluminum fibers, it is possible to enhance the effectiveness of asphalt specimen regeneration using microwave heating. This will further optimize the healing process.

4. To optimize the performance of modified hot mix asphalt and modified RAP mix, it is advised to actively promote field application and evaluation. This will help determine the effectiveness of incorporating steel wool fibers material into these mixes**.**

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Abbreviations and Acronyms

HMA	Hot Mix Asphalt
MCM	Modified Control Mix
MRM	Modified Rap Mix
S.W.F	Steel Wool Fiber
RAP	Recycled Asphalt Pavement
OBC	Optimum Binder Content
3PBT	Three-Point Bending Test
MH	Microwave Heating