Evaluation of Self-Healing Performance of the Hot Mix Asphalt Using Metallic Wool and Recycled Materials

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1. Abstract

It is obvious that, the type of fillers has significant effects on the properties of hot-mix asphalt (HMA). It is very important to understand the effect of these types of fillers on the HMA and its performance. Therefore, this paper examines the effect of different types of recycled fillers on the properties of HMA mixture. Four types of filler and three filler percentages for each one was used to evaluate the characteristics of HMA and to characterize the effect of filler in HMA. The properties of HMA evaluated include Marshall Test, indirect tensile strength (ITS) and tensile strength ratio (TSR). The research results found that fillers had a great influence on the properties of HMA. Also, this study investigates the effect of using Metallic wool on the tensile strength of the HMA. To achieve this goal, Metallic wool was added at 0.5% and 0.75% from the total mix weight. To simulate the HMA cracks, the specimens were prepared using metallic wool. Then, subjected to ITS load. After cracking the specimens, it was left for 24 hours; then subjected to heat with different temperature (60, 90, 115). Finally, the specimens were subjected to the ITS load again. The results showed that addition of metallic wool can significantly improve the self-healing behavior of HMA.

Key words: Indirect Tensile Strength, Marshall Test, Pavement Cracks, Hot Mix Asphalt.

2. Introduction

It has been known that the filler type plays a great role in the behavior and the performance of the HMA mixtures. The main role of filler is filling voids between aggregates in the mixture and modify the properties of the HMA binder, because the filler acts as an integral part of the mastic (combination of bitumen, filler, and entrapped air), Application of recycled waste lime as mineral filler improves the permanent deformation characteristics, stiffness, and fatigue endurance of asphalt concrete [1]. It was also determined that the mixtures with recycled waste lime showed higher resistance against stripping than conventional asphalt mix [1, 2, 3]. Solid waste is currently a major concern across many countries. Continuing increases in such waste also intensifies demands on available landfill space, implying that this situation requires more attention. Globally, societies are faced with issues around environmental conservation and preservation as this has an impact on our live [4, 5]. Traditionally, the optimum bitumen content was found using Marshal method. One of the advantages of Marshall method is that the performance of the mixes can be determined for local materials [6]. A cracked pavement requires a long time and costs to restore its original performance by recycling the fallen parts from the road, that required a huge number of resources to be consumed and have a bad impact on the driver comfort. Therefore, there is an urgent need to replace the traditional rehabilitation methods that consumes resources and energy. Self-healing is the promising technology that could increase the lifetime of the pavements, and that occurs by healing the cracks and restoring its original performance without eliminating the original pavements. The new technology saves costs, resources, and helps to keep clean environment. Self-healing process works on the micro cracks that appear inside the asphalt pavement that will heal these cracks gradually during a short period when exposed to the required heating to restore its performance. As a viscoelastic material with relatively strong surface wetting and diffusion capability, asphalt shows a self-healing behavior that can close its micro cracks and therefore restore its stiffness and strength. Asphalt self-healing can improve the fatigue cracking performance of asphalt pavements. Cracks can be closed when the entire self-healing process is completed [7]. This research paper aims to provide a proper design of self-healing asphalt mixture with high-performance for durable pavement construction.

3. Literature Review

With the significant growth of industries, diverse problems have more and more appeared, including rapid deterioration of natural resources and severe environmental contaminations. Daily accumulation of waste materials is one of the causes of these problems [8]. Recycling costs should become a considerable part of road construction because of the huge amount of money that consumed every year in recycling and solving the problems that appear in the constructed road, on the other hand a big number of by-products are produced every year because of the industry process at all levels of the industry, these waste harm the environment if it left without right usage. The effect of using a by-product powder and dust as a filler in the HMA are investigated in this study and it is found out its effect on the performance of HMA, it was concluded from various test results that a waste lime can be used as mineral filler and, especially, can greatly improve the resistance of asphalt concrete to permanent deformation at high temperatures [5, 9]. The increasing attention has been given to reusing waste and by-product materials to manufacture asphalt pavements, a situation which can be attributed to inflation in the cost of traditional fillers [10]. Numerous studies have observed effect of filler on physical (specific gravity, particle shape, size, texture, porosity) and chemical (mineralogy, active clay content) properties over primary pavement distresses (rutting, fatigue, low-temperature cracking, aging, and moisture susceptibility). There is a growing interest in the scientific community in replacing conventional materials with waste fillers [11]. Mostly the crack resulting from the shrinkage still cannot be kept away from the construction [12]. Several researchers have reported the formulation of new soil stabilizers by replacing the conventional additives with industrial waste products [13, 14]. The contribution of mineral filler properties to the reduction of rutting in asphalt mixtures is not well understood, and contrary findings have been reported. It is concluded that filler particle shape significantly affected the permanent deformation of asphaltic mixtures. [15]**.**

When subjected to high temperatures and heavy traffic, roads built according to Specifications with B60/70 show high rates of permanent deformation, leading to higher repair costs. The challenge, then, is to find a balance between using better quality materials and keeping the total project cost low, particularly in developing countries [16]. In arid and hot regions, such as in North Africa or Middle East, roads often deteriorate more quickly than in cold regions. These road surfaces suffer from poor mix designs resulting in substantial deformation (e.g., rutting, shoving), especially in desert regions. [17] Fillers and modifiers are defined as fine or additives materials that work to alter the characteristics of the bitumen binders and the resulting HMA. Both in research and in industrial practice, various modifiers and fillers have been used, including polymer, fly ash, hydrated lime, fiber, clay or mineral particles, brick powder, cellulose, limestone dust, OPC, or used hard bitumen viscosity to resist high temperature. [18]. Also, and asphalt mixtures are widely used in pavement construction due to its numerous advantages: short construction period, abrasion resistance, and lower tire-road noise. Despite its excellent mechanical properties, traffic loads and environmental factors can deteriorate the durability of asphalt pavements [19], and after a short time the fatigue cracks appear. Asphalt mixture is exposed to environmental changes of temperature, frost, moisture, and traffic loads. With the time, bitumen, ages, the pavement structure, and the materials start damage, which leads to the formation of cracks [120, 21]. The cracks can initiate from the bottom or from the top of the road structures, or from the interface between mineral aggregates and bitumen [6, 21]. Asphalt mixture is a self-healing material, if a crack appears in the material, bitumen may drain and flow into the crack, repairing it [21, 23]. Self-healing engineered materials were first designed in 2001 by introduction of a catalyst and microcapsules containing a healing agent in a polymer matrix [19]. The self-healing process can be explained as follow: by growth of cracks, the microcapsules break in the self-healing polymer structure and release the healing agent into the crack; the healing agent starts to polymerize upon it contact with the catalyst therefore, the two sides of the cracks mouth will close together leading to the overlap of the two sides of the crack [21].Bitumen plays a vital role in self-healing of asphalt mixtures. Furthermore, the temperature and healing time depends on the type of applied bitumen [6]. The stiffness and strength of bitumen materials may reduce when they are exposed to repetitive loading [22]. The main issue of the self-healing process is its very slow at ambient temperature; in a way that the cracks growth rate exceeds the pavement recovery rate, and the asphalt mixture can't be automatically recovered. In addition, traffic flow on the road can't be blocked to improve the self-healing [23, 24].

Previous research indicated that short and thick fibers dispersed well in the mixture, which delivered optimal performance by electromagnetic induction heating, while long and thin fibers produced clusters [11]. These technologies are based on the idea of modifying temporarily the viscosity of bitumen in cracked asphalt mixture, to break the equilibrium that keeps bitumen static and force it to drain into the cracks [13]. It is established the asphalt system model at different temperatures based on LAMMPS (Large-scale Atomic/ Molecular Massively Parallel Simulator) and proposed using different crack sizes to characterize the healing behavior of asphalt pavement [25]. At present, the research in the evaluation of self-healing performance are focus on indoor tests, image processing and micro-observation and software simulation. These methods are used to evaluate healing performance by comparing the changes of some indexes with and without using the self-healing technology.

4. Problem Statement

Road maintenance cost is one of the most important parameters that affect the network quality in Egypt as well as worldwide. In addition, the lake of material resources such as fillers would affect the mix properties,

5. Objective of the Study

1. Investigating the effect of adding by **-**products fillers in and metallic wool the HMA.

2. Obtaining the optimum metallic wool for the self-healing efficiency of asphalt mixtures.
3. Investigating the effect of different heating temperature with the optimal metallic wool content on the self-healing asphalt mixtures.

6. Experimental Program

The workflow in this research provides a comparison between ten types of mixtures using four filler types (Red brick dust, marble dust, Hashmi brick dust and Limestone as fillers). In the study limestone filler was used in the control mix with 100% of the filler content, after getting the OBC from Marshall Test the other three fillers were added, Each with three percentage with lime stone filler 35%, 70% and 100%, after the evaluation of the stability and flow of the specimens the ITS test and TSR test were performed to evaluate the water sensitivity of the mixtures.

The work program will be carried out in six steps as follow:
Step1: Physical and chemical properties of materials.
Step2: Control mix design
Step3: Preparing the samples using the three different fillers.
Step4: Selecting the best results from step 3 and test it with ITS and TSR.
Step5: Selecting the best results from step 4 and apply ITS self-healing test.
Step6: Analysis of the results

7. Physical and Chemical Properties of Materials

7.1 Aggregate

Crushed dolomite aggregate was used for this study, and the control mineral filler that used for control mix was limestone. The used aggregate is widely used in the asphalt industry and is hard, durable, and clean, of suitable shape and resist rutting. HMA prepared with a close-graded surface of coarse gradation and mixed according to the specifications of the standard Egyptians code for roads (Figure. 1). Table. 1 presents the physical characteristics of the used aggregate.

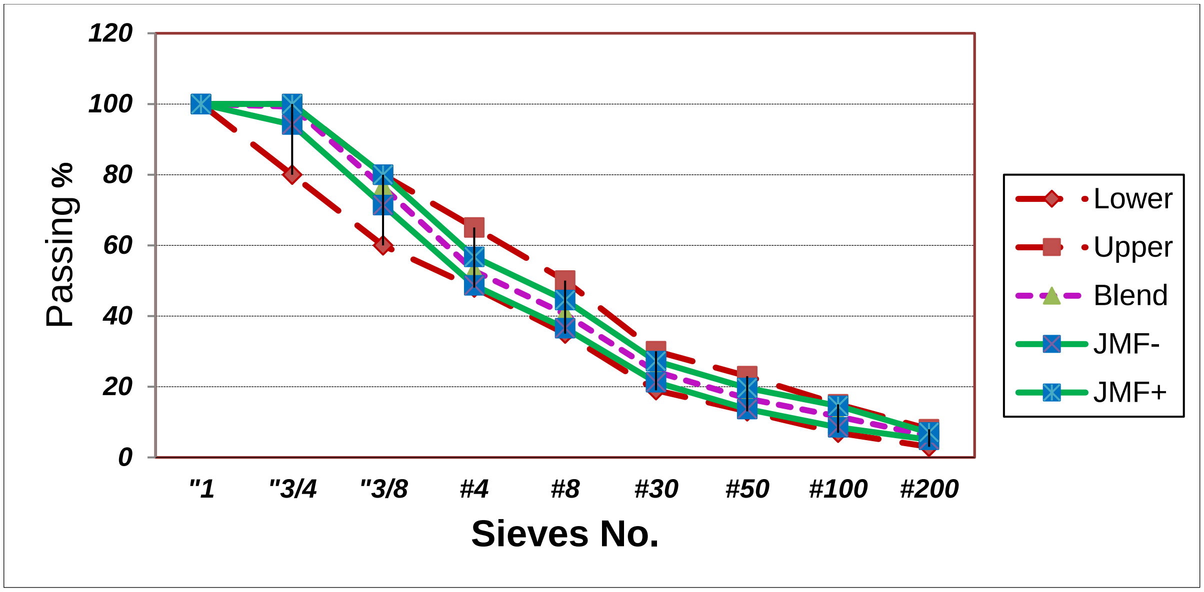


Figure 1: Aggregate Gradation

Table 1: Aggregate Physical Properties.

Tested Property	Test Specification	(25-12) mm	(12-9) mm	(9-6) mm	(6-0) mm
Bulk Density	ASTM C127	2.507	2.515	2.528	2.611
SSD		2.533	2.541	2.548	2.646
Apparent		2.714	2.712	2.719	2.756
Abrasion (L.A.)	ASTM C131	25.5	26.1	27.1	-
Clay lumps	-	0.2	0.1	0.1	-
Flat Elongate particles	ASTM D693	3.43-2.17	3.21-2.37	2.11-2.62	-
Natural stones	-	2.68	2.78	2.34	-
Water absorption	ASTM C127	1.81	1.95	2.1	1.18
L.L, P.L and PI	ASTM D4318	NP	NP	NP	NP
Sand Equivalent	ASTM C2419	-	-	-	56.4
Stripping	ASTM D1664	Nil	Nil	Nil	-

7.2. Asphalt Binder

A conventional 60/70 penetration grade asphalt binder with 49.2C° as a softening point was chosen to produce the bituminous mixtures. This bitumen grade was selected as it is normally used to produce HMA mixtures. Table. 2 presents the properties of the bitumen.

Table 2: Asphalt Bitumen Properties.

Test	Penetration test	Ductility test	Softening point	Flash point
Value	67 mm	482.5 centistoke	49.2C°	265C°

7.3. Fillers

The fillers that used in this investigation were collected from factories wastes, limestone was used as control filler in the control mix, and three other fillers were used (Marble dust, red brick powder, Hashmi brick powder). All the fillers passed from sieve 200 mm; Table 3 presents the chemical properties of each filler from the XRF test.

Table 3: Chemical Composition of Different Fillers

Compounds	SiO2	TiO2	Al2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	P2O5	CI	SO3	LOI
%Marble	1.02	0.08	<0.01	0.82	<0.01	1	53.6	<0.01	0.1	0.05	0.12	<0.01	43.18
%Hashmi	8.78	0.14	0.36	5.94	0.09	0.27	46.7	<0.01	0.18	0.09	0.39	0.12	36.7
%Limestone	0.19	0.03	<0.01	0.01	<0.01	<0.01	55.9	<0.01	<0.01	<0.01	0.04	<0.01	43.68
%Red Brick	49.18	1.96	13.41	16.21	0.1	1.84	6.5	0.26	1.43	0.04	0.94	2.33	5.5

8. Control Mix Results

8.1. Marshall Test Results

The stability of the specimen is the maximum load that required to produce failure in the specimen when load is applied at constant rate. From table below it is noticed that the maximum stability of asphalt mix is 1470 kg at 5.0 % bitumen content. Table 4 presents the results of the test.

Table 4: Control Mix Results.

Bitumen %	Unit Wt.	Max.sp.gr. (Gmm)	Air Voids %	VMA %	VFB %	Stability(kg)	Flow(mm)
4.5	2.298	2.427	5.3	17.0	68.9	1113	2.7
5.0	2.343	2.443	4.1	15.8	74.0	1470	3.1

5.5	2.37	2.441	2.9	15.2	81.0	1290	3.3
6.0	2.390	2.441	2.1	14.9	85.9	1033	4.1

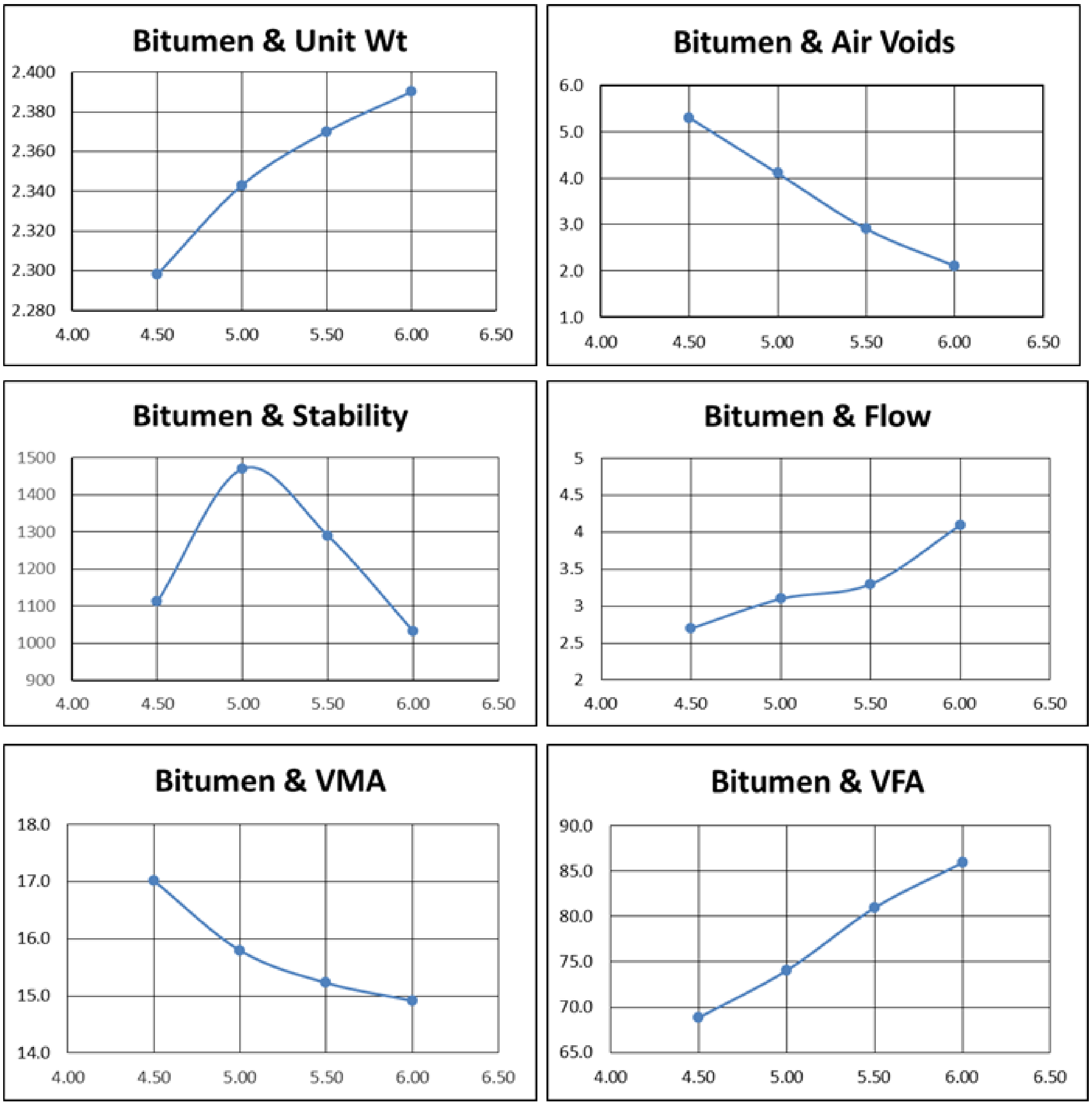


Figure 2: Marshall Mix Design

8.2. Fillers Results

There were 96 of Marshall samples of different fillers each one of them weight 1200 gm. Which were prepared by using three different percent (35%, 70% and 100 %) of total weight a of aggregates and 5.1% of bitumen content (by the weight of total mix) in ten patches. It is noticed that all values of stability with different fillers achieved the requirements of local and international specification. In case of red brick powder specimens it is found that the stability of the HMA specimens increases by substituting the lime powder with red brick powder and it continues going up as the percent of the red brick powder increases until it reaches to its maximum limit when the red brick powder became 100%, and the flow decreases as the red brick powder decreases until reaching to its optimum percent at 100% of red brick powder. in Hashmi brick powder specimens case it is noticed that the stability of the HMA specimens increase by substituting the lime powder with Hashmi brick powder and it continues going up as the percent of the Hashmi brick powder increases until it reaches to its maximum limit when the Hashmi brick powder became 100%, and the flow has a constant changing at 3 % of Hashmi brick. Also, and case of marble dust specimens it is found that the stability of the HMA specimens increases by substituting the lime powder with red brick powder and it continues going up as the percent of the marble dust increase until it reaches its maximum limit when the marble dust became 100%, and the flow changes with a non-uniform pattern as the percentage changes. The results of different types of fillers are summarized in Table 5.

Table 5: Mix Results

Filler	Lime 100%	Lime 0%	Lime 35%	Lime 65%	Lime 0%	Lime 35%	Lime 65%	Marble dust 100%	Lime 35%	Lime 65%
		Red brick 100%	Red brick 65%	Red brick 35%	Hashmy brick 100%	Hashmy brick 65%	Hashmy brick 35%		Marble dust 65%	Marble dust 35%
Stability (KN)	1206	1695	1524	1486	1670	1659	1633	1833	1436	1394
Flow (mm)	3.3	3	3.5	3.5	3.2	3.2	3.3	3.1	3.5	3.2

It is found that the minimum stability value was at 100% lime and the stability increases by substituting the lime until reaching to 100% substitution. It is noticed that the maximum values of stability were at 100% of marble dust, 100% of red brick and 100% of Hashmi brick powder respectively. Figure 3 shows Marshall Stability vs filler content.

8.3 Indirect Tensile Strength Test and Water Sensitivity Test Results

ITS test was carried out to obtain the shear resistance of the specimens using the best 6 types and percent of fillers. It is found out that the best shear resistance was at the three 100% specimens. After that moisture sensitivity was going to be tested using wet specimens, it is noticed that the best results of the moisture sensitivity were found at three 100% specimens. Figure 4 shows ITS dry specimen's results and figure 5 shows TSR results.

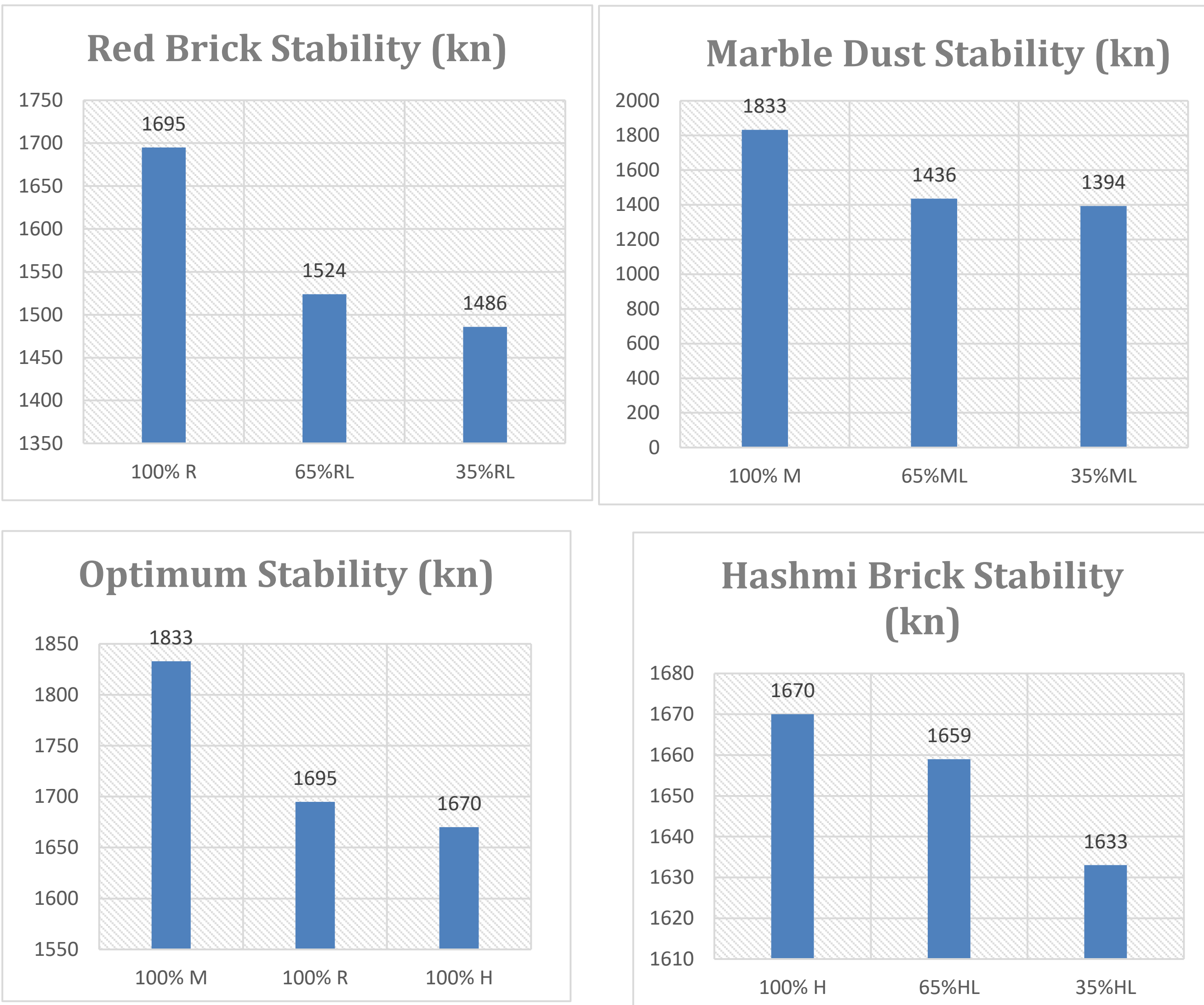


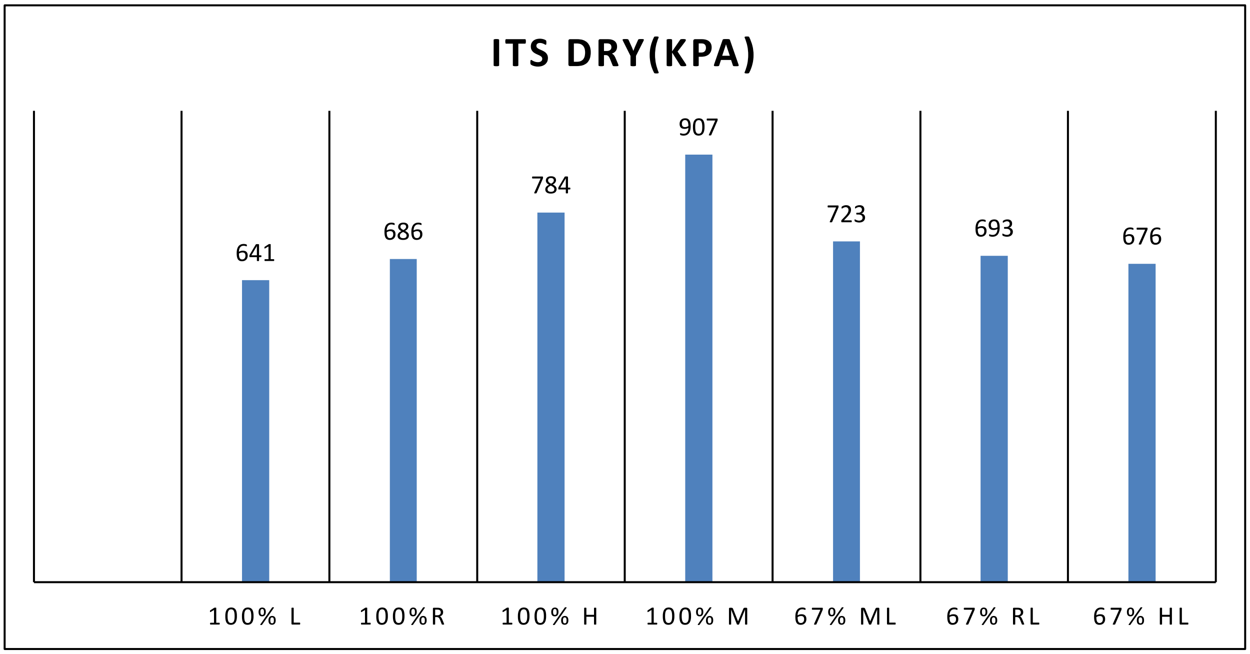
Figure 3: Marshall Stability vs Filler Content

8.4. Evaluating Self-Healing Using Indirect Tensile Strength Tests

After ITS and water sensitivity tests, self-healing of the specimens were tested by adding Nylon wires to the specimens by 0.5% and 0.75% of the whole weight of the specimens which were equivalent to (9, 12) grams, after blending the specimens are subjected to indirect force and the shear resistance was recorded. after that the specimens were subjected to heat in the oven at different temp. The heating specimens were left to be cooled and then subjected to indirect force to discover the healing rates of the specimens. The results are summarized in tables 6 and 7. Also, the results are shown in figures 5 and 6. The results shown above indicated that the ITS value of Marble is the best among the examined fillers. On the other hand, the Red Brick has the best TSR.

Figure 4: ITS Test

Figure 5: ITS Dry Specimen's Results



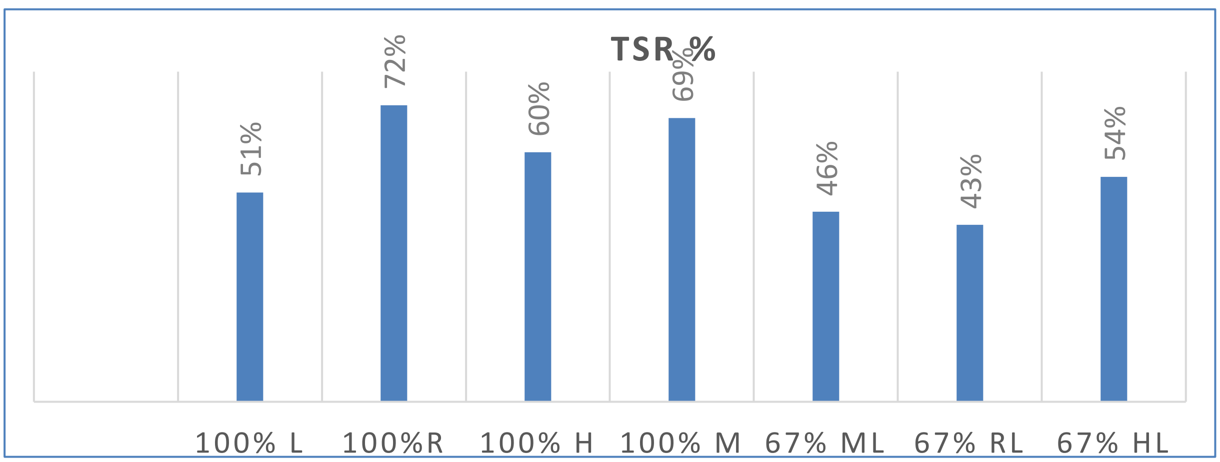


Figure 6: TSR Results

Table 6: Self-Healing ITS test Results (MPa) for 6 Grams' Specimens

6 grams of metallic wool													
ID	Temp.	Red Brick				Marble				Lime			
		Before	After	Percent		Before	After	Percent		After	Before	Percent	
1.00	60 C	13.40	8.90	0.66	0.64	13.50	7.73	0.57	0.58	12.89	8.34	0.65	0.66
2.00	60 C	13.70	9.00	0.66		12.75	7.03	0.55		12.60	8.56	0.68	
3.00	60 C	13.04	7.86	0.60		12.53	7.84	0.63		0.00	0.00	0.00	
4.00	90 C	13.10	9.14	0.70	0.68	12.78	9.50	0.74	0.72	11.86	8.71	0.73	0.68
5.00	90 C	12.08	8.50	0.70		12.33	8.20	0.67		11.16	7.09	0.64	
6.00	90 C	12.70	8.20	0.65		13.33	10.21	0.77		0.00	0.00	0.00	

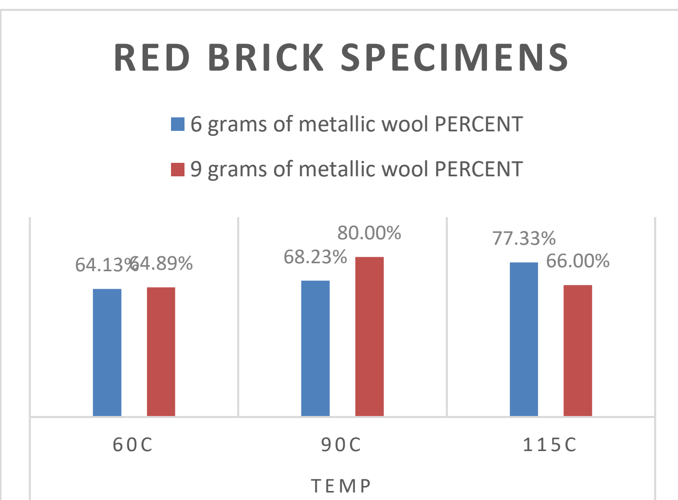
7.00	115 C	12.81	10.20	0.80		11.58	10.20	0.88		11.59	8.34	0.72	
8.00	115 C	13.42	10.00	0.75	0.77	12.39	10.30	0.83	0.81	11.92	8.58	0.72	0.72
9.00	115 C	13.49	10.50	0.78		14.03	10.25	0.73		0.00	0.00	0.00	

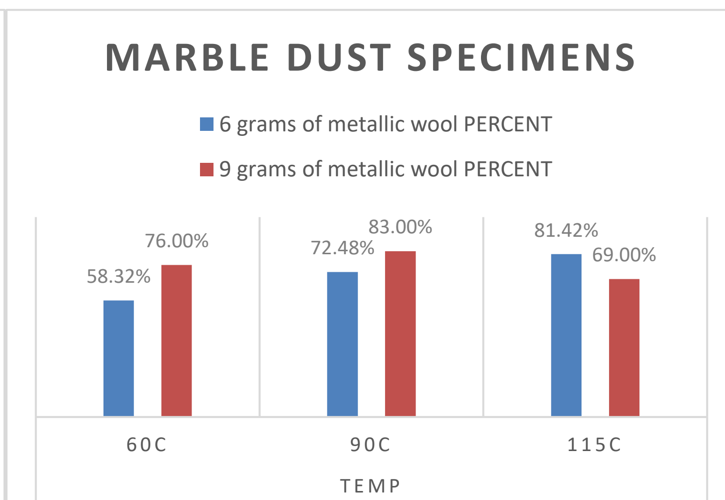
Table 7: Self-Healing ITS Test Results (MPa) for 9 Grams' Specimens

9 grams of metallic wool													
ID	Temp.	Red Brick				Marble				Lime			
		After	Before	Percent		After	Before	Percent		After	Before	Percent	
1.00	60 C	14.13	9.09	0.64		14.00	10.90	0.78		14.10	8.74	0.62	
2.00	60 C	14.24	9.32	0.65	0.65	15.72	11.56	0.74	0.76	13.47	8.35	0.62	0.62
3.00	60 C	0.00	0.00	0.00		0.00	0.00	0.00		0.00	0.00	0.00	
4.00	90 C	14.27	11.40	0.80		14.75	11.60	0.79		14.07	10.27	0.73	
5.00	90 C	14.61	11.54	0.79	0.80	15.38	12.95	0.84	0.83	14.19	10.36	0.73	0.73
6.00	90 C	0.00	0.00	0.00		0.00	0.00	0.00		0.00	0.00	0.00	
7.00	115 C	14.11	9.26	0.66		14.91	11.08	0.74		11.60	7.54	0.65	
8.00	115 C	14.88	9.70	0.65	0.66	15.91	10.27	0.65	0.69	12.18	7.92	0.65	0.65
9.00	115 C	0.00	0.00	0.00		0.00	0.00	0.00		0.00	0.00	0.00	

8.5. Comparison Using the Metallic Wool Specimens before and after Self-Healing to the Ordinary Specimens

The comparison of the metallic wool specimens results in cases specimens before and after self-healing are summarized in table 8. Also, the results are presented in figures 7, 8 and 9.





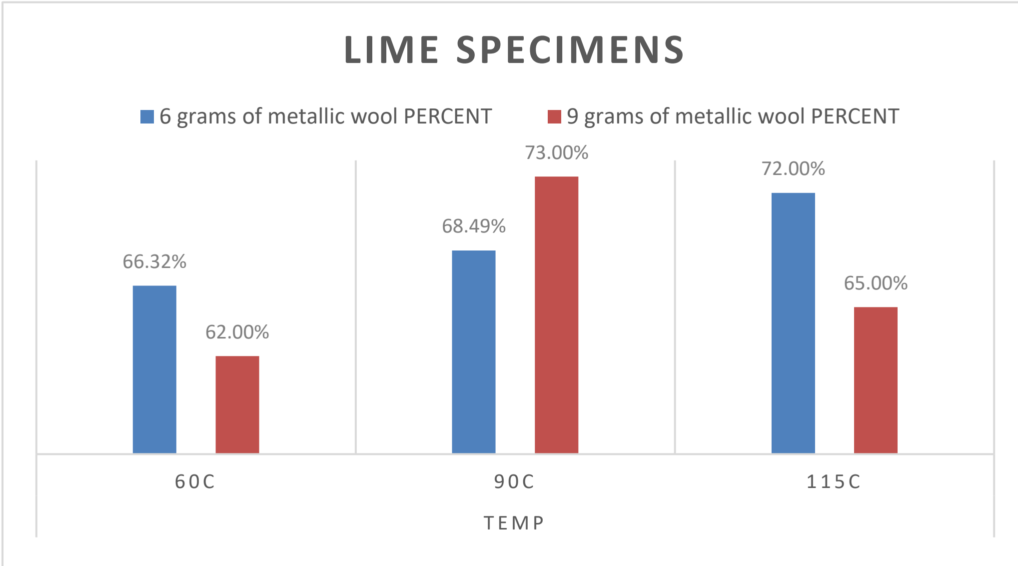


Figure 7: ITS for Self-Healing on Red Brick Powder, Marble Dust and Lime

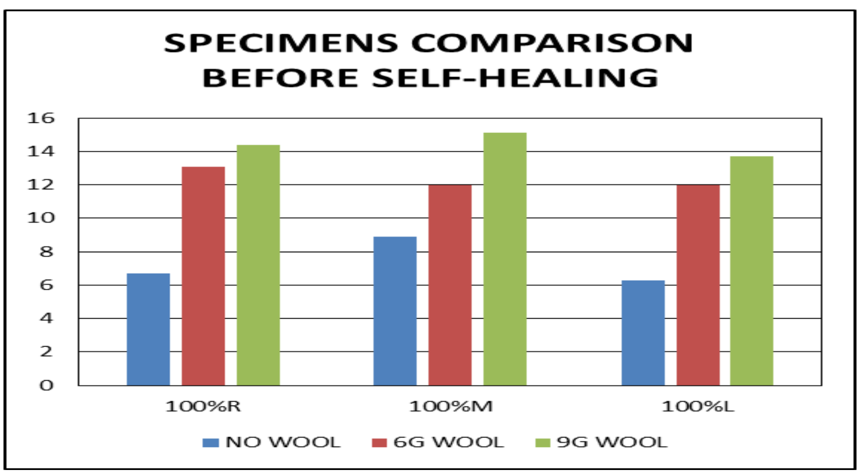


Figure 8: comparing ITS before Self-Healing.

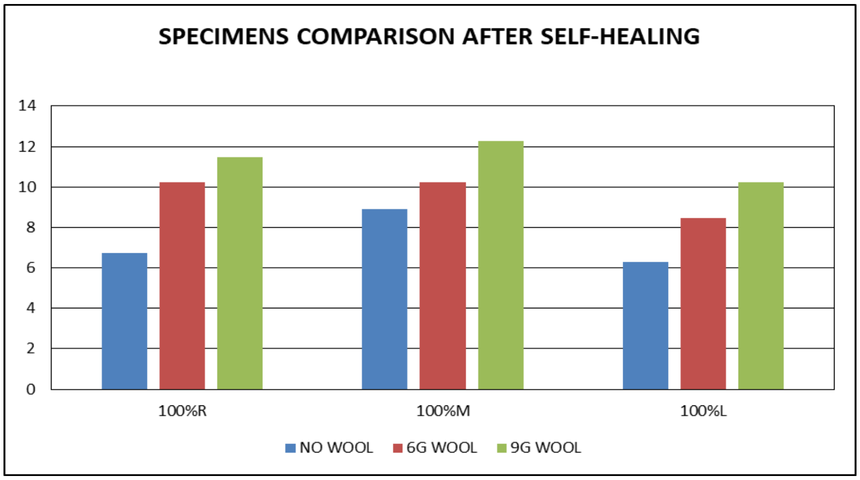


Figure 9: comparing ITS after Self-Healing

Table 8: ITS values for Self-Healing using Metallic Wool (before and after).

Material	100%R (KN)			100%M(KN)			100%L(KN)		
Case	With 6 grams of wool	With 9 grams of wool	Without wool	With 6 grams of wool	With 9 grams of wool	Without wool	With 6 grams of wool	With 9 grams of wool	Without wool
Before	13.08	14.37	6.72	12.8	15.11	8.89	12	13.7	6.3
After	10.23	11.47	6.72	10.25	12.28	8.89	8.46	10.22	6.3

As shown in Figures 7, 8, 9 and Table 8 the ITS for marble is higher than other fillers while red brick gave better TSR.

9. Conclusions

Based on the carried-out testing program results and discussions the main points that can be concluded from this research are as following:

1- The existence of different types of recycled fillers in the asphalt binder course mixture is considered as an eco-friendly material and it can be utilized as a sustainable management of waste.

2- The results of Marshall Stability, flow of the specimens is consistent with the specifications range at different percentages of filler contents.

3- Marshall Stability achieves the maximum results at the 100% of marble dust filler.

4- The flow always within range in all specimens of all different types of fillers.

5- ITS and moisture sensitivity test results achieved the maximum in the specimens of 100% (red brick, Hashmi brick, and marble dust).

6- Adding metallic wool to the HMA increases the tensile strength.

7- The optimum two cases of self-healing were found to be at 0.5% of metallic wool and 115C temp., and 0.75% metallic wool at 90C temp.

8- Marble dust showed the best results among all the fillers that have been examined in this research.

9- Self-healed specimens showed better results than the original.

10. Recommendations:

1- Further studies are needed using different types of fillers and different percentages of filler content.

2- It is recommended for the local authorities to permit using waste fillers in asphalt pavements depending on the results of this research.

3- It is recommended to monitor the field application and evaluation to find out the performance of hot mix asphalt containing waste materials.

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