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RESEARCH ARTICLE

Influence of Microcrack Healing Techniques on Tensile Strength of Asphalt Concrete

Saad Issa Sarsam, Husham Mohammed Al Tuwayyij
Department of Civil Engineering, College of Engineering, University of Baghdad, Iraq

Abstract

Asphalt concrete pavement practices repeated loading and environmental impacts and suffers distresses. Microcracks usually occurs at early stage of pavement life while the pavement can heal itself under controlled conditions. Microcrack healing process can be controlled and accelerated using various techniques. In this investigation, iron filling was implemented as partial substitute of sand to support the healing process while both induction and external heating techniques were adopted to control the healing using microwave and oven. Asphalt concrete specimens have been prepared with different percentages of iron filling and the corresponding required asphalt content. Specimens were subjected to repeated indirect tensile stresses for 600 and 1200 load repetitions. Specimens were allowed to heal using microwave and oven heating techniques. Specimens were subjected to another cycle of stress repetitions and the variation in the indirect tensile strength was detected before and after healing. The healing performance of the asphalt mixture specimens at different healing conditions was investigated by observing and testing the recovery of indirect tensile strength after healing. It was concluded that implementation of iron filling and induction heating by microwave can improve the healing and tensile properties of asphalt concrete as compared to the oven heating technique.

Keywords: Iron filling; Crack healing; Microwave; Asphalt concrete; Tensile strength; induction heating

1.Introduction

Asphalt concrete is a self-healing material. This is illustrated by the fact that under special conditions, it can repair its own damage. Its healing properties are directly linked to temperature and to the rest periods as reported by Garcez et al., [1]. Sarsam [2] stated that cracks may develop in the asphalt concrete pavement as a result of repeated traffic loads or environment impact. However, when cracks occur in the asphalt pavement, if enough energy is given to the system, it will start healing process, and if enough time is given to the process, it may even close completely. Wang et al., [3] investigated the effect of microwave heating on promotion of self-healing in asphalt concrete. Two types of specimens (neat without additives and conductive containing steel fiber and graphite) were prepared for use in thermal conductivity, microwave heating speed tests. It was found that the fatigue resistance and healing capacity of conductive asphalt concrete after microwave heating were higher than that of neat specimen. It is concluded that self-healing efficiency of asphalt concrete can be enhanced through microwave heating. Pan et al.,[4] investigated the effect of seven healing agents on crack healing ability of long-term aged asphalt and its mortar. Test results indicated that the crack healing of asphalt and its mortar depended strongly on the type of healing agent. It was concluded that the promising healing agent should be able to achieve maximum strength recovery to resist cracking as well as enough re-healing ability to deal with crack opening and closing. Magnetic induction heating and microwave heating technology could heat bituminous materials and heal cracks as reported by Karimi et al, [5]. Alakhrass, [6] studied the effect of adding iron powder on the property of the self-healing of the wearing layer in the asphalt mix. Samples were fractured by flexural fracture machine after cooled to -20°C, after that samples were heated by induction heating device (Microwave) for fixed time interval to each sample, temperature of samples was recorded, and again samples were fractured after being cooled, flexural forces were recorded. Induction heating of asphalt concrete is a technique to increase the self-healing rate of the asphalt concrete material. It basically consists in adding electrically conductive fibers to the asphalt mixture. Then, with the help of an induction heating source, it is possible to heat the fibers locally, and as a result, to heat the asphalt pavement and to heal the cracks as reported by Jendia et al., [7]. García et al. [8] added electrically conductive particles to the asphalt mixture, which is then heated with an induction heating device. Different mixtures, with different lengths, quantities and diameters of steel wool fibers have been considered. It was found that healing rates of asphalt concrete increase with the increase of temperature, and 60% of the original samples strength could be recovered. The aging of asphalt under weather and traffic was investigated by Bochove [9]. It was stated that it is associated with the formation of micro cracks in the mortar fraction. By adding a conductive material in the asphalt production, such as steel wool fibres, the possibility arises of heating up the mortar of the asphalt by an induction device. A short "heat shot" through the steel fibres, causes melting of the bituminous binder and because of that, hairline cracks in the asphalt layer are closed. The asphalt mixture will "reset" and start a new life. This can be done several times during the service life. Hechuan et al, [10] studied the effect of induction heating on asphalt binder aging in steel fibers modified asphalt concrete. The experiments showed that the binder inside asphalt concrete began aging during induction heating due to thermal oxygen reaction and volatilization of light components. Phan

*Corresponding Author:
saadisasarsam@coeng.uobaghdad.edu.iq
(Prof. Saad Issa Sarsam ORCID: 0000-0001-8426-5767)
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et al., [11] analyzed the applicability of steel slag in the asphalt mixtures for the self-healing purpose using microwave heating technique. Test results suggested that adding two percent of steel wool fibers by weight of asphalt mixture provides the best healing level for both types of aggregate mixtures. The substitution of 30% normal coarse aggregate by steel slag is very promising due to its presence not only provides better healing results but also helps the whole mixture improve the load-displacement relationship with higher ductile behavior. Li et al., [12] stated that Induction heating is a valuable technology to repair asphalt concrete damage inside. However, in the process of induction heating, induced particles will release a large amount of heat to act on asphalt binder in a short time. It has been widely proven that asphalt concrete is a self-healing material and induction heating can magnify the healing ability to extend the pavement service life. Asphalt is a viscoelastic material where two phases can be considered: a phase liquid or volatile, formed by maltenes and a solid phase composed by asphaltenes. Therefore, theoretically, when a crack appears is closed by itself, but it would do it faster if the liquid part of bitumen increases. That can be done by mixing with less dense oil, known as rejuvenator, as stated by Garcia et al.,[13]. Sun et al.,[14] applied microwave heating on steel slag asphalt mixtures. It is concluded that microwave heating can be used to promote self-healing of steel slag asphalt mixture. Contreras and Garcia,[15] believed that the microwave technology is more effective than induction heating to heal cracks in asphalt roads.

The aim of the present investigation is to assess and compare the influence of implementing induction and external heating techniques for microcrack healing with the aid of iron filling on tensile strength of asphalt concrete.

2. Materials and methods

2.1. Asphalt Cement

Asphalt cement of penetration grade (40-50) produced by Al-Nasiriyah Refinery was implemented in this investigation, the physical properties of asphalt binder are listed in Table 1.

Table 1. Physical properties of asphalt cement

Property	Test Conditions	ASTM, [16] Designation	Test results	SCRB, [17] Specification
Penetration	25ºc, 100gm, 5sec	D5-06	44	40-50
Softening Point	-	D36-95	49	-
Ductility	25ºc, 5cm/min	D113-99	140	>100
Specific Gravity	25˚c	D70	1.03	
Flash Point	Cleave land open cup	D92-05	302	>232
After Thin Film Oven Test D1754-97				
Retained Penetration of Residue (%)	25ºc, 100gm, 5sec	D5-06	81	>55
Ductility of Residue	25ºc, 5cm/min	D113-99	95	>25

2.2 Coarse and Fine Aggregates

The Aggregates used in this investigation are locally available in the quarries of Badra city in Wasit province. Such quarries are usually used as a source of materials for paving work by government companies in the southern provinces. Table 2 demonstrates the physical properties of coarse aggregates while Table 3 shows the properties of fine aggregates. Both properties are compared with the requirements of state commission for roads and bridges SCRB in Iraq.

Table 2. Properties of Coarse Aggregates

Property	ASTM, [16] Designation No.	Test results	SCRB, [17] Specification
Bulk Specific Gravity of Coarse Aggregate	C127-88	2.618	-
Apparent Specific Gravity of Coarse Aggregate	C127-88	2.688	-
Absorption in percent of Coarse Aggregate	C127-88	1 %	-
Percentage of Fractured Particles in Coarse Aggregate	D5821-13	92%	Min: 90%
Resistance to Abrasion (Los Angeles)	C131/C131M-13	23%	Max: 30%

Table 3. Properties of Fine Aggregates

Property	ASTM, [16] Designation No.	Test results
Bulk Specific Gravity of Fine Aggregate	C128-01	2.622
Apparent Specific Gravity of Fine Aggregate	C128-01	2.693
Absorption in percent of Fine Aggregate	C128-01	1.1%

2.3 Mineral Filler (Limestone dust)

Limestone dust was used as a filler, it was obtained from the asphalt plant of the Ministry of Housing and Construction. The physical properties of the filling material are listed in Table 4.

Table 4. Properties of Mineral Filler

Property	Test results
Percent passing sieve No. 200	95
Specific gravity	2.850
Specific surface area (m^2/Kg)	355

2.4 Additive (Iron Filling)

The iron filing used in this work was brought locally from the blacksmith's factories scattered in Samawah province. One size of iron filling has been implemented, it was sieved to pass through Sieve No. 8 (2.36 mm) and retained on Sieve No. 50 (0.300 mm). The specific weight of iron filings was 7.14 gm/cm³. Figure 1 shows the iron filling implemented in this work.

Figure 1. Iron Filling

2.5 Selection of Combined Gradation

Asphalt concrete was prepared for wearing course type 111-B according to the gradation limitations of SCRB,[17] listed in Table 5.

Table 5. SCRB, [17] Limitations of Aggregate Gradation

Sieve size (mm)	Percent finer by weight			
	Asphalt stabilized base course Type 1	Binder course Type 11	Wearing course Type 111-A	Wearing course Type 111-B
37.5	100	100	100	100
25.0	90-100	100	100	100
19.0	76-90	90-100	100	100
12.5	56-80	70-90	90-100	100
9.5	48-74	56-80	76-90	90-100
4.75	29-59	35-65	44-74	55-85
2.36	19-45	23-49	28-58	32-67
0.300	5-17	5-19	5-21	7-23
0.075	2-8	3-9	4-10	4-10

2.6 Preparation of Asphalt Concrete Specimens

The aggregates were dried in an oven to a constant weight at 110 ᵒC, then sieved to different sizes, and stored separately. Coarse and fine aggregates were combined with mineral filler to meet the specified gradations of asphalt concrete wearing course layer as per SCRB, [17] specifications. The combined aggregate mixture was heated to 150 ᵒC before mixing with asphalt cement. The iron filling was added as partial replacement of fine aggregate in percentages of (0, 2, 4, 6, 8)%. The asphalt cement was heated to the same temperature of 150 ᵒC, then it was added to the heated aggregate to achieve the desired amount and mixed thoroughly using mechanical mixer for two minutes until all aggregate particles were coated with thin film of asphalt cement. Marshall specimens were prepared in accordance with ASTM D1559,[16] using 75 blows of Marshall hammer on each face of the specimen. Specimens with combination of iron filling and asphalt cement have been prepared and the optimum asphalt content for each combination was evaluated. Table 6 exhibits the optimum asphalt requirements for each percentage of iron filling. Table 7 demonstrates the Marshall and volumetric properties of the design mixture. Specimens have been tested in triplicate, and the average value was considered for analysis. Figure 2 shows part of the prepared specimens. Details of determination of optimum asphalt and iron filling could be found in [18].

Table 6. Optimum Asphalt Content for Iron Filling Percentages

Percent Iron Filling %	Optimum Asphalt Content %
0	5.2
2	5.1
4	5
6	4.9
8	4.8

Table 7. Marshall and Volumetric Properties of the Design Mixture

Property	Value	SCRB, [17] Specifications
Iron Filling %	5	---
Optimum asphalt content %	4.9	4-6
Air voids %	4.1	3-5
Unit Weight	2.410	---
Marshall stability kN	11.4	8 kN minimum
Marshall Flow mm	2.8	2-4 mm
Voids in Mineral Aggregates %	15.6	14% Minimum
Voids Filled with Asphalt %	76	-----

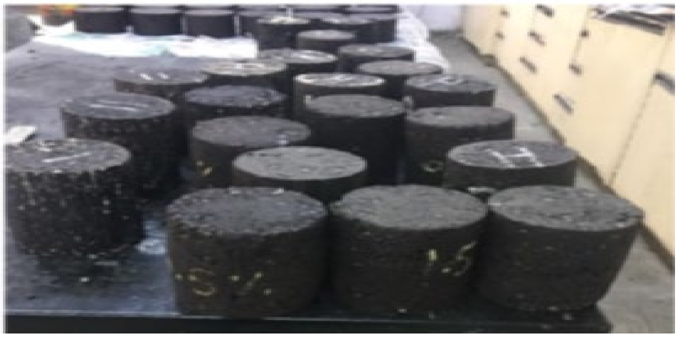

Figure 2. Part of the Prepared Specimens

2.7 Repeated Indirect Tensile Stresses Test

The repeated indirect tension stress test as specified by ASTM, [16] was conducted using the pneumatic repeated load system (PRLS). The test was performed on Marshall specimens, 102 mm in diameter and 63.5 mm in height. Repetitive indirect tensile loading was applied to the diametral specimen and the vertical strain is monitored under the load repetitions. Diametral loading is applied with a constant loading frequency of 60 cycles per minute and loading sequence for each cycle is 0.1 sec load duration and 0.9 sec rest period. Load repetitions was applied under constant stress level of 0.138 MPa, while the testing temperatures of (25) ᵒC was implemented in the test. Specimens were subjected to the application of repeated indirect tensile stresses of 600 and 1200 load repetitions. Figure 3 exhibit the repeated load sequence implemented, while Figure 4 shows the PRLS and the repeated tensile stress test setup.

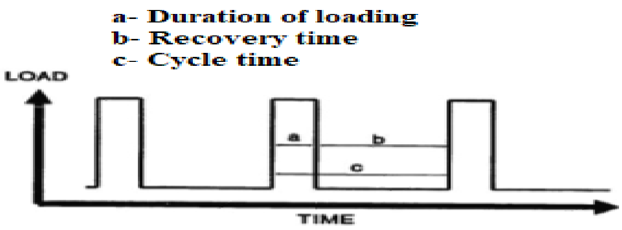

Figure 3. Repeated tensile stress loading sequence implemented

Figure 4. PRLS and Repeated Indirect Tensile Stress Test Setup

2.8 Microcrack Healing Process

Two techniques for microcrack Healing have been adopted in this work, the first technique was healing with the aid of the external heating. The second technique was the induction heating with the aid of microwave oven. The healing procedure for both techniques can be summarized as follow:

2.8.1 External Heating, after applying 600 or 1200 load repetitions to allow for the initiation of micro cracks, the test was terminated. Specimens were withdrawn from the PRLS testing chamber and stored in an oven for 120 minutes at 60 °C to allow for microcrack healing as recommended by Qiu et al, [19]; Sarsam, [20]; and Sarsam, [21]. Healing occurred in the asphalt concrete mixture specimens due to the reduction in the viscosity of asphalt cement by external heating. The specimens were cooled at room temperature for 24 hours, then transferred to the PRLS chamber. Specimens were conditioned by placing in the PRLS chamber at temperature of (25°C) for 120 minutes. Specimens were subjected to another cycle of 600 or 1200 load repetitions. After first and second cycles of load repetitions in PRLS device, and before and after healing process, the specimens were subjected to indirect tensile strength determination.

2.8.2 Induction Heating, after applying 600 or 1200 load repetitions to allow for the initiation of micro cracks, the test was terminated. Specimens were withdrawn from the PRLS testing chamber and stored in the microwave oven of (900 Watt) for 150 second then the cooling process was carried out by placing the specimens at room temperature of 25°C for 120 minutes. The temperature of the specimens was recorded after the heating process and referred as (healing temperature). Figure 5 demonstrates the heating techniques adopted.

Figure 5. Heating techniques adopted

3. Results and Discussion

Table 8 exhibits the influence of induction heating and iron filling content on the healing temperature of asphalt concrete specimens. It can be observed that as the iron filler content increase, the healing temperature increases. This may be attributed to the fact that the induction heating increases the temperature inside the mixture, while the iron filling absorbs such high temperature which support melting of asphalt binder and healing of the microcracks. The heating speed of asphalt mixture with microwave induction heating was much higher than that with external heating of 60 °C, while the temperature distribution within the asphalt mixture under induction heating was quite uniform. The effective heating depth of microwave induction heating is much higher than that of external heating. Similar behavior was reported by Hechuan Li et al., [10]; and García et al. [8]. In fact, Asphalt concrete can be healed quickly, because asphalt binder behaves as a near-Newtonian fluid when its temperature is above the softening point of the binder. As the provided healing temperature increases, a quick crack closer could be achieved. Similar finding was reported by Tang et al, [22]. It can be noted from Table 8 that the healing temperature of the control mixture (without iron filling) after 150 second of induction heating by microwave is almost like that obtained after 120 minutes of external heating at 60°C.

Table 8 Influence of Iron Filling and Induction Heating on Healing Temperature

Percent Iron Filling	Temperature of Specimen Before Induction Heating °C	Temperature of Specimen After Induction Heating °C	Percent Increase in Healing Temperature
0	20	65	225
3	20	72	260
5	20	83	310
7	20	92	365

Figure 6 exhibits the influence of iron filling and heating techniques on microcrack healing of asphalt concrete. It can be observed that specimens subjected to lower load repetitions of 600 shows almost higher indirect tensile strength after practicing induction heating as compared to those practicing external heating. This may be attributed to the fact that minimal damage in the form of microcrack occurred at lower loading sequence, and the healing by both heating techniques can almost retain tensile strength. On the other hand, implementation of 5% iron filling exhibit superior performance with both heating techniques and shows higher indirect tensile strength ITS than that of the control or specimens with other percentages of iron filling. Similar finding was reported by Alakhrass, [6].

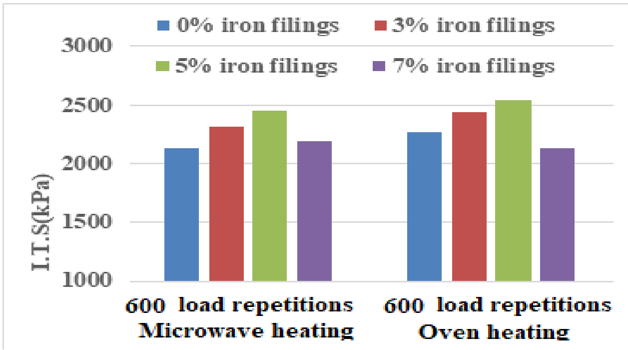

Figure 6. Healing After 600 Load Repetitions

Figure 7 exhibits the influence of iron filling and heating techniques on microcrack healing of asphalt concrete specimens subjected to higher load repetitions of 1200. It shows higher indirect tensile strength after induction heating as compared to the case of external heating. In fact, at 1200 load repetitions, the damage of the specimen starts to change from microcrack to macrocrack as stated by Sarsam and Hamdan [23].

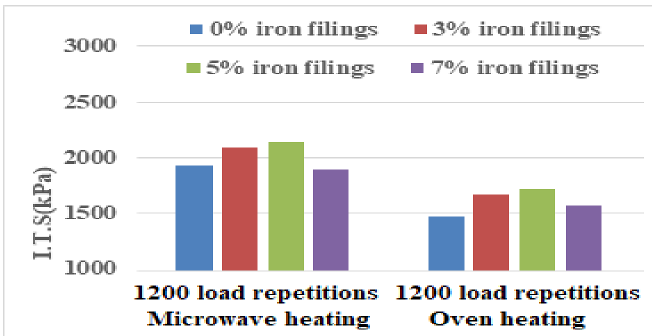

Figure 7. Healing After 1200 Load Repetitions

The damage in the form of macrocrack occurred at such high loading sequence and the healing by both heating techniques can hardly maintain the original tensile strength of control specimens. On the other hand, implementation of iron filling exhibits improvement in ITS under both heating techniques. Specimens with 5% iron filling shows superior tensile strength as compared to other iron filling content or control mixture. It can be observed that the microcracks formed after 600 load repetitions can be effectively healed by both heating techniques with and without implementing iron filling.

Table 9 illustrates the variation of Indirect Tensile Strength with Heating Technique. It can be observed that implementation of 5% iron filling had increased the ITS by (11.1, and 15) % after 600 load repetitions and (16.8, and 12.1) % after 1200 load repetitions for external and induction heating techniques respectively. It can be observed that the specimens exhibited serious damage and macrocracks formed after 1200 load repetitions. It can be noted that specimens can be effectively healed by induction heating technique rather than external heating by implementing iron filling. After practicing 1200 load repetitions, specimens exhibited 47.5% healing capacity after induction heating as compared to external heating when 5% iron filling was implemented in the mixture. Such finding agrees with Garcia [24].

Table 9. Variation of Indirect Tensile Strength with Heating Technique

Specimen	Average Indirect Tensile Strength After Healing			
	External Heating			
	After 600 Repetitions	% Change	After 1200 Repetitions	% Change
Control	1932	---	1472	---
3% Iron	2089	8.1	1665	13.1
5% Iron	2146	11.1	1719	16.8
7% Iron	1899	-2.0	1574	6.9
	Induction Heating			
Control	2129	---	2261	---
3% Iron	2318	8.9	2436	7.7
5% Iron	2447	15.0	2535	12.1
7% Iron	2186	2.6	2131	-5.7
Control	2129	---	2261	---

4. CONCLUSIONS

Based on the limited testing program, the following conclusions could be drawn.

1- Implementation of microwave induction heating after 1200 load repetitions can increase the healing capacity of asphalt concrete by 47.5% as compared to external heating when 5% iron filling was implemented in the mixture.

2- Implementation of 5% iron filling had increased the ITS by (11.1, and 15) % after 600 load repetitions and (16.8, and 12.1) % after 1200 load repetitions for external and induction heating techniques respectively.

3- Healing temperature of the control mixture (without iron filling) after 150 second of induction heating is almost like that obtained after 120 minutes of external heating at 60°C.

4- Microcracks formed after 600 load repetitions can be effectively healed by both heating techniques with and without implementing iron filling as additive.

5- Macrocracks formed After practicing 1200 load repetitions, iron filling was able to support the tensile strength of asphalt concrete when microwave induction heating was implemented rater than oven heating.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest.

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