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(Research Article)

Enhancing the Viscoelastic Properties of Asphalt Concrete by Crack Healing Process

S. I. Sarsam[1*]

[1*]*Professor, Sarsam and Associates Consult Bureau (SACB), Baghdad, IRAQ*

Abstract

Asphalt concrete pavement usually practices load repetitions and environment impacts. The quality of the pavement declines through the service life. However, the asphalt pavement can heal the micro cracks by itself. In the present investigation, slab samples of asphalt concrete were prepared at optimum asphalt cement binder requirement with the aid of roller compaction. Asphalt concrete prism specimens were extracted from the slab samples and subjected to four points flexural fatigue test at 20° C. The test was stopped when the stiffness of asphalt concrete declines to 50 % of its value at the start of the test. The beam specimens were subjected to external heating at 60° C for 120 minutes to enhance the viscoelastic properties through micro cracks healing through heating-induced healing method. Beams were tested under repeated flexural bending after the healing process. The variation in the stiffness, fatigue life, phase angle, dissipated energy and deformation after healing was monitored. It was concluded that the flexural stiffness, the phase angle, and dissipated energy were increased after healing while the deformation declines. The crack healing is recommended as a sustainable process to enhance the pavement quality.

Keywords: Asphalt concrete, Healing, Micro cracks, Stiffness, Flexure, Dissipated energy, Phase angle.

1. Introduction

Microcracks usually originate at the bottom of asphalt concrete pavement layer due to the horizontal tensile strains generated by vehicular movement. Microcracks start to propagate towards the upper layers under repeated loading which can lead to pavement distress and failure. Asphalt concrete is a viscoelastic material, it can dissipate the energy when it is subjected to mechanical work (loading and relaxiation). The energy is stored in the asphalt concrete mixture system when appling the load. On the other hand, the energy is recovered when the load is removed. The asphalt concrete mixture behaves differently during the unloading process and follows a different path to that when loaded by a phase lag which is exhibited between the applied stress and the measured strain. The energy is dissipated in the form of heat generation, damage, or mechanical work. During a fatigue test, the stiffness reduces, the fatigue process starts and micro-cracks are induced in the material; therefore the dissipated energy varies per loading cycle and usually increases for controlled stress tests and decreases for controlled strain tests as revealed by Maggiore et al., [1]. Qiu et al., [2] stated that the asphalt cement bider has an advantageous ability to fully or partially heal the cracks by itself. However, this healing ability is typically not accounted for performance prediction of the asphalt concrete mixture, and the mechanical degradation of the bitumen is normally overestimated as stated by Ayar et al., [3]. The overestimated degradation of asphalt concrete has resulted in a conservative pavement structural design. It was felt by Sarsam [4] that addressing the crack healing effect of the asphalt binder in the selection of material and structural design has been a new focus and a non-negligible step in sustainable pavement design. Experimental investigations were conducted by Varma et al., [5] using four-point bending at two different temperatures and four strain levels for four types of asphalt mixtures. a new strategy to separate the total dissipation of energy into fatigue and viscous dissipation was proposed based on a constitutive assumption for the viscous dissipation of damaged asphalt concrete mixture. Li et al., [6] revealed that Healing index increases due to the decrease of the damage level or advance of rest duration. Higher damage levels as introduced by longer loading time or higher load levels can effectively decrease the binders' healing potentials when the binders are at the relatively low damaged levels. The healing potential becomes low when the material is at severe damage state, thus will remain at that low levels even though the damage level increases. Lv et al., [7] developed a recovery index to capture the asphalt recovery evolution after cyclic loading, including the fatigue resistance recovery and modulus recovery. Results indicated that the recovery process can be divided into three stages, in which the fatigue resistance recovery always lags behind the modulus recovery. Within the

*Corresponding Author: e-mail: saadisasarsam@coeng.uobaghdad.edu.iq
Tel-+00964-7901878167*

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analytical pavement design methods, the calculation procedure is based on the assumption that the pavement behaves as a set of superimposed continuous elastic layers, which fail due to fatigue cracking. Ageing of the pavement asphalt layers results in stiffening and transverse cracking and the asphalt concrete layers are no longer of infinite extent in the horizontal direction and their response resembles that of a slab as reported by Pérez-Jiménez et al., [8].The calculation method determines the stresses produced by the loading at the base of the asphalt concrete layer and estimates the number of cycles that the pavement can withstand as these loads pass. For the design of asphalt concrete pavement layer, and calculation of the pavement stresses, it is assumed that all the pavement layers, including the granular layers and subgrade, are elastic and can be characterised by their Poisson's ratio and modulus of elasticity. The response of flexible pavement materials is very much affected by the mode of load application. Cyclic tests are used in the characterisation of asphalt concrete mixtures, which apply stresses at high frequencies (10–30) Hz and Cyclic loading is the basis of the tests for the fatigue analysis of bituminous mixes, since such loading mode allow the application of a large number of loads in a very short time as addressed by Pereira and Pais, [9]. A flexural test is usually performed on asphalt concrete, which consists of subjecting a beam specimen to a repeated flexural bending at a controlled strain amplitude. Figure 1 demonstrates that the asphalt concrete pavement mixture experiences a high loss of stiffness at the start of the test as exhibited in phase I, which continues more slowly as the test progresses to phase II, and which again ends with a rapid and sharp loss of its mechanical properties as in phase III. Only phase II is considered for determination of the fatigue failure.

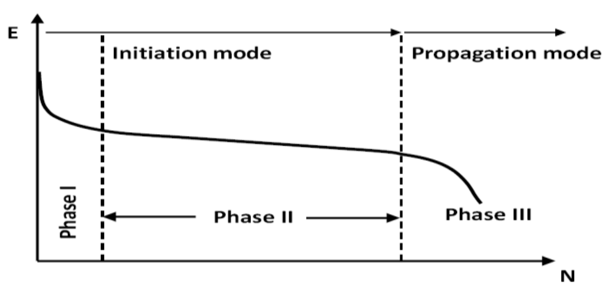

Figure 1. Fatigue behavior of asphalt concrete, after Pérez-Jiménez et al., [8]

The behavior of asphalt concrete through Phase I is associated with the non-linearity of the material and to the adaptation of the specimen to the test . However, phase I and II correspond to the same type of response of the material. There is an internal modification process of the properties and rheological characteristics, which takes place from the start of the test and is the same in both phases. The loss of stiffness is related to the dissipated energy in each cycle. For the same strain level, there is a linear relationship between the dissipated energy and the modulus of the material. This relationship is the same at the start of the test, phase I, as when it continues in phase II as explained by Pérez-Jiménez et al., [10]. Liu et al. [11] concluded that activation the healing of microcracks by thermal process was clearly practical to extend the fatigue life of asphalt concrete. Different kinds of asphalt binder needed to be heated to specific softening point related temperatures to substantially enhance the rate and healing ability. Kringos et al., [12] addressed that it only microcrack can be effectively healed, and the rate of healing and healing potential of asphalt concrete can be dramatically reduced as the crack evolved from microcrack to macrocrack. Xiao, [13] revealed that the existing self-healing techniques, which are considered as resource-saving and environment-friendly techniques, include heating-induced healing and polymer healing methods. Such methods can effectively enhance the service life of asphalt concrete pavement by reducing the repair and maintenance cost of road surface, and also helps to reduce carbon dioxide emissions and energy conservation. Barrasa et al., [14] reported that the fatigue damage process of Asphalt concrete can be considered as the internal micro crack's initiation and development. The micro cracks which first appeared in the asphalt concrete under the load repetitions can be regarded as the crack development area. However, when the load is terminated, Asphalt concrete crack development area will practice stress relaxation followed by interface healing. For viscoelastic materials such as asphalt concrete mixture, Stress relaxation provides a good condition for interfacial healing, so a better self-healing effect can be obtained. Self-healing is an effective method of enhancing the ability of asphalt pavement to heal, especially on micro cracks healing as addressed by Ghazali et al., [15]. It was revealed that innovation of self-healing of asphalt concrete by external heating can help enhance the temperature absorption of the binder, which can help in improvement of its fatigue resistance under repeated traffic loading. Asphalt healing processes mainly entail the wetting of micro cracked surfaces, diffusion of binder molecules between aggregate-binder interfaces, and the randomization of these diffused molecules, which can help achieving the strength of cracked interfaces relatively similar to that of the original materials. Varma et al., [16] quantifies healing of asphalt concrete beam specimens. Experiments are conducted at a controlled displacement rate and at −15°C environment. After the crack propagation, samples are given a rest period of 2 h at 10°C to promote healing before retesting them. The amount of healing after the rest period is quantified using various healing indices based on the recovery of fracture toughness, stiffness, fracture energy, and peak load. It was observed that the quantum of healing is different when comparing different healing indices. The stiffness-based healing index demonstrated the healing ability of asphalt binder.

The aim of the present work is to monitor the possible enhansement of the viscoelastic properties of asphalt concrete in terms of the stiffness, fatigue life, phase angle, dissipated energy and deformation after practicing microcrack healing. Roller compacted beam specimens will be prepared and tested under repeated flexural fatigue stresses.

2. Materials Properties and Methods of Testing

All the materials used in this are work are currently implemented for the construction of asphalt concrete pavement, and locally available.

2.1 Asphalt cement: Asphalt cement having a penetration grade of 40-50 which is equivalent to PG 64-16 performance grade specifications was obtained from Dura oil refinery and implemented in the present investigation, Table 1 illustrates its physical properties.

Table 1. Physical properties of asphalt cement binder

Physical properties	ASTM, [17] Designation	Test results
Ductility Cm	D113-99	100+
Specific gravity	D70	1.04
Penetration	D5-06	41
Flash point °C	D92-05	275
Softening point °C	D36-95	49.4
Retained penetration of residue	D5-06	27
Loss in weight (163°C, 50g,5h) %	D-1754	0.3
Ductility of residue	D113-99	40+

2.2 Fine and coarse aggregates: The coarse and fine aggregates used are crushed quartz; it was obtained from Al-Nibaee quarry. Table 2 demonstrates the physical properties of fine aggregates, while Table 3 presents some of the physical properties of crushed coarse aggregates with 97 % of fractured faces.

Table 2. Physical properties of fine aggregates

Property	ASTM, [17] designation	Test value
Sand equivalent (%)	D-2419	51
apparent specific gravity	C-128	2.664
Bulk specific gravity	C-128	2.604
Water absorption (%)	C-128	1.42

Table 3. Physical properties of coarse aggregates

Property	ASTM, [17] designation	Test value
Water absorption (%)	C-127	0.57
apparent specific gravity	C-127	2.608
Bulk specific gravity	C-127	2.584
Soundness in sodium sulfate solution (%)	C-88	2.67
Los Angeles abrasion (%)	C-131	13
Flat and elongated particles (crushed) (%)	D-4791	1.6

2.3 Mineral filler: Ordinary Portland cement was obtained from Badoush cement factory and used as mineral filler. Table 4 presents its physical properties.

Table 4. Physical properties of mineral filler

Property	Test value
Specific surface area (m^2/Kg)	312.5
Bulk specific gravity	3.150
Passing sieve No. 200 (%)	96

2.4 Selecting the combined gradation of aggregates: The selected combined gradation of aggregates in the present work follows the requirements of SCRB, [18] specification for dense graded wearing course pavement layer. The selected gradation of aggregates has a nominal maximum size of 12.5 mm. Figure 2 exhibits the selected combined aggregate gradation.

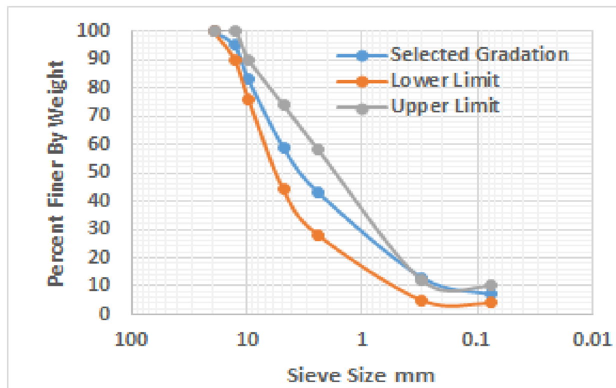

Figure 2. Aggregates combined gradation for wearing course according to SCRB, [18]

2.5 Preparation of asphalt concrete paving mixture and specimens: The mineral filler was combined with coarse and fine aggregates to meet the specified gradation for wearing course as per SCRB, [18]. The asphalt cement binder was heated to 150 ºC, then, it was added to the aggregates which were subjected to heating to 160 ºC to the desired amount and mixed thoroughly for two minutes until a homogeneous mixture was obtained. The optimum asphalt binder content was 5.3% based on Marshall test. More details of obtaining the optimum asphalt binder content may be referred to Sarsam and Alwan, [19]. The asphalt concrete mixtures were poured in a slab mold of (300 x 400 x 60) mm and practiced the roller compaction to a target bulk density according to EN12697-33, [20] at a compaction temperature of 150 °C. Details of the compaction process may be found at Sarsam, [21]. Asphalt concrete slab samples were left overnight to cool. Beam specimens having 63±2 mm width, 50±2 mm height, and 400 mm length were extracted from the compacted slab sample using the Diamond-saw. The total number of the obtained beam specimens was eight, while the casted slabs were three. Table 5 exhibits the volumetric properties of the prepared asphalt concrete mixture at optimum binder content.

Table 5. Volumetric properties of the design mixture

Air voids Vv %	Voids in mineral aggregates VMA %	Voids filled with asphalt VFA %
2.3	13.7	82.8

2.6 Repeated flexural bending beam test: The dynamic flexural bending test was implemented with the aid of four-point repeated flexural bending beam as per AASHTO T321, [22] to monitor the flexural stiffness and fatigue life of asphalt concrete beam specimens at 20 °C environment, and under constant micro strain level of 250. Throughout the fatigue test, the load frequency is set to 5 Hz, while the deformation due to loading was evaluated at the center of the beam. The test was terminated when the stiffness of the beam has declines to 50 % of its original value. A repeated sinusoidal (compression-tension) load was applied to the two inner clamps on the beam specimen. Figure 3 exhibit the flexural bending beam test setup.

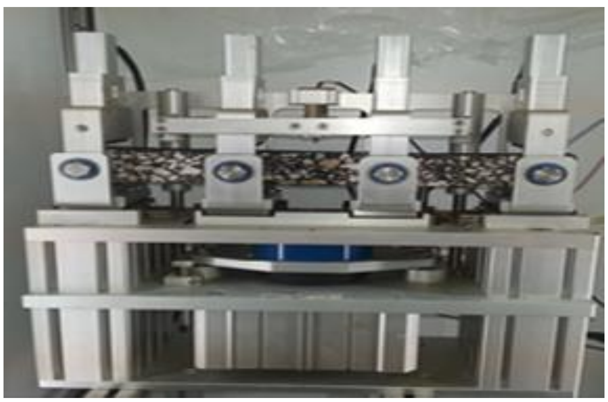

Figure 3. Dynamic flexural bending beam test

2.7 Crack healing technique: The micro crack healing technique implemented in this work was healing by the external heating as per Sarsam, [23] recommendation. After the initiation of micro cracks due to flexural stresses repetitions for the beam specimens, the test was terminated. Beam specimens were removed from the testing chamber and stored in an oven at 60 ° C for 120 minutes to allow for micro crack healing process. Specimens were subjected to another cycle of repeated flexure stress at 20 ° C for another course of load repetitions. The testing Temperate was (20ºC), while the applied compressive stress was (138) kPa.

3. Results and Discussion

3.1 Influence of healing on flexural stiffness: Figure 4 demonstrates the influence of crack healing process on the flexural stiffness of asphalt concrete through its fatigue life. It can be noticed that a sharp loss in the flexural stiffness at the early loading exists which may represent phase one of the fatigue process. The decline in flexural stiffness changes to be steady as the loading proceeds, this can represent phase two of the fatigue process. Further increase in the loading had exhibited sharp decline of flexural stiffness, which represent phase three of the fatigue process. Similar trend was reported by Pérez-Jiménez et al., [10]. However, the drop in the flexural stiffness through the fatigue life of asphalt concrete is lower when the specimens practice the micro crack healing process. Even at the start point of the test, the flexural stiffness of the healed mixture is higher than that of the control mixture by 10 %. On the other hand, at the end of phase three, the healed mixture exhibit higher flexural stiffness by 73.3 % than that of the control mixture (before healing). This may be attributed to the stiffening of the asphalt concrete mixture through the healing period.

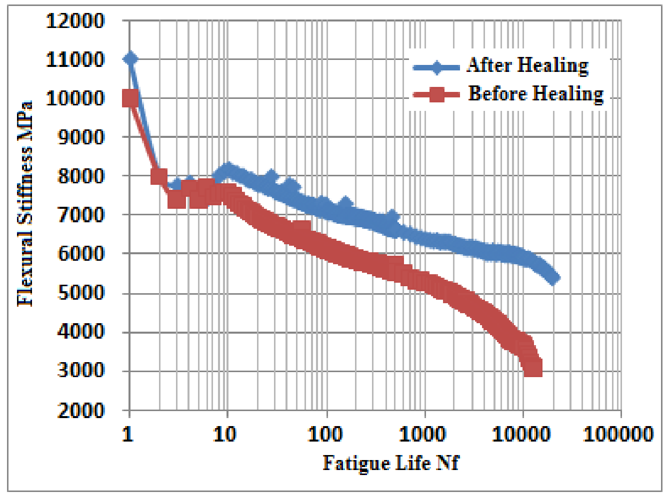

Figure 4. Influence of healing on flexural stiffness

3.2 Influence of healing on dissipated energy: Figure 5 demonstrates the influence of healing on cumulative dissipated energy and fatigue life relationship. Dissipated energy is considered as a measure for evaluation of the fatigue life of asphalt concrete mixtures. The dissipated energy was measured after each load cycle, and the change in dissipated energy for different cycles can indicate the initial state of failure and cracking of the material.

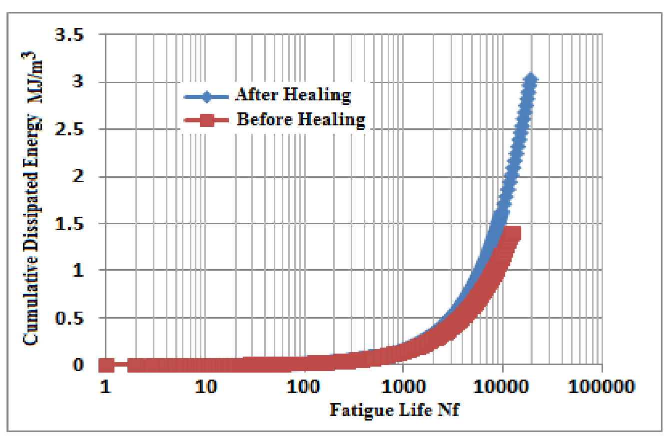

Figure 5. Influence of healing on dissipated energy and fatigue life relationship

The cumulative dissipated energy is the sum of dissipated energy in every cycle until collapse of the material. It can be detected that the cumulative dissipated energy for asphalt concrete increases gently at the early stages of loading, then after 2000 load repetitions, the rate of increase changes to sharp. At failure, the cumulative dissipated energy is higher by 100 % after the healing process as compared with that of the control mixture. This could be attributed to the stiffening of the mixture during the healing process. On the other hand, the fatigue life of the healed asphalt concrete is higher by 54 % than that of the control mixture. Findings agree with Abojaradeh, [24].

3.3 Influence of healing process on the phase angle: Figure 6 present the influence of the healing process on the phase angle of asphalt concrete. It can be observed that the phase angle is higher after micro crack healing as compared with the control mixture. The phase angle can be considered as an indicator of viscoelastic behavior. The observation of Phase angle is important for understanding the structural material behavior. It was observed that the rate of change of the phase angle value became stabile after the first 30 % of the test period, while it exhibits sharp increase which starts slightly before failure point. Such sudden increase in the phase angle may be considered as one of the indicators of the end of the material fatigue life. Similar behavior was reported by Mandula and Olexa, [25]. At the initial stages of loading, the phase angle of the healed mixture is higher than that of control mixture by 27.2 %, while at failure, the phase angle of the healed mixture declines by 11.4 % as compared with the control mixture.

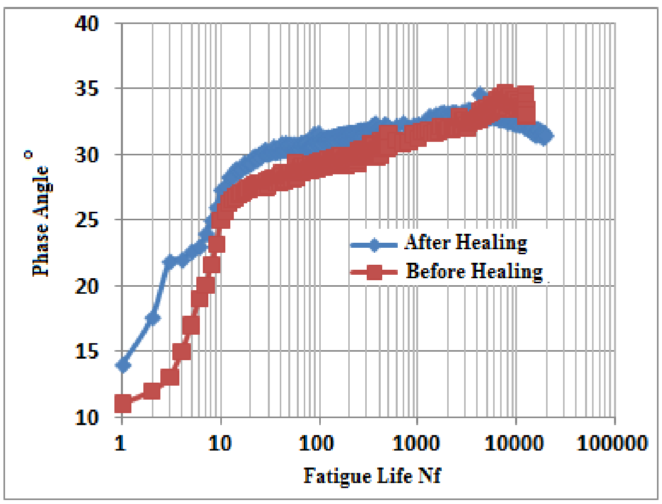

Figure 6. Influence of healing process on phase angle

3.4 Influence of healing on stiffness-phase angle relationship: Figure 7 shows the influence of healing on flexural stiffness-phase angle relationship. The phase angle of the control, and the healed mixtures declines gently from (35 to 25) ° and from (34 to 25) ° respectively as the flexural stiffness increases up to a moderate stiffness of 7500 MPa. Then it declines sharply from (25 to13) ° and (25 to 17) ° until reaching the failure stage. However, higher phase angle is detected for healed mixture as compared with the control mixture.

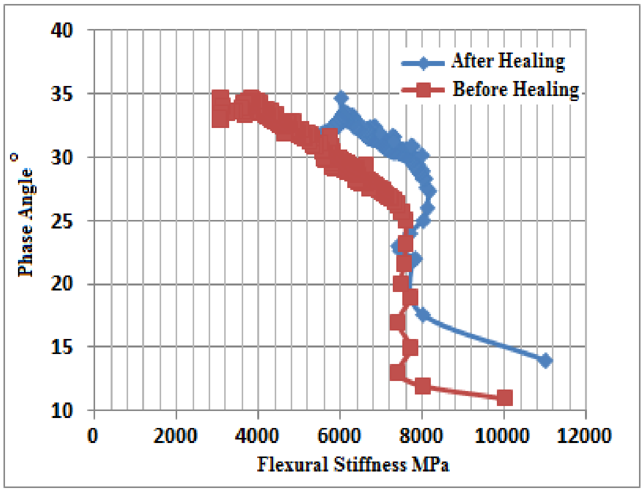

Figure 7. Influence of healing process on flexural stiffness-phase angle relationship

3.5 Influence of healing on permanent deformation: Figure 8 exhibit the influence of healing on permanent deformation – fatigue life relationship. It can be noticed that the healed mixture exhibits lower deformation at the early stages of loading as compared with the control mixture. After the first load repetition, the healed mixture shows lower deformation by 65.2 % as compared with the control mixture. This could be attributed to the higher viscosity of the binder after the healing process and the loss of binder's volatiles which reduces the flexibility of the mixture.

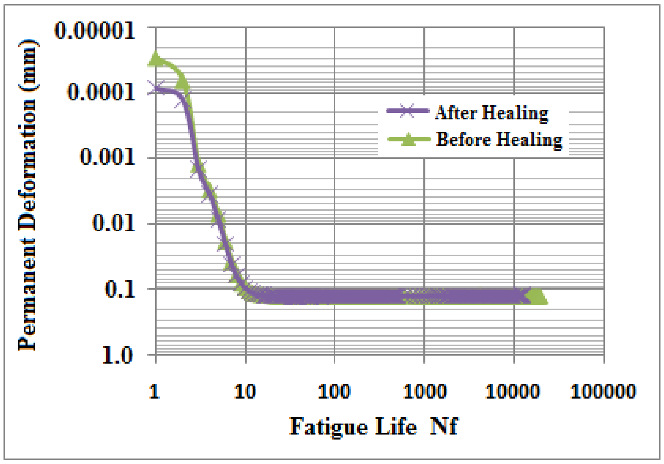

Figure 8. Influence of healing on flexural stiffness-deformation relationship

4. Conclusions

The conclusions can be addressed based on the limitations of materials and testing techniques.

- The flexural stiffness of the healed mixture is higher than that of the control mixture by 10 %. At failure, the healed mixture exhibit higher flexural stiffness by 73.3 % than that of the control mixture.
- The cumulative dissipated energy for asphalt concrete increases gently at the early stages of loading, then sharper trend after 2000 load repetitions is noticed. At failure, the cumulative dissipated energy is higher by 100 % after the healing process as compared with that of the control mixture.
- At the initial stages of loading, the phase angle of the healed mixture is higher than that of control mixture by 27.2 %, while at failure, the phase angle of the healed mixture declines by 11.4 % as compared with the control mixture.
- After the first load repetition, the healed mixture shows lower permanent deformation by 65.2 % as compared with that of the control mixture
- Micro crack healing process exhibit higher flexural stiffness, phase angle, and cumulative dissipated energy.

5. Recommendations

The micro crack healing process is recommended as a sustainable process to enhance the pavement quality.

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Biographical notes

Prof. Saad Issa Sarsam was born in Baghdad (1955), got his BSc. Degree in Civil Engineering (1977); Post graduate Diploma in Transportation Engineering (1978); MSc in Transportation Engineering (1980). Worked as senior material Engineer for NCCL (National center for construction laboratories) (1982-1988); Served as Director of NCCL- Mosul, (1988-1992). Joined the academic staff at University of Mosul (1992-2005) and at University of Baghdad (2005) and got the Professor degree at (2007). Head of the Department of Civil Engineering, (2016-2018). Published six books, and 360 research papers. Member of editorial board, and reviewer of nine international scientific journals. Supervised 45 MSc Thesis and participated in 50 national and international scientific conferences. Consultant engineer for Ministry of Industry and Military Manufacturing, FAW General Directory (1989-1990). Consultant engineer for Mosul Municipality on urban road resurfacing and construction (2001-2003). Consultant engineer for quality control on rehabilitation of Mosul International Hotel (2004). Consultant engineer for middle Euphrates international airport (2011-2013). Consultant engineer for the state company for implementation of transportation facilities, Ministry of transportation (2011-2014). Consultant engineer for NCCLR, Baghdad (2011-2015). Consultant engineer for AFM Group-Switzerland, Baghdad international airport rehabilitation (2014). Consultant engineer for ministry of transport (2017). Director of Sarsam and Associates Consult Bureau SACB, Baghdad-Iraq (2020). Consultant Engineer for Triple S GMBH, Germany for Diwaniya poultry project, (Pavement Design). (2020). Consultant Engineer for Abraj Al-Bilad Company, Mall of Iraq Project, (Traffic impact assessment), (2022). Areas of specialization and interest (Environmental impact, Safety issues in roadway operation, Airport Engineering; Nano materials in asphalt pavement, Roller compacted concrete; Modified asphalt concrete; Asphalt stabilized embankment models; Road user characteristics).