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Impact of Repeated Load on Crack Healing Cycles of Asphalt Concrete

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Abstract: Asphalt concrete pavement is designed to under take repeated loading for its design life with minimal maintenane requirements. Under such loading mode, micro cracks appears in the flexible pavement structure, while it exhibit self healing ability of micro cracks. In this work, the impact of repeated tensile and shear stresses on accumulation of permanent strain of asphalt concrete and micro crack healing cycles have been investigated. Asphalt concrete specimens of 100 mm diameter and 63 mm height have been prepared with optimum asphalt requirement and with extra 0.5% asphalt above and below the optimum. Specimens exhibits permamemt strain under repeated tensile and shear stresses using three stress levels (69, 138 and 207) kPa at 25°C environment. The loading cycle consists of load repetitions application for 0.1 second followed by 0.9 seconds of rest period. Specimens were allowed to heal by external heating at 60°C for 120 minutes after each 1000 load repetitions, then subjected to another load repetition cycles. The healing cycle was repeated twice. It was concluded that as the crack healing cycles proceeds, the resilient modulus increases while the permanent strain decreases. The impact of asphalt content on resilient modulus is variable through the crack healing cycles among tensile and shear stresses. After crack healing cycles, the permanent strain was reduced by an average of (45, 36 and 23)%, for (69, 138, and 207) kPa respectively as compared to reference mix under punching shear stress (PSS), while it was reduced by an average of (5, 23 and 21)%, for (69, 138, and 207) kPa respectively as compared to reference mix under indirect tensile stress (ITS).

Keywords: Asphalt Concrete, Stress Level, Healing Cycles, Repeated Tensile, Repeated Shear, Strain

1. Introduction

The flexible pavement is expected to sustain the repeated vehicular wheel load and retain its theoritical elastic behaviour and serviciability through out its design life. Excessive wheel load and environmental impact will initiate micro cracks in the pavement layer, which will develop to macro cracks and then to many other types of pavement distresses if (no action) alternative was implemented, [1]. Asphalt concrete mixture is known to have self healing capability when proper heating or rest periods are allowed. The self healing process of damage in asphalt concrete consists of two main phases, namely the crack closure and the strength gain phase, [2]. The driving force can be either thermal (temperature) or mechanical (by confinement, pressure). The self healing capability is related to the viscosity of the asphalt cement, which increases with increasing healing time, temperature and when the crack size is very small, [3]. Healing occurs due to temperature increases while in the micro-cracking range, it increases the useful life of the pavement [4]. A test was developed by Roque et al. [5] to evaluate the healing behavior of asphalt mixtures. The testing procedure consists of repeated loading damage tests (resilient modulus) during the damage phase followed by a healing phase during which resilient modulus tests are performed only periodically to measure modulus recovery (healing). A decrease in resilient modulus with an increasing number of load cycles is indicative of accumulation of micro-damage during the damage phase. Recovery of resilient modulus during the healing phase is indicative of damage recovery or healing. [6] Reported that under repeated traffic loading asphalt mixes deteriorate and the stiffness decreases. However, due to the healing effect asphalt mixes demonstrate strength recovery. [7] Stated that Crack healing rate was determined in terms of the recovered stiffness, deformation, and increment in fatigue life. Beam specimens were subjected to load repetitions at 20°C until 50% of the stiffness was retained, then beams were stored in an oven for two hours at 85°C, cooled to 20°C, then subjected to another cycles of load repetitions. It was concluded that Steric hardening appeared to play a significant role in a mixture's response during the loading and healing portions of laboratory tests. The healing phenomena could be utilized to overcome the negative impact of crack initiation. It was believed that crack healing may retain the resilient properties of asphalt concrete, [8]. The aim of this investigation was to assess the asphalt content and resilient modulus susceptability of asphalt concrete to crack healing. The resilient modulus Mr will be determined using indirect tensile strength ITS and double punching shear strength PSS testing techniques.

2. Materials and Methods

2.1. Asphalt Cement

The Asphalt cement was obtained from Dora refinery, the physical properties are listed in Table 1.

Table1. *Physical Properties of Asphalt Cement.*

Test Procedure ASTM [9]	Result	Unit	SCRB Specification [10]
Penetration (25°C, 100g, 5sec) ASTM D 5	43	1/10mm	40-50
Ductility (25°C, 5cm/min). ASTM D 113	156	Cm	≥ 100
Softening point (ring & ball). ASTM D 36	49	°C	50-60
After Thin-Film Oven Test ASTM D-1754			
Retained penetration of original, % ASTM D 946	31	1/10mm	< 55
Ductility at 25 °C, 5cm/min,(cm) ASTM D-113	147	Cm	> 25

2.2. Coarse and Fine Aggregates

Coarse and fine aggregates have been obtained from Al-Nibaee quarry, their physical properties are illustrated in Table 2.

Table 2. *Physical Properties of Al-Nibaee Coarse and fine Aggregates.*

Property	Course Aggregate	Fine Aggregate
Bulk Specific Gravity (ASTM C 127 and C 128)	2.610	2.631
Percent Water Absorption (ASTM C 127 and C 128)	0.423	0.542
Percent Wear (Los-Angeles Abrasion) (ASTM C 131)	20.10	-

2.3. Mineral Filler

Ordinary Portland cement has been implemented as mineral filler in the asphalt concrete mixture, the Physical properties of Portland cement are shown in Table 3.

Table 3. *Physical properties of Portland cement.*

Physical Properties	
% Passing Sieve No.200 (0.075mm)	98
Apparent Specific Gravity	3.1
Specific Surface Area (m^2/kg)	3.55

2.4. Selection of Asphalt Concrete Gradation

Dense graded asphalt concrete usually used for Wearing course as per SCRB, [10] Specification with 12.5 (mm) nominal maximum size of aggregates has been implemented in this work. Table 4 shows the selected aggregate gradation and the specification limits.

Table 4. *Selected gradation of Aggregate for Wearing Course, SCRB, [10].*

Sieve size (mm)	Percentage finer by weight of total Aggregate	
	Specification Limits (SCRB)	Gradation adopted
19	100	100
12.5	90-100	95
9.5	76-90	83
4.75	44-74	59
2.36	28-58	43
0.3	5-21	13
0.075	4-10	7

2.5. Preparation of Hot Mix Asphalt Concrete

The aggregate was sieved to different sizes, separated, and stored in plastic containers. Coarse and fine aggregates were combined with mineral filler to meet the specified gradation. Both of the combined aggregate mixture and asphalt cement have been heated to 150°C before mixing with asphalt cement. Then, asphalt cement 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, [9] using 75 blows of Marshall hammer on each face of the specimen. The optimum asphalt content was determined to be 4.9% by weight of aggregates. Additional asphalt concrete specimens have been prepared using asphalt cement of 0.5% above and below the optimum asphalt content. The prepared Marshall Specimens were divided into two groups, the first group was subjected to the repeated indirect tensile stresses at 25°C, while the second group was subjected to repeated double punching shear stresses at 25°C. Each set of specimens was subdivided into three sets for testing under three stress levels of (10, 20, and 30) Psi (69, 138 and 207) kPa and two healing cycles. Specimens have been tested in duplicate, and the average value was considered for analysis.

2.6. Testing of Asphalt Concrete Specimens Under Repeated Indirect Tensile Stress

Fig. 1 demonstrates the ITS test setup inside the Pneumatic repeated load system (PRLS). Specimens were subjected to repeated indirect tensile stress (ITS) for 20 minutes at 25°C to allow the initiation of micro cracks. Such timing and test conditions were suggested by [11] and [12]. Compressive repeated loading was applied on the specimen which was centered on the vertical diametrical plane through two parallel loading strips (12.7 mm) wide. Such load assembly applies indirect tensile stress on the specimen in the form of rectangular wave with constant loading frequency of (60) cycles per minutes. Three stress levels of (10, 20, and 30) Psi (69, 138 and 207) kPa have been implemented. A heavier sine pulse of (0.1) sec load duration and (0.9) sec rest period was applied over test duration period. Before the test, Specimens were stored in the chamber of the testing machine at room temperature (25±1°C). A digital video camera was fixed on the top surface of the (PRLS) to capture dial gage reading. The test was continued for 20 minutes, upon completion of test, the recording was terminated. The Specimens were withdrawn from the testing chamber and stored in an oven for 120 minutes at 60°C to allow for crack healing initiation. Specimens were returned to the testing chamber, conditioned for 120 minutes at 25°C, and then subjected to another cycle of repeated indirect tensile stresses at 25°C for 20 minutes. The deformation of the specimens under repeated indirect tensile stress and the number of load repetitions were recorded. The procedure of heating, conditioning and testing of the specimen was repeated for another cycle of healing and testing. The average of two sample of each asphalt cement percentage was calculated and considered for analysis as recommended by [12].

2.7. Testing of Asphalt Concrete Specimens Under Repeated Double Punch Shear Stress

Asphalt concrete specimens were subjected to repeated double punch shear stresses (PSS) for 20 minutes at 25°C to allow the initiation of micro cracks. Compressive repeated loading was applied on the specimen which was centered between the two plungers of 25.4mm diameter as per the procedure described by [13]. Such load assembly applies compressive load which was resisted by the specimen through shear resistance. The stress on the specimen is in the form of rectangular wave with constant loading frequency of (60) cycles per minutes. Three stress levels of (10, 20, and 30) Psi (69, 138 and 207) kPa have been implemented. A heavier sine pulse of (0.1) sec load duration and (0.9) sec rest period is applied over test duration. Before the test, Specimens were stored in the chamber of the testing machine at room temperature (25±1°C). A digital video camera was fixed on the top surface of the (PRLS) to capture dial gage reading. The test was continued for 20 minutes, upon completion of test, the recording was terminated. The Specimens were withdrawn from the testing chamber and stored in an oven for 120 minutes at 60°C to allow for crack healing initiation. Specimens were returned to the testing chamber, conditioned for 120 minutes at 25°C, and then subjected to another cycle of repeated shear stresses at 25°C for 20 minutes. The deformation of the specimens under repeated punching shear stress and the number of load repetitions were recorded. The procedure of heating, conditioning and testing of the specimen was repeated for another cycle of healing and testing. The average of two sample of each asphalt cement percentage was calculated and considered for analysis as recommended by [13]. Fig. 2 demonstrates the (PRLS) System with (PSS) setup.

2.8. Crack Healing Cycles Technique

The crack healing technique implemented in this work was healing by the external heating, specimens have been stored in an oven at 60°C for 120 minutes after each loading cycle. Specimens were returned to the testing chamber of the (PRLS) and conditioned for 120 minutes at 25°C, and subjected to another cycle of load repetitions. Fig. 3 shows the heating of specimens for crack healing purpose.

Fig. 1. *PSS test setup.*

Fig. 2. *ITS test setup.*

Fig. 3. *Heating for crack healing.*

3. Results and Discussion

3.1. Impact of Asphalt Content on Permanent Strain of Asphalt Concrete at ITS Stress Levels

As demonstrated in Fig. 4, the permanent strain increases as the stress level increase. For reference mixes under (ITS), the variation in permanent micro strain was not significant at low stress level of 10 Psi (69) kPa, while it increases as the stress level increase. At 30 Psi (207) kPa, the strain ranges between (320 - 370) micro strains for various asphalt percentages.

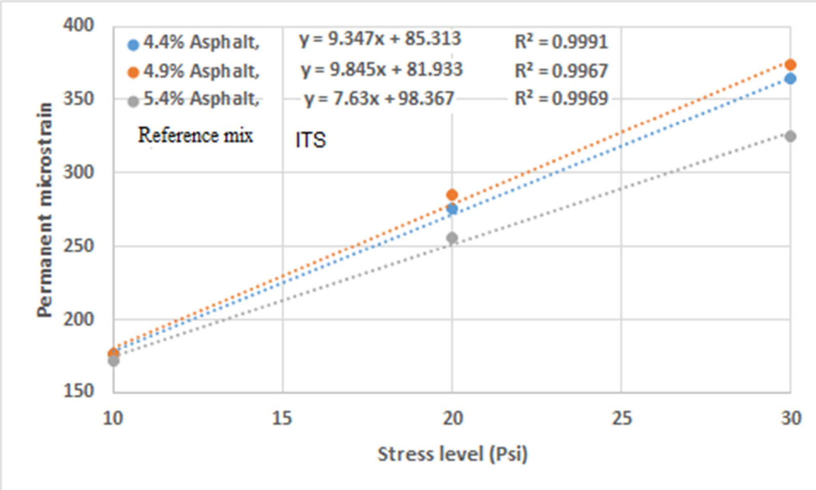

Fig. 4. *Impact of asphalt content on permanent strain for reference mix at ITS stress levels.*

Fig. 5 shows the impact of one healing cycle on the permanent strain, it can be observed that the impact of asphalt content was not significant at all the stress levels investigated. The slope decreases while the intercept values increase when compared to reference mix.

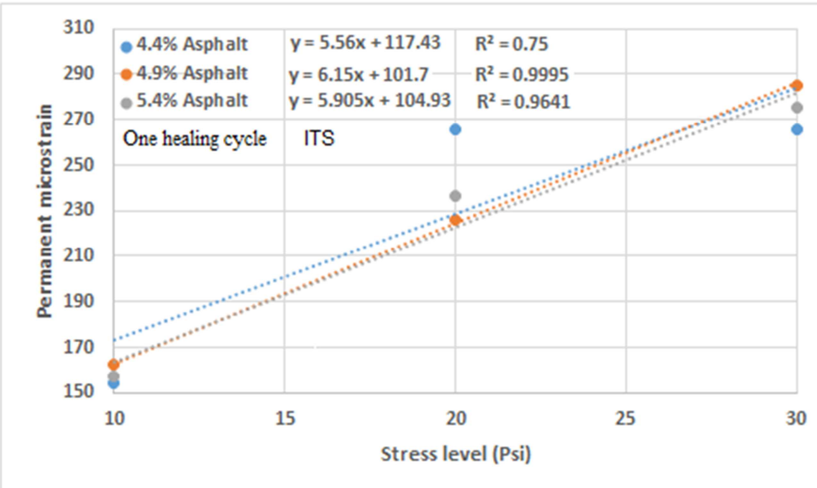

Fig. 5. *Impact of asphalt content on permanent strain after one healing cycle at ITS stress levels.*

Fig. 6 present the impact of two healing cycles on the permanent strain, it can be observed that the intercept also increases while the slope decreases. The optimum asphalt content has retained the maximum slope variation and minimum intercept as compared to other asphalt percentages. The intercept represents the permanent strain at N=1 (N is the number of load cycles), the higher the value of the intercept, the larger is the strain and the potential of permanent deformation. The slope represents the rate of change in the permanent strain as a function of the change in loading cycles (N) in the log-log scale. High slope of the mix indicates an increase in material deformation rate, hence, less resistance against rutting. Such findings agrees well with [2]. A mixture with low slope is preferable as it prevents the occurrence of rutting. It can be noted that crack healing cycles have positive influence on preventing the permanent strain. Table 5 summarizes the impact of asphalt content on permanent strain characteristics of asphalt concrete subjected to 1000 repeated (ITS) load.

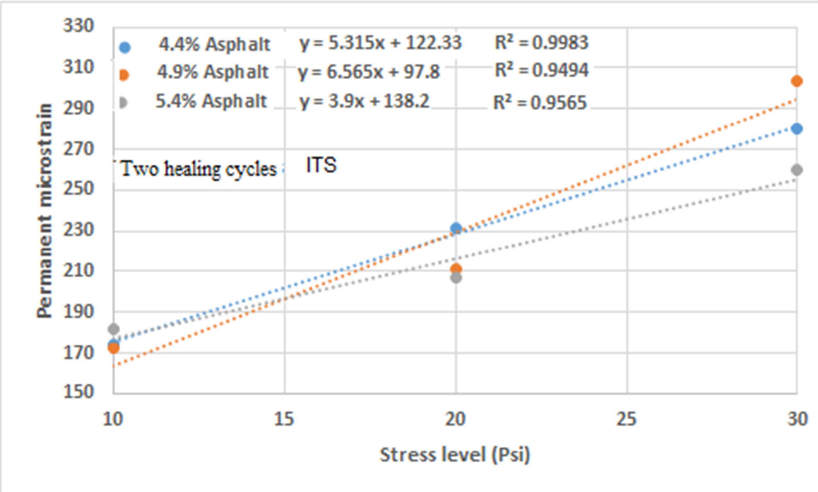

Fig. 6. *Impact of asphalt content on permanent strain after two healing cycles at ITS stress levels.*

Table 5. *Summary of permanent strain characteristics after 1000 loading cycles of (ITS).*

Asphalt content (%)	Repeated indirect tensile stress (ITS) after 1000 loading cycles					
	Micro crack healing cycles					
	Reference mix		One		Two	
	Intercept	Slope	Intercept	Slope	Intercept	Slope
4.4	85.3	9.34	117.4	5.56	122.3	5.31
4.9	81.9	9.84	101.7	6.15	97.8	6.56
5.4	98.3	7.63	104.9	5.90	138.2	3.90

3.2. Impact of Asphalt Content on Permanent Strain of Asphalt Concrete at PSS Stress Levels

As demonstrated in Fig. 7, the permanent strain gently increases as the stress level increase. For reference mixes under (PSS), the variation in permanent micro strain was not significant at high stress level of 30 Psi (207) kPa, while it increases as the stress level decrease. At 10 Psi (69) kPa, the strain ranges between (220 - 320) micro strains for various asphalt percentages.

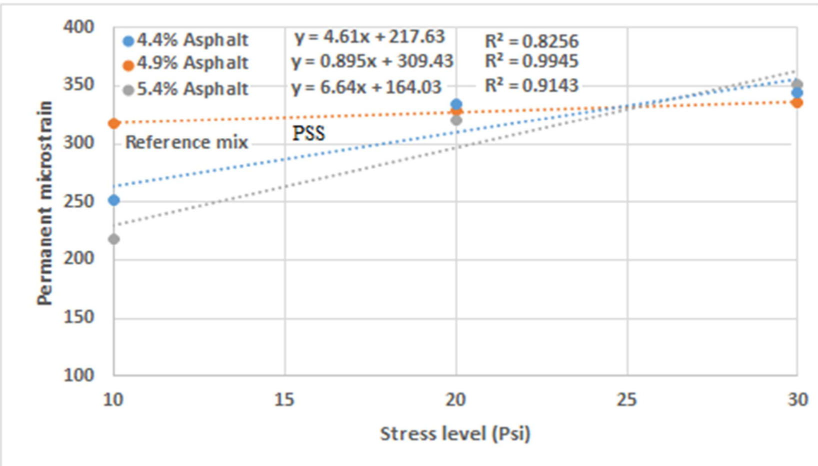

Fig. 7. *Impact of asphalt content on permanent strain for reference mix at PSS stress levels.*

Fig. 8 shows the impact of one healing cycle on the permanent strain, it can be observed that the impact of asphalt content was not significant at moderate stress level of 20 Psi (138) kPa. The slope was variable while the intercept values decrease when compared to reference mix. At 30 Psi (207) kPa stress level, the variation of permanent strain was in the range of (250-300) micro strain among various asphalt percentages. Similar finding was reported by [11].

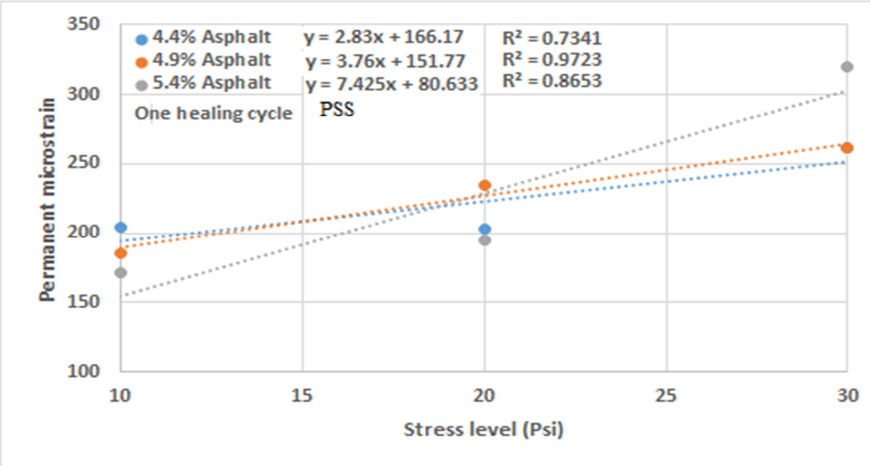

Fig. 8. *Impact of asphalt content on permanent strain after one healing cycle at PSS stress levels.*

Fig. 9 present the impact of two healing cycles on the permanent strain, it can be observed that the intercept also decreases while the slope is variable. The optimum asphalt content has retained the minimum slope variation and maximum intercept as compared to other asphalt percentages. It can be noted that crack healing cycles have positive influence on preventing the permanent strain. Table 6 summarizes the impact of asphalt content on permanent strain characteristics of asphalt concrete subjected to 1000 repeated (PSS) load.

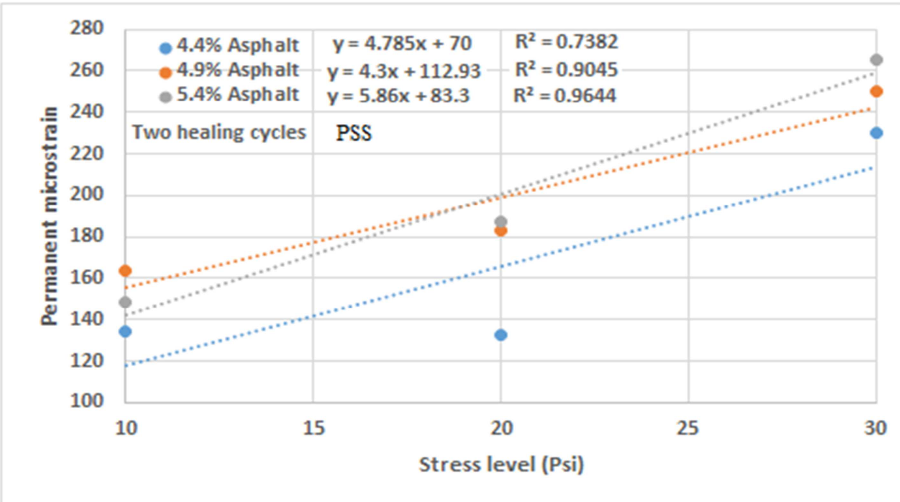

Fig. 9. *Impact of asphalt content on permanent strain after two healing cycles at PSS stress levels.*

Table 6. *Summary of permanent strain characteristics after 1000 loading cycles of (PSS).*

Asphalt content (%)	Repeated punching shear stress (PSS) after 1000 loading cycles					
	Micro crack healing cycles					
	Reference mix		One		Two	
	Intercept	Slope	Intercept	Slope	Intercept	Slope
4.4	217.6	4.61	166.1	2.83	70.0	4.78
4.9	309.4	0.89	151.7	3.76	112.9	4.30
5.4	164.0	6.64	80.6	7.42	83.3	5.86

3.3. Influence of ITS Stress Levels and Crack Healing on Permanent Strain

Fig. 10 illustrates the influence of ITS stress levels on permanent micro strain at various healing cycles, it can be observed that as the ITS stress level increases, the permanent strain increases in a range of (61 – 111)% for control mix. Similar trend could be noticed when healing cycles were introduced, the permanent strain increases in a range of (39 – 76)% and (22 - 76)% for one and two healing cycles respectively. On the other hand, after crack healing cycles, the permanent micro strain have been reduced by a range of (3 – 8)% as compared to that of reference mix at 10 Psi (69 kPa) stress level, while the reduction of permanent micro strain was in the range of (20 – 26)% and (23 – 19)% for 20 and 30 Psi (138 – 207 kPa) respectively. Such findings are in agreement with [12].

3.4. Influence of PSS Stress Levels and Crack Healing on Permanent Strain

Fig. 11 presents the influence of PSS stress levels on permanent micro strain at various healing cycles, it can be observed that for reference mix, as the PSS stress level increases, the permanent strain increases as well in a range of (3 – 5)%. After the specimens have experienced one healing cycle, the variation in permanent micro strain among various stress levels was in the range of (26 – 40)%. After two healing cycles, the variation in permanent micro strain among various stress levels was in the range of (11 – 52)%. On the other hand, after crack healing cycles, the permanent micro strain have dramatically been reduced by a range of (41 – 48)% as compared to that of reference mix at 10 Psi (69 kPa) stress level, while the reduction of permanent micro strain was in the range of (28 – 44)% and (22 – 25)% for 20 and 30 Psi (138 – 207 kPa) respectively.

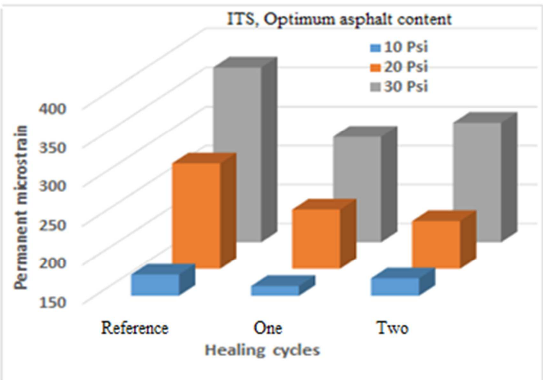

Fig. 10. *Influence of ITS stress level on healing.*

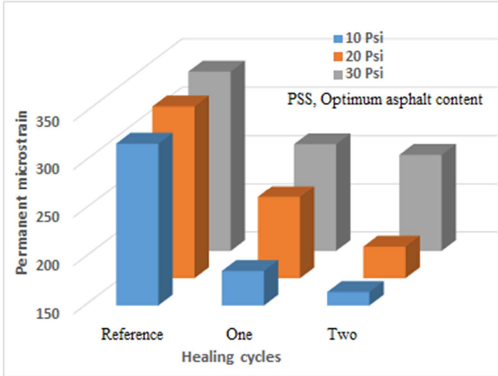

Fig. 11. *Influence of PSS stress level on healing.*

3.5. Influence of Crack Healing on Resilient Modulus (Mr) of Asphalt Concrete

Fig. 12 shows that the maximum resilient modulus could be achieved at optimum asphalt content for the repeated ITS test. The resilient modulus increases by a range of (25 - 42)% as the asphalt content rises from (4.4 - 4.9)%, while it decreases by a range of (63 - 78)% when asphalt content rises from (4.9 - 5.4)%. On the other hand, the crack healing cycles have a posative impact on the resilient modulus. One cycle of crack healing had increased (Mr) by 100%, while two healing cycles causes 400% increament in (Mr) as compared to reference mix with no healing cycles for mixes with 4.4% asphalt content. The posative impact of crack healing on (Mr) for mixes with optimum asphalt percentage was in the range of (75 – 366)% for one and two healing cycles respectivelt as compared to reference mix. At higher asphalt content of 5.4%, the posative impact of crack healing on (Mr) was in the range of (90 – 171)% for one and two healing cycles respectivelt as compared to reference mix. Such behaviour may be attributed to the fact that optimum asphalt content is capable for supporting the elastic and flexible properties of asphalt concrete, while lower or higher percentage of asphalt could support the stiffness and plastic properties of asphalt concrete respectively. Similar findings have been reported by [13].

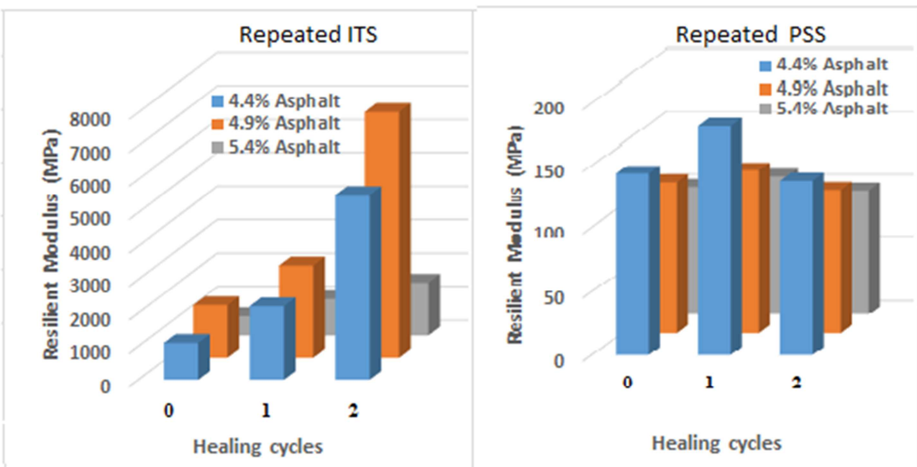

Fig. 12. *Influence of crack healing on resilient modulus.*

When the repeated PSS is considered, Fig. 12 demonstrates that the behaviour is different among asphalt content and healing cycles as compared to those of ITS case. As the asphalt content increases, the resilient modulus decreases. The maximum resilient modulus could be achieved at 0.5% asphalt lower than the optimum asphalt content for the repeated PSS test. The resilient modulus decreases by a range of (16 – 24)% as the asphalt content rises from (4.4 - 4.9)%, while it decreases by a range of (15 – 20)% when asphalt content rises from (4.9 - 5.4)%. On the other hand, the crack healing cycles have a posative impact on the resilient modulus. One cycle of crack healing had increased (Mr) by 11%, while two healing cycles causes 16% reduction in (Mr) as compared to reference mix with no healing cycles for mixes with 4.4% asphalt content. At optimum asphalt content, The posative impact of crack healing on (Mr) was 9%, for one healing cycle while it decreases by 7% after two healing cycles as compared to reference mix. At higher asphalt content of 5.4%, the posative impact of crack healing on (Mr) was 16% for one healing cycle while it decreases by 5% after two healing cycles as compared to reference mix. Such behaviour may be attributed the variation in the testing techniques and requirements of asphalt concrete to overcome the applied mode of stress. It complies to the fact that lower asphalt content is capable for supporting the stiffness property of asphalt concrete against compression load and shear stress, while higher percentage of asphalt could support the plastic properties of asphalt concrete which reduces the elastic property required.

4. Conclusions

Based on the testing program, the following conclusions could be drawn:

(1) Crack healing cycles have a positive impact on the resilient modulus. One cycle of crack healing had increased (Mr) by 100%, while two healing cycles causes 400% increment in (Mr) as compared to reference mix under ITS.

(2) One cycle of crack healing had increased (Mr) by 11%, while two healing cycles causes 16% reduction in (Mr) as compared to reference mix under PSS.

(3) After crack healing cycles, the permanent micro strain have dramatically been reduced by a range of (41 – 48)%, (28 – 44)% and (22 – 25)% for 10 Psi (69 kPa), 20 and 30 Psi (138 – 207 kPa) respectively as compared to that of reference mix under PSS.

(4) After crack healing cycles, the permanent micro strain have been reduced by a range of (3 –8)%, (20 – 26)% and (23 – 19)% for 10 Psi (69 kPa), 20 and 30 Psi (138 – 207 kPa) respectively as compared to that of reference mix under ITS.

(5) The impact of stress level on permanent strain is more pronounced under tensile stress as compared to that under shear stress for control mix.

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