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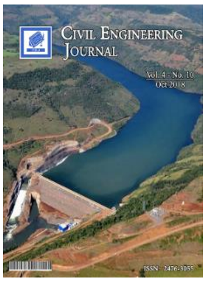

Deformation and Resilient Behavior of Hot and Warm Mix Asphalt Concrete

Zainalabidine Nihad [a*], Saad Issa Sarsam [b]

[a] *MSc. Student , Department of Civil Engineering, College of Engineering/University of Baghdad, Iraq.*

[b] *Professor and Head, Department of Civil Engineering, College of Engineering/University of Baghdad, Iraq.*

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Abstract

Development of hazardous gases emissions through the production and construction of Hot Mix Asphalt (HMA) have encouraged the transition to Warm Mix Asphalt (WMA) which is considered as one of the best choices of sustainable materials in asphalt pavement. The temperature reduction in the mixing, handling, and compaction of the mix gets in saving energy, cutting emissions and significant cuts in construction costs. In this investigation, two WMA mixtures have been prepared in the laboratory using medium curing cutback (MC-30) and cationic emulsion asphalt. HMA mixture was also prepared for comparison. Marshall size Specimens of (101.6 mm) in diameter and (63.5 mm) in height were constructed from these mixtures and subjected to repeated Indirect Tensile Strength test (ITS) to determine the effect of asphalt type and content on deformation and resilient behavior of asphalt mixture. Another group of cylindrical specimens of (101.6 mm) diameter and (101.6 mm) in height have been constructed from these mixtures and subjected to repeated compressive stresses test to determine the rutting resistance of asphalt mixture. Test results were analyzed and compared. It was concluded that, the permanent deformations for cutback and emulsion treated WMA was higher than that of HMA by (50 and 35) % respectively. The Resilient Modulus (Mr) at 25^{0} C under repeated (ITS) for cutback and emulsion treated WMA was lower than that of HMA by (39.95 and 27.94) % respectively. On the other hand, the (Mr) for cutback and emulsion treated WMA was higher than that of HMA by (43.75 and 5.47) % respectively under repeated compression load at stress level 0.138 (MPa).

Keywords: Warm Mix; Emulsion; Cutback; Indirect Tensile Strength; Rutting Resistance; Resilient Modulus.

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1. Introduction

The general expression of WMA refers to the variety of mixtures which are produced at temperatures (20-30 °C) less than the typical production temperature for HMA. The lower temperature of the WMA offers sustainable and environmentally friendly mixture as compared with HMA by reducing the fuel consumption and greenhouse gas emission [1]. The fundamental concept of the WMA is to decrease the mixing and compaction temperatures of the mixture through reduction of viscosity of the asphalt binder. WMA principally does not differ from HMA. It still includes of asphalt binder, aggregates, filler and liquid asphalt, however, the difference precisely lies in the temperature applied to obtain appropriate mixing and workability [2]. The low production and paving temperature of WMA significantly reduce the emissions and fumes, [3]. Every 11^{0}C decrease in mixing temperature causes the emissions in the atmosphere, decreasing to half [4], this is a fundamental decline in the carbon footprint of the asphalt production plant taking into consideration the existing equipment can still be used, [5]. The energy consumption of WMA production is typically (60-80) % lower than HMA production, [6]. Lower production temperatures can also potentially

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[*] Corresponding author: zainalabidine.civil@outlook.com

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improve pavement performance by reducing binder aging, providing added time for mixture compaction, and allowing improved compaction during the cold weather paving, [7]. The low viscosity of liquid asphalt will improve the coating of aggregates [8], while the curing period will provide the increment in mechanical strength, and durability during traffic exposure, [9] and [10]. WMA's disadvantages addressed by Esenwa et al. (2011) and Rashwan (2012) are mainly related to the potential to reduce material durability, and it has potential for rutting and moisture susceptibility issues [11, 12]. WMA has a higher degree of compaction, which provides better workability of compaction compared to HMA mixture and the WMA mixture has a lower (Mr) than HMA mixture which could suggest that WMA mixture is more susceptible to rutting [13, 14]. The resistance of the WMA-emulsified asphalt to rutting is quite remarkably less than their counterpart the HMA. Moreover, this resistance is significantly decreased by reducing the compaction temperature. Emulsified asphalt reduces the cohesive tensile strength of the binder because of the reduction in the binder surface tension and work of cohesion [15]. López et al. (2017) studied determine the laboratory performance of field-produced mixtures which used the WMA to evaluate the effect of lowering production temperature on the mixture characteristics in the field and find there was no difference in the rutting performance of WMA compared with HMA [9]. The WMA decreases the extent of oxidative aging in bitumen mixture and increase the susceptibility of mixture to rutting [16]. Bhargava et al. (2018) and Sebaaly et al. (2015) have been determined the effect of aging and stated the aging increases resistance to permanent deformation of the WMA and stress levels is vital in assessing the permanent deformation of asphalt mixture. The reduction in the stiffness of WMA when compared to a conventional HMA mixture increases the potential of permanent deformation during the initial service life [17, 18]. However, field assessment in terms of rutting has shown performance of WMA technology comparable to HMA [19]. A recent study by Sarsam (2018) had concluded that HMA specimen can sustain more than 100% of load repetitions to failure higher as compared to WMA, On the other hand, the tensile strain of WMA with cutback and emulsion was (37.5 and 54) % lower than that of HMA respectively. A sharp reduction in the stiffness rate could be noticed for WMA mix with cutback as compared to the gentle reduction in the case of WMA mix of emulsion and HMA [20].

The goal of this investigation is to evaluate the influence of implementing medium curing cutback (MC-30) and cationic emulsion as a binder on the deformation and resilient behavior of WMA under repeated (ITS) and rutting resistance of the WMA.

2. The Research Methodology

This research methodology was divided into four stages, the first stage will cover obtaining the properties of raw materials includes aggregate and liquid asphalt (cationic emulsions and medium curing cutback asphalt). The second stage includes the design of the warm mix using the available materials and obtaining the design asphalt content of each case. The third stage includes the measurement of permanent deformation and resilient modulus of the mixtures under repeated indirect tensile stresses, while the fourth stage was concerned with rutting resistance and resilient modulus determination under repeated compressive stresses.

3. Materials and Methods

3.1. Asphalt Cement

The Asphalt Cement of (40-50), penetration grade was obtained from Al-Dura Refinery and used for HMA specimens. Table 1 presents the physical characteristics of asphalt cement.

Table 1. Physical characteristics of asphalt cement

Test	Result	SCRB Specification Limits [21]	ASTM Specification No. [22]
Penetration (25^{0}C, 100(gm.) and 5sec)	43 (0.1 mm)	40 - 50	D-5
Ductility, (25 ^{0}C and 5cm/minute),	164 (cm)	≥ 100	D-113
Softening point, (ring and ball)	49 ^{o}C	—	D-36
Absolute Viscosity @ 60 ^{0}C	2150 (Poise)	—	D-2171
After Thin-Film Oven Test			
Retained penetration, of original, (%)	67.4 (1/10 mm)	—	D-5
Ductility (25^{0}C and 5cm/minute)	96 cm	—	D-113

3.2. Cutback Asphalt

Medium Curing cutback asphalt (MC-30) was used as a binder for WMA production. It was obtained from AL-Dura Refinery. Tests implemented on the cutback asphalt complies with ASTM [22]. Table 2 presents the cutback characteristics as supplied by the refinery.

3.3. Emulsified Asphalt

Cationic emulsified asphalt was used as a binder for WMA production, it was brought from state company for the mining industries. Test implemented on the emulsified asphalt complies with ASTM [22]. Table 3 presents the characteristics of emulsion as supplied by the producer.

Table 2. Physical characteristics of cutback asphalt

Test	Results	limits of Specification [22]		ASTM Designation [22]
Flash Point	38	38	—	D-3143
Water % V (max)	0.2	—	0.2	D-95
Viscosity @ 60°C	40	30	60	D2170
Test on Residue from Distillation				
Penetration, (25°C, 100 gm. , 5 sec and (1/10) mm)	150	120	250	D-2027
Solubility in Trichloro Ethylene % wt. (min)	99	99	—	D-2027
Ductility (25 °C)	100	100	—	D-2027

Table 3. Physical characteristics of cationic emulsified asphalt

Test	ASTM Designation No. [22]	Results	Specification Limits [22]	
			Min.	Max.
Particle Charge Test	D-244	positive	positive	—
Storage Stability Test, 24 h (%)		0	—	1
Viscosity Say bolt Furl at (50 °C)	D-245	260	50	450
Coating Stability and Water Resistant				
Coating-Dry Aggregate	—	Good	Good	—
Coating-After Spraying	—	Fair	Fair	—
Oil Distillate by Volume of Emulsion (%)	—	89	65	—
Sieve Test (%)	D-6933	0	—	0.1

3.4. Coarse and Fine Aggregates

The coarse aggregates (crushed) which retained on the sieve No.4 were brought from AL-Nibaee quarry. Such aggregates are widely used in Baghdad city for asphalt concrete mixture. Crushed sand and natural sand was used as fine aggregate (passing sieve No.4 and retained on sieve No. 200). It consists of tough grains, hard, free from loam and other deleterious materials. The aggregates were tested for physical properties and Table 4 presents the test results.

Table 4. Physical characteristics of fine and coarse aggregates

Laboratory Test	ASTM, [22] Designation No.	Test Results
Coarse Aggregate		
Apparent Specific Gravity	C-127	2.642
Bulk Specific Gravity		2.61
Water Absorption, (%)		1.471
AC (40-50) Absorption, (%)	D4471	0.4
Emulsion Absorption, (%)	D4469	1
Cutback Absorption, (%)	D-4470	0.6
Los Angeles Abrasion, (%)	C-131	19
Fine Aggregate		
Apparent Specific Gravity	C-128	2.683
Bulk Specific Gravity		2.631
Water Absorption, (%)		3.734
AC (40-50) Absorption, (%)	D-4471	0.6
Emulsion Asphalt Absorption, (%)	D-4469	1.4
Cutback Asphalt Absorption, (%)	D-4470	0.9

3.5. Mineral Filler

The mineral filler utilized in this investigation is Portland cement, it was produced by Al-Mas Company and obtained from the market. The physical characteristics of the mineral filler are listed in the Table 5.

Table 5. Physical properties of Portland cement

Property	Test result	Requirements [21]
% Passing Sieve No.200	98	95
Bulk Specific Gravity	3.1	—
Fineness by Blaine (m^2/kg)	312.5	≥ 230

3.6. Selection of Aggregates Gradation

Selection of the aggregates in this investigation is following SCRB, [21] for binder course with nominal maximum size of aggregate of 19 (mm). Figure 1 presents the selected aggregates gradation for binder course.

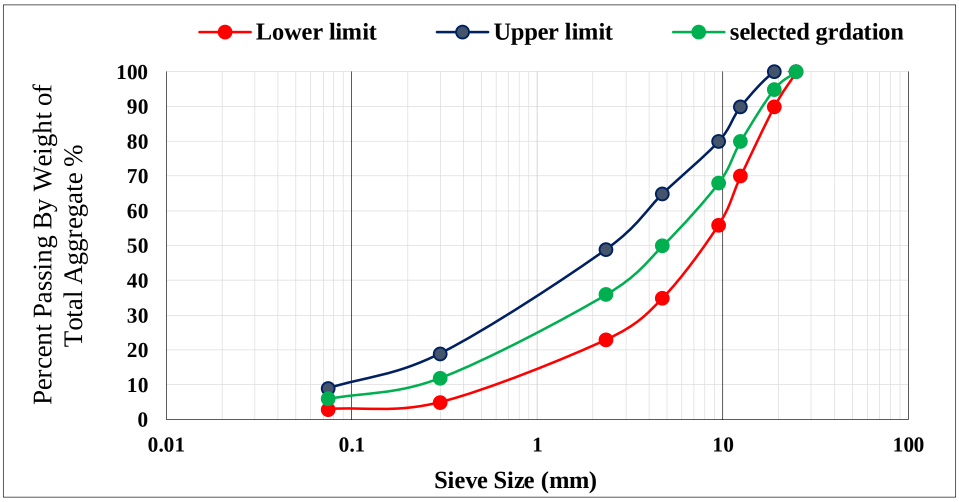

Figure 1. Gradation of the aggregates for binder course layer according to SCRB, [21]

4. Preparation of WMA

The virgin aggregates were sieved and separated to different sizes then combined to reach the specified gradation for the binder course layer according to SCRB [21]. The combined aggregates were heated to (110 ^{0}C), before mixing with (emulsion or cutback asphalt), then the optimum requirement of liquid asphalt at 20°C was added to the preheated aggregate to reach the desired amount of asphalt content and mixed thoroughly by hand for (2-3) minutes until all aggregates were coated with asphalt. Mixtures with 0.5 % of liquid asphalt above and below the optimum have also been prepared to verify the impact of asphalt content on the indirect tensile strength and rutting resistance. The procedure of obtaining the Optimum Asphalt Content (OAC) and the volumetric properties was published elsewhere, [23]. The Marshall Specimens were subjected to 75 blows on each side of the specimen as per [22] while the cylindrical specimens of (101.6 mm) diameter and (101.6 mm) in height were subjected to static compaction to the target density. The compaction temperature was maintained to 100^{0}C. In case of cutback asphalt mixtures, specimens were collapsed after removal from the mold, then it was decided to use the Short-Term Aging (STA) technique as recommended by AASHTO TP4 and cited by [24]. The specimens were removed from a mold after 24 hours. Figure 2 shows group of the prepared Marshall Size specimens.

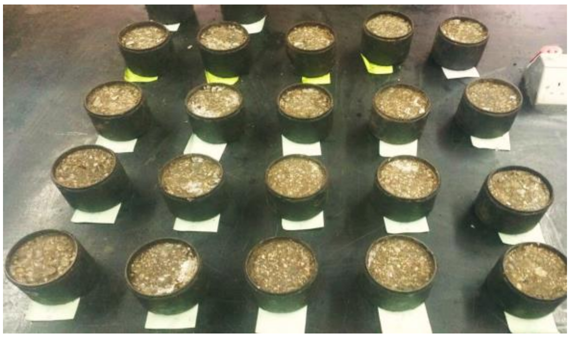

Figure 2. Group of the prepared Marshall specimens

5. Preparation of HMA

The virgin aggregates and filler were sieved and combined to meet the specified gradation for binder course layer, [21]. The combined aggregates, were heated to (160 °C), while the bitumen was heated to a temperature (150°C) to produce the kinematic viscosity of (170 ± 20 centistokes), then the desired amount of asphalt was added to a preheated aggregate. The asphalt and the aggregate were mixed in the mixing bowl by hand on the hot plate for (3-4) minutes until asphalt had adequately coated the surface of the aggregate, while the mixing temperature was maintained to 145°C. The specimens were compacted with Marshall Hammer using 75 blows on each side according to [22] while the cylindrical specimens of (101.6 mm) in diameter and height were subjected to static compaction to the target density. The samples were removed from the mold after 24 hours. Mixtures with 0.5 % of asphalt cement above and below the optimum requirement have also been prepared to verify the impact of asphalt content on the indirect tensile strength and rutting resistance.

6. Short-Term Aging (STA)

The loose mixture of cutback-aggregate was placed in the pan and spread to a thickness ranging among (25-50) mm, the asphalt mixture in the pan was put in the conditioning oven for 4 hours ± 5 minutes at 135±3°C and the mixture was stirred every 1 hours throughout the short term aging (STA) process to obtain a homogeneous aging. At the end of the aging period, the mixture was cooled to the compaction temperature of 100°C and poured into the mold and subjected to 75 blows on each side of the specimen with Marshall Hammer, while the cylindrical specimens of (101.6 mm) in diameter and height were subjected to static compaction to the target density. This procedure was implemented as recommended by AASHTO TP4 as cited by [24].

7. Indirect Tensile Strength under Repeated Load Test (ITS)

The (ITS) test under repeated load was performed according to the procedure of [14] by utilizing the Pneumatic Repeated Load system (PRLS). Marshall Samples were utilized in this test. The specimen was centred among two parallel loading strips on a vertical diametrical plane, stainless steel loading strip on the top and bottom, running parallel to the axis of the cylindrical sample. In this test method, the repeated load was applied to the diametral sample and the resilient vertical strain is quantified. The diametral loading was applied with the constant loading rate (60 cycles/min.). The load sequence of every cycle by (1/10 second) period of load and of (9/10 second) rest duration for simulating the field conditions according to Shell procedure as cited by [25]. This test was performed at a stress level of (0.138 MPa). The sample was stored in the testing chamber for (2 hours) in order to allow for uniform distribution of temperature within the sample. The video camera was placed in a suitable place to cover the view and capture the dial gauge reading. The test was completed after 1200 load repetitions or when the sample fractures. During the test, the permanent deformation and total deformation were recorded every 10 seconds until 20 minutes or when the specimen fractures. The permanent microstrain was measured according to of the following equation:

$$\mathcal{E}\text{p} = \frac{\text{Pd} \times 10^6}{h} \tag{1}$$

Where:

$\mathcal{E}_\text{p}$ = Permanent strain (microstrain)

h= Specimen height (mm)

Pd = Permanent axial deformation

Resilient axial strain was measured as per of the following relation;

$$\mathcal{E}\text{r} = \frac{\Delta\text{r}}{\text{h}} \tag{2}$$

Where:

$\mathcal{E}_r$ = axial resilient strain (microstrain)

Δr, L = low deformation reading (permanent deformation)

Δr = axial resilient deformation = (Δr, H –Δr, L)

h= Specimen height (mm)

Δr, H = high deformation reading (total deformation)

Resilient Modulus (Mr) is the important property for mechanistic design approaches of paving structure. The (Mr) is the ratio of an applied stress to the recoverable strain when the applied stress has been removed. It is an elastic modulus which quantifies of the materials responses to the applied load and deformation. In general, higher modulus refers to greater resistance to deformation. The (Mr) is quantified by following the [22], ASTM (D-4123). The Mr is calculated by the following equation:

$$\text{Mr} = \frac{\sigma}{\mathcal{E}\text{r}} \tag{3}$$

Where:

Mr= Resilient modulus (MPa)

ε_r = axial resilient strain (mm/mm)

σ = repeated axial stress (MPa)

The following classical power model was performed in this study [26], [27]:

$$\varepsilon p = aN^{b} \tag{4}$$

Where:

ε_p = Permanent Deformation in Microstrain

b = Slope of the Deformation

a = Intercept with the Deformation in Microstrain

N = No. of Repetitions at the end of the Test

Parameters (b and a) are the slope and intercept respectively of the permanent microstrain curve in the log-log scale, intercept signifies to the permanent microstrain at the number of repetitions equal to one. The higher value of (a) signifies to the higher strain, therefore, the higher potential for permanent microstrain [28]. The slope signifies to the rate of change in permanent microstrain as a function of change in the cycles of load at log-log scale. The high slope for the mixture refer to an increase in the rate of deformation, therefore, less resistance to permanent deformation. The mixture which has the lower slope is recommended as it provides the occurrence the permanent deformation at a slower rate [29]. Coefficients for permanent deformation α "Alpha" and μ "Mu" are calculated using the following relationships [27]:

$$\mu = \frac{a \times b}{\varepsilon r} \tag{5}$$

$$\alpha = 1 - b \tag{6}$$

Where:

μ = parameter of permanent microstrain refer to the constant of proportionality among permanent strain and resilient strain.

α = parameter of permanent microstrain refer to the ratio of decreases in the incremental permanent microstrain as the number of load repetitions increases.

Figure 3 shows test setup of the specimen under repeated (ITS) and the mode of failure, while Figure 4 exhibits the pneumatic repeated load system and specimen.

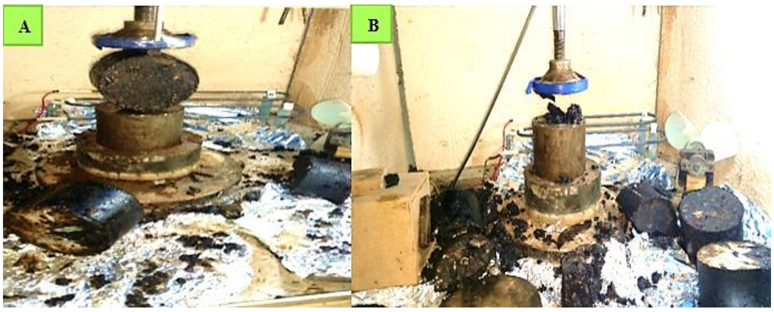

Figure 3. A: Repeated ITS setup, B: Specimen after fracture

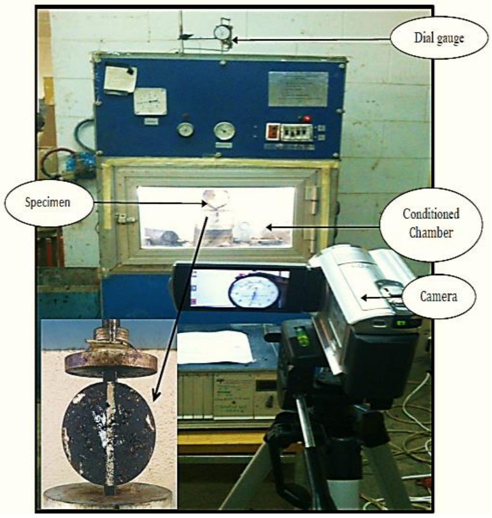

Figure 4. The pneumatic repeated load system and specimen [30]

8. Rutting Resistance Test

This test was conducted to describe the rutting performance of the mixtures by relating the permanent and resilient axial strain to the number of load repetition. Also, to evaluate the effect of mixing variables and loading conditions on rutting of mixture. The (PRLS) was utilized in this test to quantify the vertical displacement in the sample through the repeated compressive load testing. For each specimen the number of load repetitions was plotted against the permanent microstrain in log-log scale to show the effect of each variable on the determination of the plastic strain [31]. This test was performed at three levels of stress (0.069, 0.138 and 0.207 MPa), repeated compressive loading was continued to 1200 cycles or when the specimen fractured. The loading rate is 60 cycles/min. for load period of (1/10 second) and the resting duration of (9/10) second for simulating the field conditions [32]. Figure 5 shows the specimen under repeated compressive load test and the mode of failure.

Figure 5. A: Specimen under repeated load test, B: Specimen after fracture

9. Results and Discussion

9.1. Effect of Asphalt Type and Content on Deformation Behavior under Repeated ITS

The high permanent deformation is related to increase of asphalt content, as presents in Table 6 and Figure 6.

Table 6. Effect of asphalt type and content on deformation under repeated (ITS) at stress level (0.138 MPa) and 25°C

Asphalt content %	HMA	WMA- Cutback	WMA- Emulsion
	Permanent microstrain	Permanent microstrain	Permanent microstrain
OAC–0.5	4120	10400	6000
OAC	4000	6000	5400
OAC+0.5	4700	11600	5800

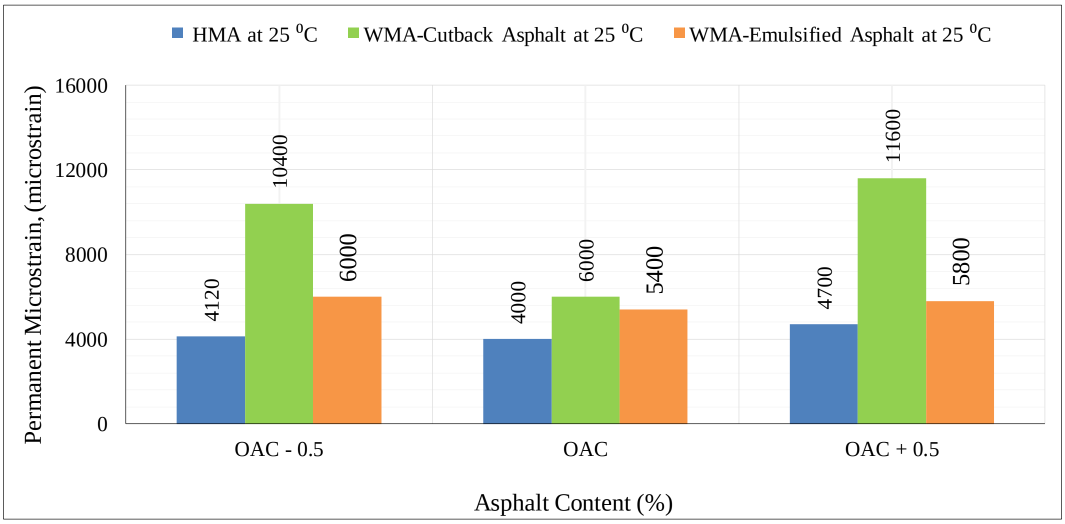

Figure 6. Effect of asphalt type and content on deformation under repeated (ITS) at stress level (0.138 MPa) and 25°C

The results of HMA presents that, the permanent deformation was increased by (17.5 and 3) % when the asphalt content increased and decrease by 0.5 % from (OAC) respectively, this behavior of materials conform to the results of [33]. The results of WMA-cutback asphalt presents that the permanent deformation was increased by (93.33 and 73.33) % when the asphalt content increased and decreased by 0.5 % from (OAC) respectively. The results of WMA-emulsified asphalt show that the permanent deformation was increased by (7.41 and 11.11) % when the asphalt content increased and decreased by 0.5 % from (OAC) respectively, this behavior of materials conform with the results of [34]. The WMA-cutback asphalt has higher permanent deformation as compared to other mixtures. This may be attributed to the fact that the STA is not sufficient to make the mixture stiff enough which makes the sliding of aggregate particles easier. Therefore, causes increasing in the deformation of the pavement material.

9.2. Effect of Asphalt Type and Content on Resilient Modulus Behavior under Repeated ITS

Based on the results, it appears that the examined impacts of asphalt type and content on (ITS) have an effect on the plastic responses of materials, as shown in Table 7 and Figure 7.

Table 7. Effect of asphalt type and content on resilient modulus under repeated (ITS) at stress level (0.138 MPa) and 25°C

Asphalt content %	HMA	WMA-Cutback Asphalt	WMA-Emulsified Asphalt
	Resilient Modulus (MPa)	Resilient Modulus (MPa)	Resilient Modulus (MPa)
OAC-0.5	363	164	115
OAC	383	230	276
OAC+0.5	276	86	138

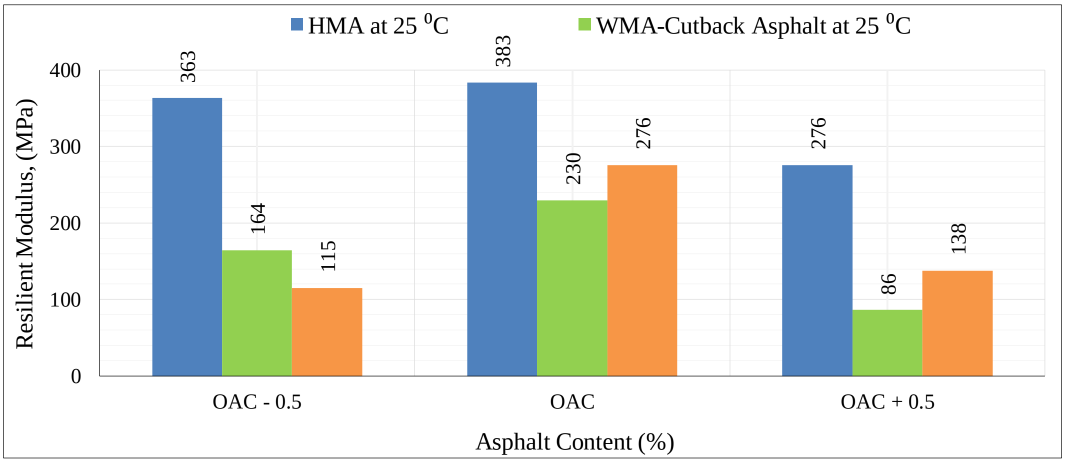

Figure 7. Effect of asphalt type and content on resilient modulus under repeated (ITS) at stress level (0.138 MPa) and 25°C

The (Mr) decreased by (28 and 5.26) % when the asphalt content increased and decreased by 0.5 % from (OAC) respectively, this behaviour of materials conform to the results of [33]. The results of WMA-cutback asphalt presents that, the (Mr) was decreased by (62.5 and 28.57) % when the asphalt content increased and decreased by 0.5 % from (OAC) respectively. The results of WMA-emulsified asphalt shows that, the (Mr) was decreased by (50 and 58.33) % when the bitumen content increased and decreased by 0.5 % from (OAC) respectively, this behaviour of materials conform to the results of [35]. The WMA has lower Mr Values as compared to HMA. This could be attributed to the lower viscosity of the binders and higher volatile content. The excess voids after evaporation of such volatiles caused reduction of Mr for WMA as compared to that of HMA. The higher asphalt content decreases the Mr because the excess asphalt will decrease the inter particle connection, producing more lubrication action which decreases the Mr [33].

9.3. Effect of Asphalt Type and Content on Deformation Behavior under Repeated Compressive Stress

The high permanent deformation is related to increase of asphalt content as presented in Table 8 and Figure 8. The results of HMA at 0.069 (MPa) shows that the permanent deformation was increased by (60 and 50) % when the asphalt content increased and decreased by 0.5 % from (OAC) respectively, this behavior of materials conform with the results of [36]. The results of WMA-cutback asphalt shows that, the permanent deformation increased by 18.5% when the asphalt content decreased by 0.5 % from (OAC), while when the asphalt content increased by 0.5 % from (OAC), specimen was fractured. The results of WMA-emulsified asphalt presents that, the permanent deformation was increased by (9.8 and 1.96) % when the asphalt content increased and decreased by 0.5 % from (OAC) respectively, this behavior of materials conform to the results of [16]. The results of HMA at 0.138 (MPa) presents that, the permanent deformation was increased by (41.67 and 29.17) % when the asphalt content increased and decreased by 0.5 % from (OAC) respectively, this behavior of materials conform to the results of [37]. The results of WMA-cutback asphalt presents that, the permanent deformation equal 15250 microstrain at (OAC) and when asphalt content increased and decreased by 0.5 % from (OAC) respectively specimen was fractured, such behavior of materials comply with the findings of [38, 39].

Table 8. Effect of asphalt type and content in deformation behavior under repeated compressive strength at different levels of stress

	Asphalt content %	OAC-0.5	OAC	OAC+0.5
HMA	Permanent Microstrain at (0.069 MPa)	1875	1250	2000
	Permanent Microstrain at (0.138 MPa)	3875	3000	4250
	Permanent Microstrain at (0.207 MPa)	12750	9125	15750
WMA-Cutback Asphalt	Permanent Microstrain at (0.069 MPa)	8000	6750	0
	Permanent Microstrain at (0.138 MPa)	0	15250	0
	Permanent Microstrain at (0.207 MPa)	0	18250	0
WMA-Emulsified Asphalt	Permanent Microstrain at (0.069 MPa)	3250	3188	3500
	Permanent Microstrain at (0.138 MPa)	11000	4000	4313
	Permanent Microstrain at (0.207 MPa)	0	10500	19250

The results of HMA at 0.207 (MPa) presents that, the permanent deformation was increased by (72.60 and 39.73) % when the asphalt content increased and decreased by 0.5 % from (OAC) respectively, this behaviour of materials conform to the results of [40]. The results of WMA-cutback asphalt shows that the permanent deformation equals 18250 microstrain at (OAC) and when asphalt content increased and decreased by 0.5 % from (OAC) respectively, specimens were fractured. The results of WMA-emulsified asphalt presents that, the permanent deformation was increased by 83.33 % when asphalt content increased by 0.5 % from (OAC) and when asphalt content decreased by 0.5 % from (OAC) the specimen was fractured, this behaviour of materials conforms to the results of [41 and 42].

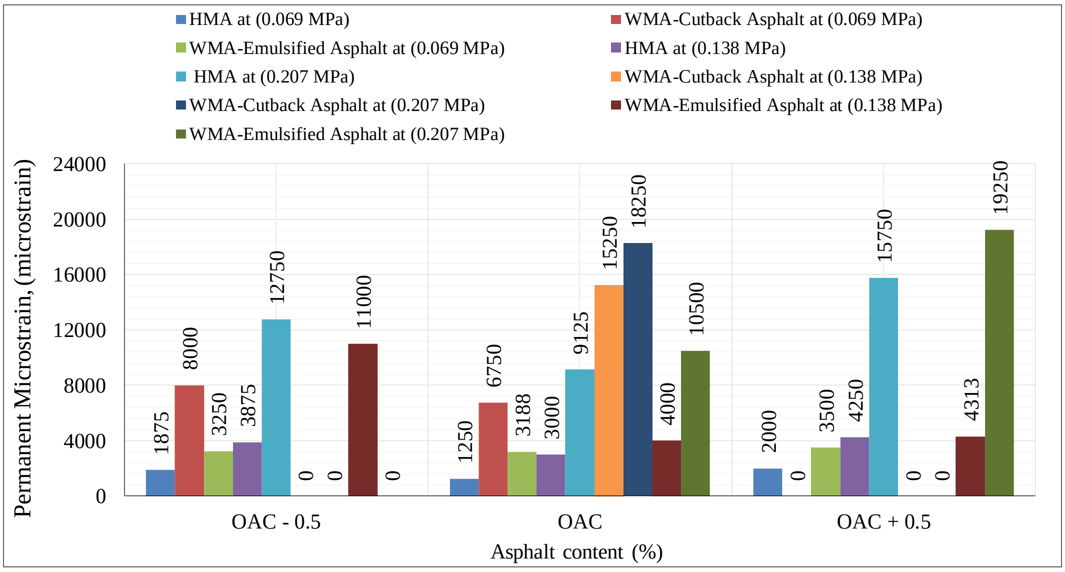

Figure 8. Impact of asphalt type and content on the deformation behavior under repeated compressive strength

9.4. Impact of Asphalt Type and Content on Resilient Modulus Behavior under Repeated Compressive Stress

The high Mr is related to increase of asphalt content as presents in Table 9 and Figure 9.

Table 9. Effect of asphalt type and content in resilient modulus behavior under repeated compressive strength at different levels of stress

	Asphalt content %	OAC-0.5	OAC	OAC+0.5
HMA	Resilient Modulus (MPa) at (0.069 MPa)	98	120	92
	Resilient Modulus (MPa) at (0.138 MPa)	85	128	82
	Resilient Modulus (MPa) at (0.207 MPa)	59	83	45
WMA-Cutback Asphalt	Resilient Modulus (MPa) at (0.069 MPa)	81	162	0
	Resilient Modulus (MPa) at (0.138 MPa)	0	184	0
	Resilient Modulus (MPa) at (0.207 MPa)	0	127	0
WMA-Emulsified Asphalt	Resilient Modulus (MPa) at (0.069 MPa)	98	125	100
	Resilient Modulus (MPa) at (0.138 MPa)	75	135	96
	Resilient Modulus (MPa) at (0.207 MPa)	0	118	83

The results of HMA at 0.069 (MPa) presents the Mr was decreased by (23.33 and 17.92) % when the asphalt content increased and decreased by 0.5 % from (OAC) respectively. The results of WMA-cutback asphalt presents that the Mr decreased by 49.93 % when the asphalt content decreased by 0.5 % from (OAC) and when asphalt content increased by 0.5 % from (OAC) specimen was fractured. The results of WMA-emulsified asphalt presents that, the Mr was decreased by (19.77 and 21.20) % when the asphalt content increased and decreased by 0.5 % from (OAC) respectively.

The results of HMA at 0.138 (MPa) presents that, the (Mr) was decreased by (35.94 and 33.59) % when the asphalt content increased and decreased by 0.5 % from (OAC) respectively. The results of WMA-cutback asphalt presents that, the (Mr) equal to 184 (MPa) and when asphalt content increased and decreased by 0.5 % from OAC respectively, specimens was fractured. The results of WMA-emulsified asphalt presents that, (Mr) was decreased by (28.89 and 44.44) % when the asphalt content raised and decreased by 0.5 % from OAC respectively.

The results of HMA at 0.207 (MPa) presents the Mr was decreased by (45.61 and 28.69) % when the asphalt content increased and decreased by 0.5 % from OAC respectively. The results of WMA-cutback asphalt presents the (Mr) equal to 127 (MPa) and when asphalt content increased and decreased by 0.5 % from OAC respectively, specimens was fractured. The results of WMA-emulsified asphalt presents the (Mr) decreased by 29.78% when the asphalt content increased by 0.5 % from OAC and when bitumen content decreased by 0.5 % from OAC, specimens were fractured.

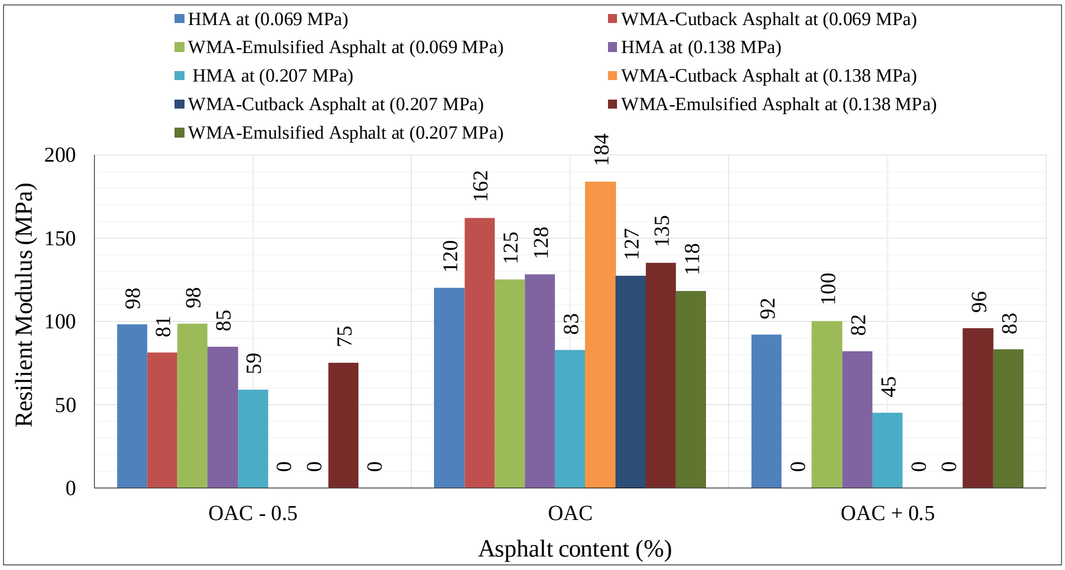

Figure 9. Effect of asphalt type and content in resilient modulus behavior under repeated compressive strength

10. Effect of Stress Level

The development of permanent deformation strongly depends on the stress level. Three stress levels were used in this study, 0.069, 0.138 and 0.207 (MPa). Tables 10 and 11 shows the variation of resilient modulus, permanent microstrain, resilient microstrain and total microstrain as well as permanent deformation parameters (intercept and slope).

Table 10. Resilient modulus, resilient microstrain, permanent microstrain, total microstrain, intercept and slope at OAC under different levels of stress

Mixture Type	HMA			WMA-Cutback Asphalt			WMA-Emulsified Asphalt		
Parameters	**Stress level (MPa)**			**Stress level (MPa)**			**Stress level (MPa)**		
	0.069	0.138	0.207	0.069	0.138	0.207	0.069	0.138	0.207
Resilient modulus (MPa)	120	128	83	162	184	127	125	135	118
Resilient microstrain	750	1100	4875	875	2750	5250	313	500	4750
Permanent microstrain	1250	3000	9125	6750	15250	18250	3188	4000	10500
Total microstrain	2000	4100	14000	7625	18000	23500	3500	4500	15250
Intercept (a)	37.1	50.9	303.5	302.9	108.2	125.7	496.2	350.8	387.2
Slope (b)	0.476	0.532	0.460	0.636	0.885	1.040	0.277	0.299	0.441

Table 11. Variation (%) of resilient modulus, resilient strain, permanent microstrain, total microstrain, intercept and slope for different mixtures at OAC

Parameters	Variation (%) between HMA and WMA-Cutback Asphalt			Variation (%) between HMA and WMA-Emulsified Asphalt		
	Stress level (MPa)			Stress level (MPa)		
	0.069	0.138	0.207	0.069	0.138	0.207
Resilient modulus (MPa)*	-35.3	-43.3	-53.8	-4.5	-4.9	-42.9
Resilient microstrain*	-16.7	-150.0	-7.7	58.3	54.5	2.6
Permanent microstrain *	-440.0	-408.3	-100.0	-155.0	-33.3	-15.1
Total microstrain *	-281.3	-339.0	-67.9	-75.0	-9.8	-8.9
Intercept (a)*	-715.5	-112.4	58.6	-1236.2	-588.6	-27.6
Slope (b)*	-33.5	-66.3	-126.1	41.9	43.8	4.1

*(-) refer to increases value (%)

From the data presented in Table 10, the increase in the stress level will decrease the value of (Mr) and it will increase the permanent microstrain, resilient microstrain and total microstrain by different percentage, such behavior of the materials complies with the findings of [37] for HMA. The higher (Mr) could be achieved in the stress level at 0.138 (MPa) at the (OAC). This is attributed to the requirement of asphalt, which must be sufficient to bind the aggregates under the moderate traffic loading which represented by the stress level at 0.138 (MPa). The higher level of stress at 0.207 (MPa) will possess additional tensile stresses which the mixture is unable to accommodate moreover, lower level stress at 0.069 (MPa) will not be adequate for bitumen to show real (Mr) property, such behavior of materials comply with the findings of [33, 37].

11. Conclusions

Based on limitations of materials and test conditions, the conclusions could be addressed as follows:

- The WMA has less resistance to permanent deformation than HMA under repeated (ITS) at stress level 0.138 (MPa), 25 ^{0}C and the (OAC). The permanent deformations were (6000 and 5400) microstrain for WMA-cutback asphalt and WMA-emulsified asphalt respectively. Both were higher than HMA by (50 and 35) % respectively.
- The WMA has less (Mr) than HMA under repeated (ITS) at stress level 0.138 (MPa) and (OAC). The (Mr) at 25 ^{0} C under repeated (ITS) are (230 and 276) MPa for WMA-cutback asphalt and WMA-emulsified asphalt respectively. Both were lower than HMA by (39.95 and 27.94) % respectively.
- The WMA has higher (Mr) than HMA under repeated compression load at stress level 0.138 (MPa) and (OAC). The (Mr) at 25 ^{0} C under repeated compression load were (184 and 135) MPa for WMA-cutback asphalt and WMA-emulsified asphalt respectively. Both were higher than HMA by (43.75 and 5.47) %, respectively, as the stress level increases the permanent deformation increases and the (Mr) at (OAC) increases when the stress increases from 0.069 (MPa) to 0.138 (MPa) and decreases when the stress increases from 0.138 (MPa) to 0.207 (MPa).

12. References

[1] Saad I. Sarsam. “Behavior of Warm Mix Asphalt Concrete under Moisture Damage.” International Journal of Engineering Papers, (3 February 2018) vol. 3 (1), PP. 21–28.

[2] Audrius Vaitkus, Donatas Čygas, Alfredas Laurinavičius, Viktoras Vorobjovas and Zigmantas Perveneckas. “Influence of Warm Mix Asphalt Technology on Asphalt Physical and Mechanical Properties.” Construction and Building Materials, (Jun 2016) 112, 800-806. doi:10.1016/j.conbuildmat.2016.02.212.

[3] John D'Angelo, Eric Harm, John Bartoszek, Gaylon Baumgardner, Matthew Corrigan, Jack Cowsert, Thomas Harman, Mostafa Jamshidi, Wayne Jones and Dave Newcomb. “Warm-mix asphalt: European practice: International Technology Scanning Program.” Federal Highway Administration, Office of Policy, Office of International Programs (February 2008) (No.FHWA-PL-08-007).

[4] Robert N. Hunter, Andy Self and John Read. “The Shell Bitumen.” (6th ed.), Shell Bitumen (Jan 2015), doi:10.1680/tsbh.58378.

[5] Kent R. Hansen and Audrey Copeland. “Annual Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage.” (National Asphalt Pavement Association), (December 2013).

[6] Olof Kristjansdottir. “Warm Mix Asphalt for Cold Weather Paving.” Department of Transportation, University of Washington (2006), (No. WA-RD 650.1), USA.

[7] Randy West, Carolina Rodezno, Grant Julian and Brian Prowell. “Engineering Properties and Field Performance of Warm Mix Asphalt Technologies.” National Cooperative Highway Research Program (February 2014), Washington, DC, USA, NCHRP Final Report Project, No. NCHRP 09-47A.

[8] Mohd E. Abdullah, Mohd R. Hainin, Nur I. Md. Yusoff Kemas, Ahmad Zamhari and Norhidayah Hassan. "Laboratory Evaluation on The Characteristics and Pollutant Emissions of Nanoclay and Chemical Warm Mix Asphalt Modified Binders.", Construction and Building Materials, (June 2016), vol. 113, pp. 488-497, doi:10.1016/j.conbuildmat.2016.03.068.

[9] Carlos López, Thenoux G., Armijos V., Antonio Ramírez, Guisado F. and Moreno E., "Study of Warm Mix Asphalt with Super Stabilized Emulsion." Revista Ingenieríade Construcción (April 2017), vol. 32(1), No. 0718-5073, PP.57-64.

[10] Amar Raghavendra, Marcelo Medeiros, Marwa M. Hassan, Louay N. Mohammad and William King. "Laboratory and Construction Evaluation of Warm-Mix Asphalt." Journal of Materials in Civil Engineering, American Society of Civil Engineers (July 2016), vol. 28(7), No. 0899-1561, doi: 10.1061/(ASCE)MT.1943-5533.0001506.

[11] Michael Esenwa, Davidson J. Keith, and Anton S. Kucharek."Evaluation of Warm Mix Asphalt Behaviour – Stability and Strength Perspective." CTAA Annual Conference Proceedings-Canadian Technical Asphalt Association (November 2011), vol. 56, No. 0068-984X, pp. 27-40.

[12] Mohamed H. Rashwan. "Characterization of Warm Mix Asphalt (WMA) Performance in Different Asphalt Applications." Ph. D. Thesis, Civil Engineering Department, Iowa State University (2012), doi:10.31274/etd-180810-1335.

[13] Siti N. Kamarudin, Mohd R. Hainin, Mohd K. Satar and Muhammad N. bin Mohd Warid. "Comparison of Performance between Hot and Warm Mix Asphalt as Related to Compaction Design.", Journal of Physics: Conference Series, (July 2018), doi:10.1088/1742-6596/1049/1/012036.

[14] Amjad H. Albayati. "Performance Evaluation of Plant Produced Warm Mix Asphalt.", Journal of Engineering, (May 2018), vol. 24, No. 5, pp. 145-164, doi:10.31026/j.eng.2018.05.10.

[15] Venon Jalali. "Performance of Warm Mix Asphalt Compacted at Reduced Temperature." Ph.D. Thesis, Department of Civil Engineering, University of Nottingham (February 2016).

[16] Dallas N. Little, David H. Allen and Amit Bhasin. "Modeling and Design of Flexible Pavements and Materials.", Springer (2018), doi: 10.1007/978-3-319-58443-0.

[17] Nishant Bhargava, Bhaskar P. Das and Anjan K. Siddagangaiah. "Synergistic Influence of Aging and Moisture on Performance of Warm Mix.", International Journal of Pavement Research and Technology, (June 2018) doi:10.1016/j.ijprt.2018.06.002.

[18] Peter E. Sebaaly, Elie Y. Hajj and Murugaiyah Piratheepan. "Evaluation of Selected Warm Mix Asphalt Technologies.", Road Materials and Pavement Design, (April 2015) vol. 16, pp. 475-486, doi:10.1080/14680629.2015.1030825.

[19] Nathan Bower, Haifang Wen, Shenghua Wu, Kim Willoughby, Jim Weston and Joe DeVol. "Evaluation of The Performance of Warm Mix Asphalt in Washington State.", International Journal of Pavement Engineering, (January 2016) vol. 17, No. 5, pp. 423-434, doi:10.1080/10298436.2014.993199.

[20] Sarsam, Saad Issa. "Flexural Behavior of Warm Mix Asphalt Concrete." Journal of Transport Engineering and Applications 5, no. 2 (2018): 10-20.

[21] SCRB. "General Specification for Roads and Bridges." Section R/9, Hot-Mix Asphalt Concrete Pavement, Revised Edition. State Corporation of Roads and Bridges (2003), Ministry of Housing and Construction, Republic of Iraq.

[22] SCRB. "General Specification for Roads and Bridges." Section R/9, Hot-Mix Asphalt Concrete Pavement, Revised Edition. State Corporation of Roads and Bridges (2003), Ministry of Housing and Construction, Republic of Iraq.

ASTM. "Road and Paving Materials Vehicle Pavement Systems." Annual Book of ASTM Standards (2015), Vol. 04.03, American Society for Testing and Materials.

[23] Zainalabidine N. Abdul Mahdi. "Warm Mix Asphalt Concrete." MSc Thesis, Civil Engineering department, Collage of Engineering, University of Baghdad (2018).

[24] Mohamed A. Al-Jumily. "Influence of Aging on Performance of Asphalt Paving Materials." Ph.D. Thesis, Civil Engineering department, Collage of Engineering, University of Baghdad (2007).

[25] Ali H. Alwan. "Durability of Superpave Asphalt Concrete Pavement." MSc. Thesis, Civil Engineering department, Collage of Engineering, University of Baghdad (October 2013).

[26] Richard D. Barksdale. "Compressive Stress Pulse Times in Flexible Pavements for Use in Dynamic Testing." Highway Research Record, HRB (1971), vol 345, PP.32-44, NRC Washington, DC.

[27] Yang H. Huang. "Pavement Analysis and Design." (2 ed.). Pearson Prentice Hall (2004), Upper Saddle River, NJ 07458, USA.

[28] Witczak M., "Specimen Geometry and Aggregate Size Lab Test Study." (1999) NCHRP Project, PP.9-19.

[29] Waqar A. Gul. "Effect of Recycled Cement Concrete Content on Rutting Behaviour of Asphalt Concrete." Ph.D. Thesis, Civil Engineering Department, Middle East Technical University (July 2008), Ankara.

[30] Samer M. Al-Sadik. "Modeling the Aging Behavior of Various Local Asphalt Cement." MSc. Thesis, Civil Engineering department, Collage of Engineering, University of Baghdad (October 2013).

[31] Hilal, "Prediction of Permanent Deformation Models For Asphalt Pavement in Hot Climate." Ph.D. Thesis, Civil Engineering department, University of Technology (2001).

[32] Ahmed M. Mohammed. "Effect of Lime on Performance Related Properties of Asphalt Concrete Mixture." MSc. Thesis, Civil Engineering department, Collage of Engineering, University of Baghdad (June 2013).

[33] Hanan K. Hussain. “Healing of Asphalt Concrete Mixture at Different Conditions of Loading and Moisture Exposure.” MSc Thesis, Highway and Transportation Engineering Department, College of Engineer, AL-Mustansiriayah University (October 2016).

[34] Anand Sampath. “Comprehensive Evaluation of Four Warm Asphalt Mixture Regarding Viscosity, Tensile Strength, Moisture Sensitivity, Dynamic Modulus and Flow Number.” Civil and Environmental Engineering Department in the Graduate College of the University of Iowa (May 2010).

[35] Jesse D. Doyle, John F. Rushing, Mariely MejÃ-as-Santiago, Timothy J. McCaffrey, Lance C. Warnock and Kevin M. Taylor. “Laboratory Performance Testing of Warm-Mix Asphalt Technologies for Airfield Pavements.” Engineer Research and Development Center Vicksburg MS Geotechnical and Structures Lab (December 2013).

[36] Yassir M. Abualmaali. “Rutting Prediction of Asphalt Concrete Mixture for Hot Climate Area.” MSc Thesis, Civil Engineering department, Collage of Engineering, University of Baghdad (December 2014).

[37] Alaa H. Abed. “Required Criteria for Implementation of the Superpave System in Local Pavement Design.” Ph.D. Thesis, Civil Engineering department, Collage of Engineering, University of Baghdad (May 2010).

[38] Graham C. Hurley and Brian D. Prowell. “Evaluation of Potential Processes for Use in Warm Mix Asphalt.” Journal of the Association of Asphalt Paving Technologists (2006a), vol.(75), PP.41-90.

[39] Jun Zhang. “Effects of Warm-Mix Asphalt Additives on Asphalt Mixture Characteristics and Pavement Performance.” M.Sc. Thesis, University of Nebraska-Lincoln (December 2010), USA.

[40] Wayne Lee, Satish K. Gundapuneni and Ajay Singh. “Effects of Asphalt Binder Grade on the Performance of Rhode Island Hot-Mix Asphalt.” Rhode Island Department of Transportation, College of Engineering, University of Rhode Island (2010).

[41] Xu Shifa, Xu Liting, Jia Jonathan and Xie Yongqing. “The Application of Emulsion Warm Mix Asphalt in Long Tunnel Pavement.” Material Design, Construction, Maintenance, and Testing of Pavements (GSP 193) (August 2009), PP.37- 42, doi:10.1061/issno(352)6.

[42] Kadhum L. Al-Attaby. “Permanent Deformation Model for Asphalt Concrete Wearing Course.” MSc. Thesis, Civil Engineering department, Collage of Engineering, University of Baghdad (March 2014).