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Model Development for the Prediction of the Resilient Modulus of Warm Mix Asphalt

Huda Mahdi [a*], Amjad H. Albayati [b]

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

[b] *Professor, Department of Civil Engineering, University of Baghdad, Baghdad, Iraq.*

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Abstract

Increasing material prices coupled with the emission of hazardous gases through the production and construction of Hot Mix Asphalt (HMA) has driven a strong movement toward the adoption of sustainable construction technology. Warm Mix Asphalt (WMA) is considered relatively a new technology, which enables the production and compaction of asphalt concrete mixtures at temperatures 15-40 °C lower than that of traditional hot mix asphalt. The Resilient modulus (Mr) which can be defined as the ratio of axial pulsating stress to the corresponding recoverable strain, is used to evaluate the relative quality of materials as well as to generate input for pavement design or pavement evaluation and analysis. Based on the aforementioned preface, it is possible to conclude that there is a real need to develop a predictive model for the resilient modulus of the pavement layer constructed using WMA. Within the experimental part of this study, 162 cylindrical specimens of WMA were prepared with dimensions of 101.6 mm in diameter and 63.5 mm in thickness. The specimens were subjected to the indirect tension test by pneumatic repeated loading system (PRLS) to characterize the resilient modulus. The test conditions (temperature and load duration) as well as mix parameters (asphalt content, filler content and type, and air voids) are considered as variables during the specimen's preparation. Following experimental part, the statistical part of the study includes a model development to predict the Mr using Minitab vs 17 software. The coefficient of determination (R^2) is 0.964 for the predicted model which is referred to a very good relation obtained. The Mr value for the WMA is highly affected by the temperature and moderately by the load duration, whereas the mix parameters have a lower influence on the Mr.

Keywords: Warm Mix Asphalt (WMA); Hot Mix Asphalt (HMA); Resilient Modulus (Mr).

1. Introduction

Warm-Mix Asphalt (WMA) is an asphalt mixture that is commonly used in technologies that allow the manufacturing of asphalt mixtures at lower temperatures than those used for the preparation of Hot-Mix Asphalt (HMA). WMA is used as a technique to reduce the emissions of pollutant, energy consumption, and viscosity of the asphalt binder. The benefits of reducing the viscosity are that sufficient aggregate coating is obtained during the mixing, which enhances its workability and allows mix compaction at reduced temperatures [1].

WMA is offers different advantages from the conventional HMA. Firstly, it allows reduction of the production temperature of asphalt mixtures, which in turn help save more energy as compared to that by HMA, which depends mainly on the type of fuel used and the production temperature. Secondly, it offer the possibility of reducing greenhouse gas emissions through the reduced temperature of WMA production [2]. WMA achieve all the properties

* Corresponding author: huda93mahdi@gmail.com

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similar to HMA meanwhile reducing flaws of HMA by adding different types of additives like emulsions, wax-based, chemical and foam technologies [3]. All these steps reduce the bitumen viscosity, which improves the workability of the mixture to produce lower emissions and improve its working conditions [4]. Goh et al. (2007) briefly summarized the benefits of this technique as reduced fuel cost, reduced mixing and compaction temperature, slower aging of the binder, lower plant wear, reduced fumes and emissions, more ease of opening the work site early, improved workability, and extended paving window [5]. In this study, zeolite has used as an additive to achieve the desired asphalt warm mixture and added the same to the mixture at about 0.3% of its weight, which resulted in a reduction of the production temperature by about 30^{o}C as compared to the control mixture [6]. The resilient modulus is the elastic modulus which is related to the theory of elasticity. It is well known that most of the paving materials are not elastic, but after load repetition and due to traffic load some permanent deformation occurs [7].

The Resilient modulus (Mr) is the modulus of elasticity of material under the influence of repeated loads. This value is used to measure the load's distribution through the pavement layers. Generally, under the uniaxial dynamic loading, the proportion of the maximum applied stress to the maximum unit deformation is known as the Mr. Typically, pavement materials can be described as un-elastic, and, each time the load is repeated, it produces a small amount of plastic (permanent) deformation. However, if the strength of the material is greater than a load of traffic and, after a certain number of load repetitions, the deformation in each load is almost completely recoverable and proportional to the load and hence can be considered as elastic [8]. After approximately 100–200 load repetitions, the strain is practically all recoverable, as indicated by (ε_r). In confining the triaxial test, the ratio of deviator stress ($\sigma_d = \sigma_1 - \sigma_3$) to recoverable strain (ε_r) is termed as the Mr [8, 9]. The indirect tension test is the most common test under repeated load because of its simplicity for the measurement of the Mr of asphalt. In this test, a compressive load is applied with sine waveform in the vertical diametral plane of cylindrical specimens and then the resulting horizontal recoverable deformation is measured [10]. Owing to the difficulty of testing the Mr and the unavailability of the required equipment, it becomes necessary to predict the modulus of resilience from several variables, including temperature, loading waveform, and loading time [11]. Wibisono and Nikraz (2019) showed an increase in air voids, short load duration, a coarse aggregate gradation, and a small diameter of specimens gives the highest resilient modulus value [12].

You et al (2011) illustrated the effect of test and compaction temperature on the Mr by indirect tensile test. Two types of mixtures (HMA and WMA) were tested at 4 different temperatures (4, 21.1, 37.8, and 54.4 ^{o}C) for the 2 different percentages of Aspha-min (WMA additive) (0.3 and 0.5%). At the high temperature, the Mr increased slightly for both the Aspha-min® additive percentages in comparison to HMA. The test results at the high temperatures reveal that the Mr of WMA when compacted at 120^{o}C was slightly higher when compared to those for WMA compacted at 100^{o}C. Finally, when the compaction temperature increased, the Mr increased and made the high-temperature asphalt extremely soft and flowy [13]. Hurley et al. (2005) concluded that the addition of Aspha-min did not affect the Mr; however, the Mr decreased with a decrease in the compaction temperature [14]. Hamzah et al. (2008) noted that the Mr decreased by >90% when the temperature increased from 10oC to 40oC, which suggests that asphalt mix is sensitive to temperature change [15].

WMA with Aspha-min additive showed similar Mr at different temperatures as that of HMA [16]. Hilal (2018) reported that the average Mr decreased by 65.73% when the temperature increased from 10 to 25^{o}C, while the average Mr decreased by 97.71% when the temperature increased from 25 to 40^{o}C [17]. The average resilient modulus for WMA is lower than that of HMA by 23.8% at highest temperature of 40 °C as shown by Albayati (2018) [18]. Abdulmajeed et al. (2017) studied the effect of temperature on the Mr by using 3 types of asphalt binder and found that the Mr reduced by 39, 37, and 30% with asphalt binders 80-100, 60-70, and PG76, respectively, when the temperature increased from 30 to 40 ºC. In addition, when the temperature increased from 40 to 50 ºC, the three samples, respectively, showed lowering of the Mr by 77, 67, and 59% [19]. Little et al. (1992) reported that the most significant factors affecting the modulus of the asphalt-treated materials was the duration of the applied dynamic load. The increase in the duration of applied dynamic load decreased the modulus of the mixture [20].

Khan et al. (2015) proposed that the decrease of Mr from 30 to 18% increased the loading time of the vehicle; this increase indicates that the pavement deformed rapidly [21]. Shafabakhsh et al. (2016) explained the results of indirect tensile tests on Marshall specimens at different temperatures and loading times for haversine and square pulses, with different pulse widths for simulating the diverse vehicle speeds, while the square and haversine pulse forms represented stress pulse in the surface and binder layers successively. The Mr ratios at the low temperatures of 5 and 25^{o}C slightly depended on the loading duration. At the high test temperature of 40^{o}C, the differences between Mr of the binder and surface layers were time-dependent and decreased with an increase in the loading duration. The test results revealed that the difference between resilient behavior of the binder and surface layers was more apparent at high temperatures and under fast traffic loadings, as also reported elsewhere [22]. Under different traffic loading the WMA less elasticity than that of HMA mixture as illustrated by Sarsam and Nihad (2019) [23]. Neham (2015) illustrated the effect of asphalt content on the resilient modulus, it was showed that the resilient modulus increased by 18.35 % when asphalt content increased just 1% by weight of mix design [24]. Puzi (2010) showed that increasing of asphalt content lead to rapidly reduced the values of MR, this increase reduce the strength of the specimen [25]. Hilal (2018) noted the values of Mr changed with filler type, when it was used Portland cement as a mineral filler is almost 4.422% increases the value for resilient modulus corresponding to limestone as a mineral filler [17]. Huan et al. (2011) illustrated the effect of three types of fillers (cement, hydrated lime, and quicklime) on resilient modulus, it is noted that cement gives the highest resilient modulus because cement displayed a much stronger and more active reaction capacity rather than hydrated lime, and quicklime [26].

The main objective of this research was to predict the Mr model of WMA from several variables that are otherwise used in mix design condition, such as asphalt content, filler content, filler types, and passing sieve no. 4, along with other variables that are used in test conditions such as temperature and load duration.

2. Materials and Methods

Local raw materials were used in this research, which were used for the pavement construction in Iraq: asphalt binder, aggregate, and mineral filler. Laboratory physical properties tests were implemented to the materials, and the results are given in the following paragraphs. The flowchart of the experimental design is presented in Figure 1.

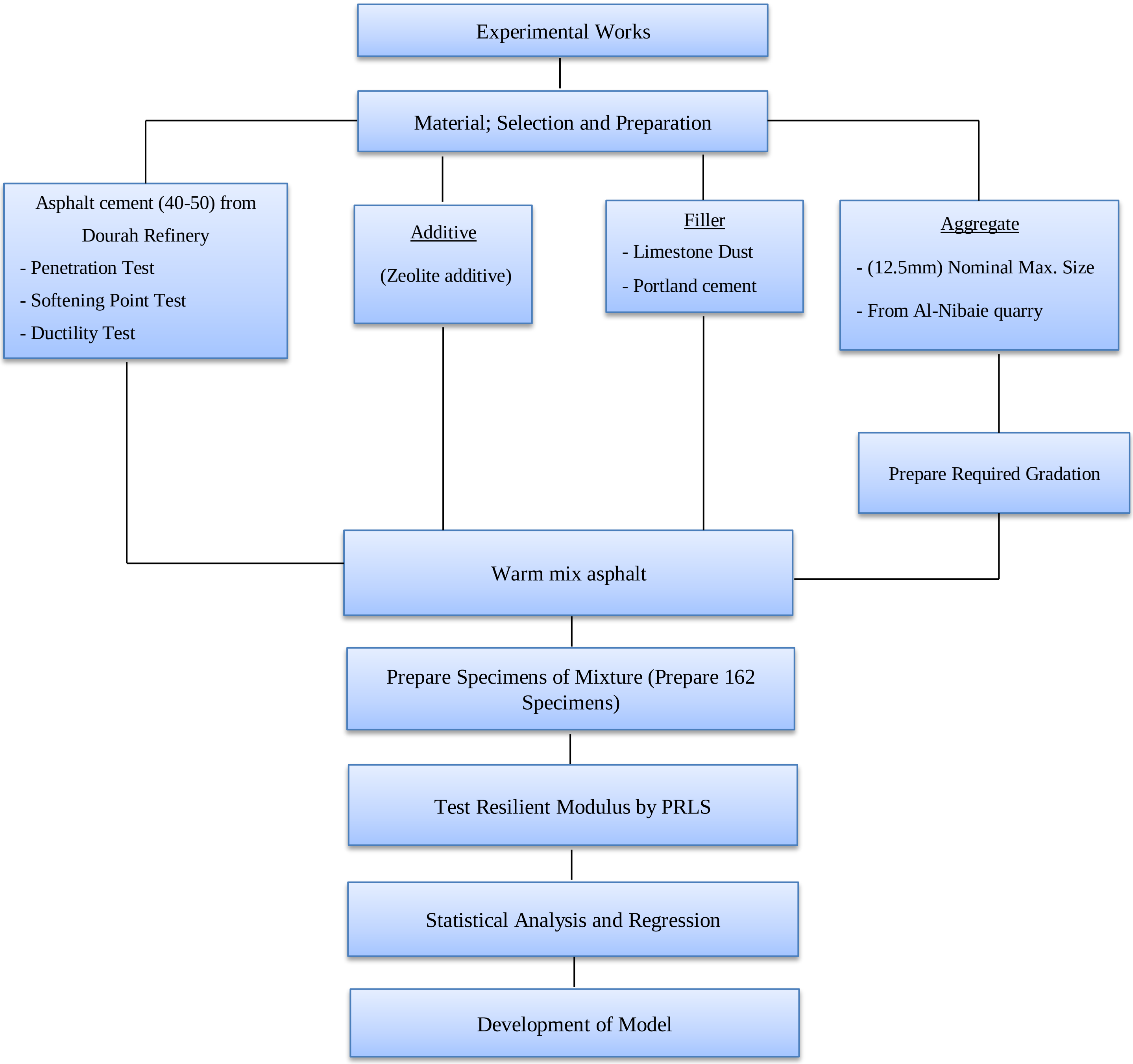

Figure 1. Flow chart of the experimental design

2.1. Asphalt Binder

A type of asphalt binder used (40-50) was of penetration grade provided from the Dora refinery. Different tests were conducted (Table 1) for the determination of the physical properties of asphalt binder.

Table1. Physical properties of asphalt cement

Physical Properties	ASTM Designation	Asphalt Cement 40-50	
		Test Result	SCRB Specification
Penetration (100 gm; 250 C , 5 sec., 0.1 mm)	D5	46	40-50
Ductility (250 C ,5 cm/min)	D113	132	>100
Softening point (4±1) 0 C/min.	D36	49	-
Properties After Thin - Film Oven Test ASTM D 1754			
Penetration(100 gm; 250 C; 5 sec., 0.1 mm)	D5	29	-
Retained Penetration (250 C)	-	65	55 (Min.)
Ductility (250 C ,5 cm/min)	D113	80	>25
Softening point (4±1)0 C /min.	D36	50.6	-

2.2. Aggregate

In this study, the source of aggregate for sample preparation was crushed quartz provided from the Al-Nibaie quarry. The physical properties of coarse and fine aggregates are presented in Table 2. The aggregate gradations was selected according to the SCRB R/9 2003 [27] of wearing courses (Table 3), with the maximum aggregate size of 19 mm (¾ inch), filler contents (4%, 6%, 8%) using passing sieve no. 4 (59 ± 6) (See Figures 1 to 4).

Table 2. Coarse and fine aggregate physical properties

Physical Properties	Test Results	SCRB Specification limit
Coarse aggregate		
Apparent Specific Gravity	2.675	-
Bulk Specific Gravity	2.64	-
Water Absorption,%	0.15	-
Percent Wear (Los Angeles Abrasion),%	19.55	30 Max
Soundness Loss by Magnesium Sulphate Solution, %	3.62	18 Max
Fine aggregate		
Apparent Specific Gravity	2.685	-
Bulk Specific Gravity	2.624	-
Water Absorption,%	0.46	-
Sand Equivalent,%	60.45	45 Min
Clay Lumps and Friable Particles,%	2.75	3 Max

Table 3. Selected gradation for wearing course asphalt concrete mixture according to Iraqi specifications

Sieve Size		Percent Passing (%)									SCRB (2003) Specifications Limits (Type IIIA)
		Wearing Course									
Sieve No.	Sieve Opening (mm)	P_{200}, 4%			P_{200}, 6 %			P_{200}, 8 %			
		Mix A	Mix B	Mix C	Mix D	Mix E	Mix F	Mix G	Mix H	Mix M	
¾ in	19	100	100	100	100	100	100	100	100	100	100
½ in	12.5	95	95	95	95	95	95	95	95	95	90-100
3/8 in	9.5	83	83	83	83	83	83	83	83	83	76-90
No. 4	4.75	59	53	65	59	53	65	59	53	65	44-74
No. 8	2.36	43	43	43	43	43	43	43	43	43	28-58
N0.50	0.3	13	13	13	13	13	13	13	13	13	5-21
No. 200	0.0075	4	4	4	6	6	6	8	8	8	4-10

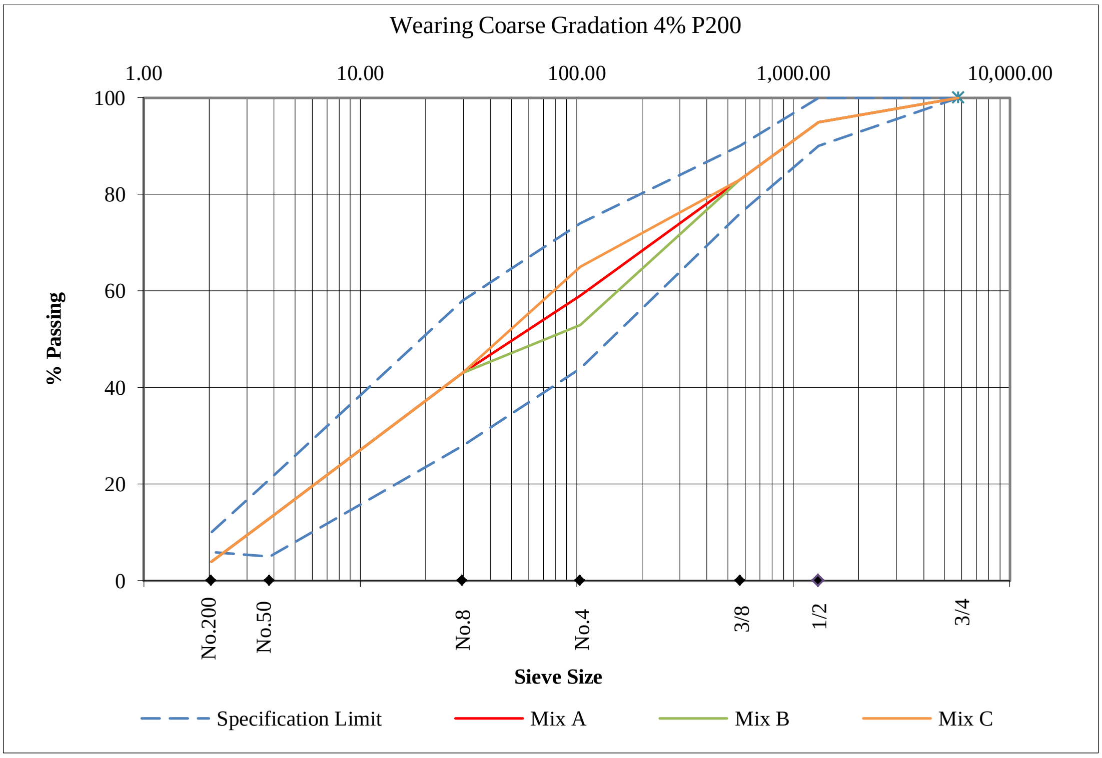

Figure 2. Gradation of wearing coarse at 4% filler content

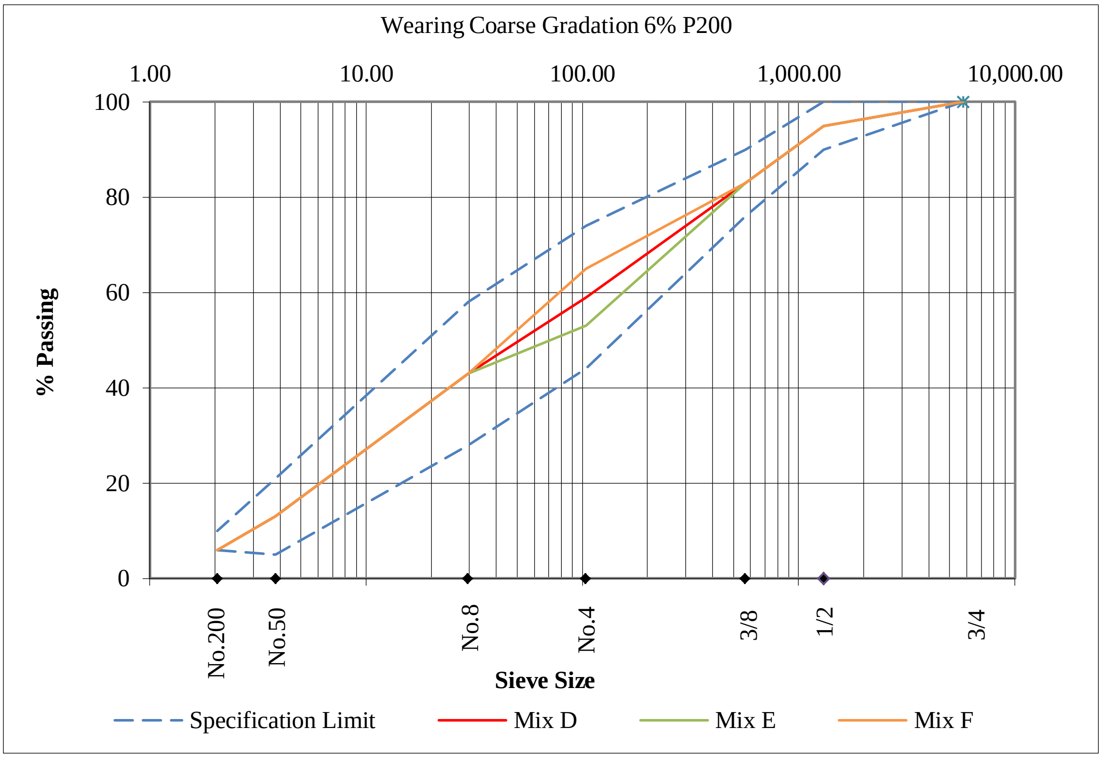

Figure 3. Gradation of wearing coarse at 6% filler content

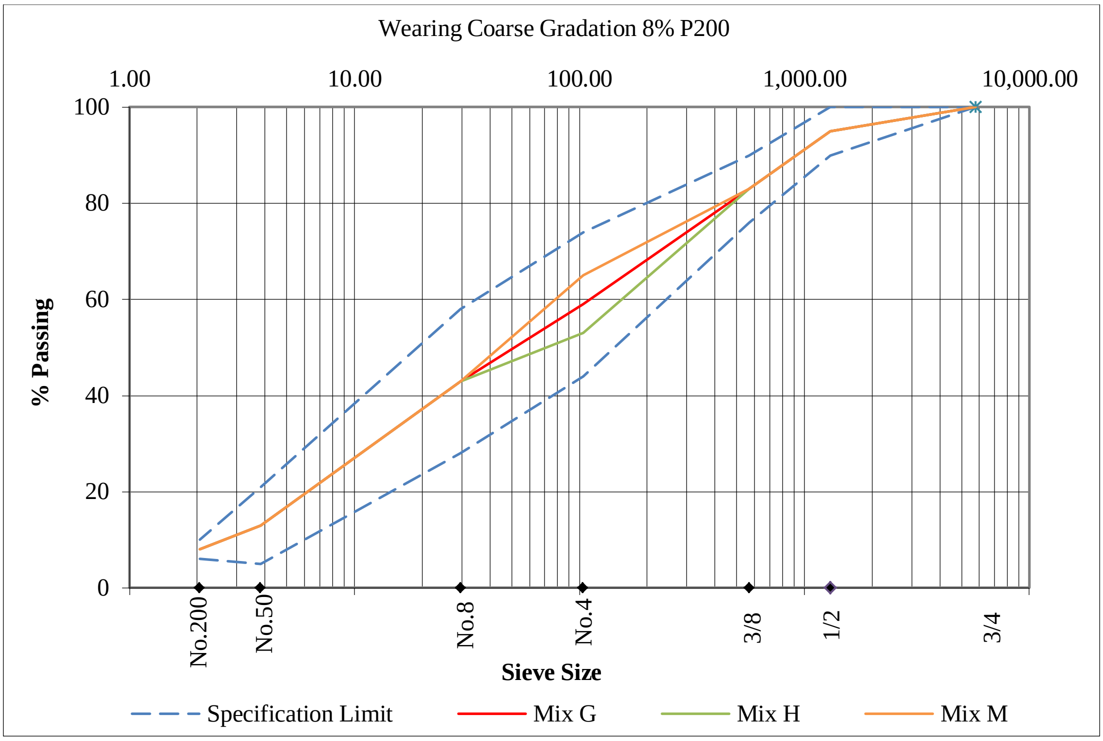

Figure 4. Gradation of wearing coarse at 8% filler content

2.3. Mineral-Filler

Two types of filler were used in this study, including limestone dust and Portland cement. Limestone was sourced from the lime factory in the Karbala city and cement from the Almas factory in Sulaymaniyah Governorate. The physical properties of these two types of filler are given in Table 4.

Table 4. Physical properties of Mineral Filler

Filler type	Physical Properties		
	Specific gravity	Surface area (m^2/kg)	% Passing sieve No. 200 (0.075)
Limestone	2.84	247	95
Portland cement	3.14	290	98

2.4. Aspha-min

Aspha-min (Figure 5) is an additive that was hydrothermally crystallized into a fine powder and used in the production of a warm mixture. It was prepared from synthetic sodium aluminium, silicate, or zeolite. It contains approximately 21% (by weight) of water, which is released in the temperature range of 85–180 ^{o}C. The addition of Aspha-min to the asphalt mixture is done at a dosage of 0.3% (by weight) of the mixture. During the manufacturing of WMA, the reduction in the production and placement temperature is approximately 30 ^{o}C, as demonstrated elsewhere [6]. The physical and chemical features of the Aspha-min are illustrated in Table 5.

Figure 5. Aspha-min Powder

Table 5. Physical and Chemical Properties of the WMA additive: Aspha-min

Property	Result
Ingredients	Na2O.Al2O3.2SiO2(Sodium aluminosilicate)
SiO2	32.8 percent
Al2O3	29.1 percent
Na2O	16.1 percent
L.O.I	21.2 percent
Physical state	Granular powder
Colour	White
Odor	Odorless
Specific gravity	2.03
Bulk Density	568 kg/m^3
Ph value	11.6
Solubility in water	Insoluble

2.5. Specimens' Preparation and Tests

The Marshall compactor was used for the preparation of cylindrical specimens, with the dimensions of 102 mm (diameter) and 64 mm (height). The Pneumatic-repeated loading system (PRLS) (Figure 6) was used to test the Mr by applying repeated indirect compressive load. Nearly 162 specimens were compacted to build the Mr model.

Indirect tension test was applied to measure the Mr of the warm mix in accordance with the ASTM D4123 [28]. The test of the specimens was performed at a different range of temperature, loading duration, and applied loads, and each of the prepared specimens were subjected to 9 tests at 15, 35, and 45^{o}C test temperatures to load durations of 100, 400, and 700 ms with 3 levels of stresses of 10, 20, and 30 Psi. This test consisted of applying a repetitive compressive load with one or more load duration, followed by 0.9-s rest period at 1-Hz frequency interval. The load was applied vertically to the diametric plane of the cylindrical specimen and the horizontal deformation was measured by using 2 linear variable differential transducers (LVDTs) (Figure 6). Mr in the indirect tension method was computed using the following Equation 1:

$$Mr = \frac{P(v+0.27)}{H \times L} \tag{1}$$

Where, Mr = resilient modulus (MPa); P: The maximum amount of repeated vertical force (N); v: Poisson ratio of asphalt mixture which is equal to (0.35); H: is the total recoverable deformation in (mm), L: is the specimen thickness in (mm).

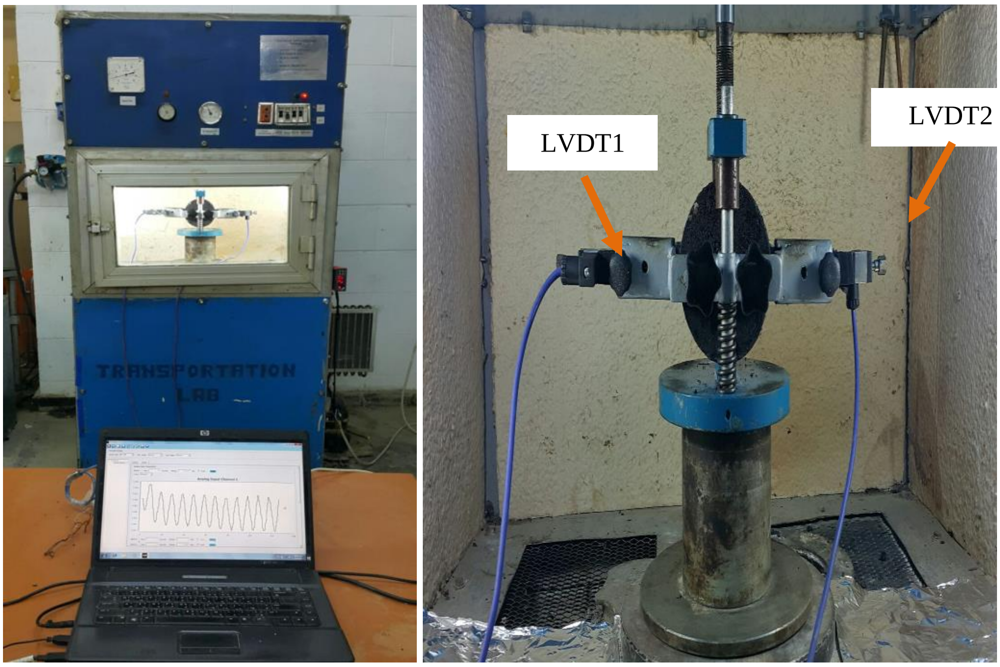

Figure 6. Pneumatic repeated load system

3. Results and Discussion

3.1. Effect of Asphalt Content on Mr

Three asphalt contents were used in this research (4.3, 4.8, and 5.3). Figure 7 shows the relationship of resilient modulus with the asphalt content. As illustrated in figure7, the average Mr increased with the increase in the asphalt content because when the asphalt content increased, complete adhesion was achieved between the aggregate inter-particles due to the decreased recoverable strain, which increased the Mr. As the asphalt content increases, the resilient modulus of the specimens increase up to a maximum, then decreases as the asphalt content continue to increase.When the content of asphalt increases from 4.3 to 4.8%, the average resilient modulus increased by 10% whereas when the asphalt content was increased from 4.8 to 5.3 % the average resilient modulus increased by 8.66%. The results agree with Neham (2015) [24] and Puzi (2010) [25].

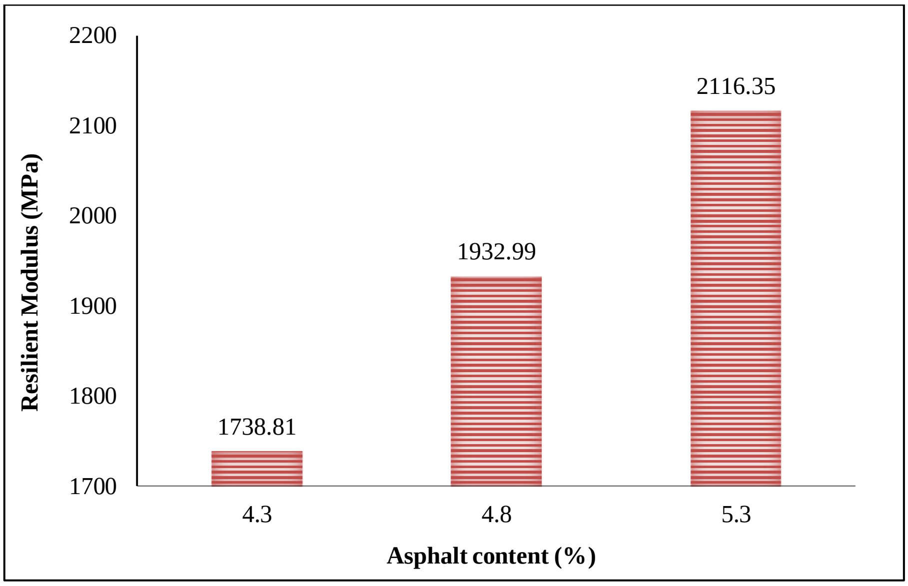

Figure 7. Relationship between Asphalt Content and Resilient Modulus

3.2. Effect of Filler Content and Type on Mr

Three content of fillers were used (4, 6, and 8) with 2 types of fillers (limestone and Portland cement). Figure 8 represents the relationship between the Mr and filler content. It has been found that when the filler content increased, the average value of Mr also increased. When the filler content increased from 4 to 6%, the average Mr increased by 6.89%; while, when the filler content increased from 6% to 8%, the average Mr increased by 5.88%. This observation can be attributed to the fact that when the filler content increased, the air voids in the mixture decreased, leading to reduction of the recoverable strain, thereby increasing the Mr.

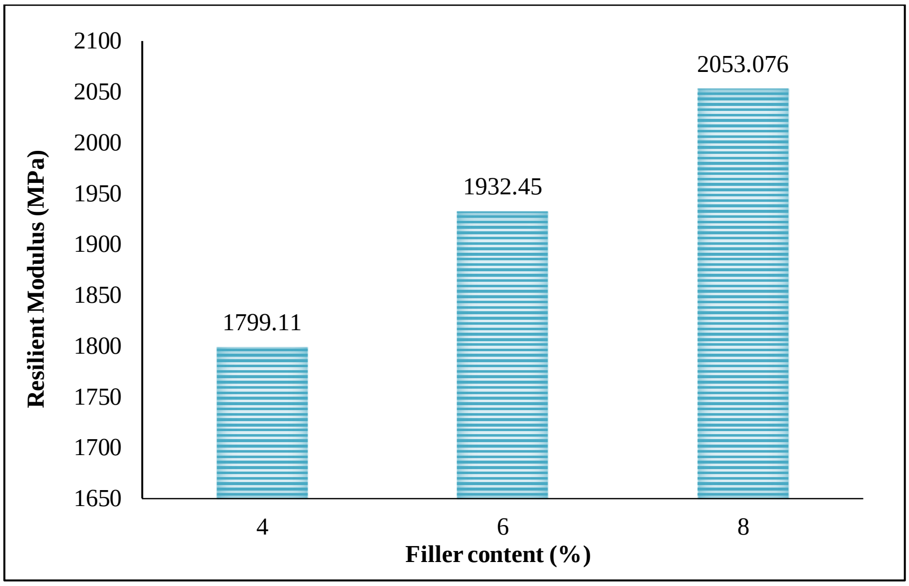

Figure 8. Relationship between the resilient modulus and filler content

The effects of filler types are illustrated in Figure 9. When Portland cement was used in the asphalt mixture as mineral filler, the average Mr increased by 10.71% rather than with the use of limestone, which could be because these types of fillers differ in their void content, surface texture, area, shape, and mineral composition. Also the specimens containing Portland cement were prepared in the summer, their homogeneity was better than the limestone because the specimens with limestone were prepared in the winter and as a result of the cold weather and heating of the aggregates to a lesser degree than the hot mixture by 30°C. It led to the difficulty of homogeneity of the mixture and thus gave less stiffness than the specimens contain cement. The results agree with Hilal (2018) [17] and Huan et al. (2011) [26].

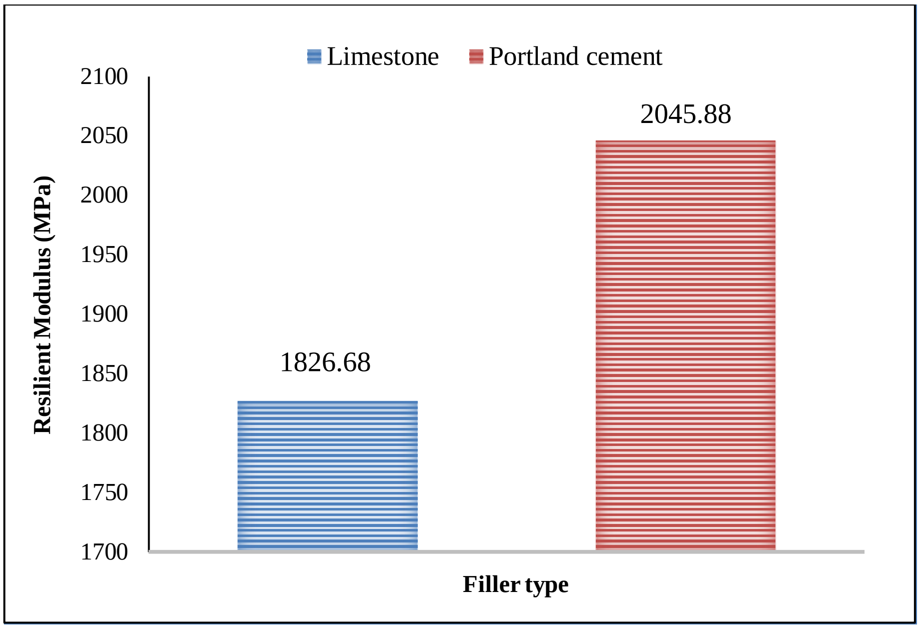

Figure 9. Relationship between Mineral Filler Type and Resilient Modulus

3.3. Effect of Load Duration on Mr

Three different levels of load duration were applied in this research (100, 400, and 700 ms) to each of the tested temperature. Figure 10 depicts the effect of load duration on the Mr. When the loading time increased from 100 to 400 ms, it led to a decrease in the Mr by 24.72%; while, when the loading time increased from 400 to 700 ms, it decreased the Mr by 29.28%. This was expected because longer load duration indicated that the asphalt sample was exposed to a high strain, which caused larger deformations with lesser recovery of the deformations, thereby reducing the Mr. Longer load duration means the slow traffic, which has the most damage effect on the asphalt pavement, causing severe rutting and deformations in the structure of pavement. The results agree with Khan et al. (2015) [21], Shafabakhsh and Tanakizadeh, A. (2016) [22], Sarsam and Nihad (2019) [23].

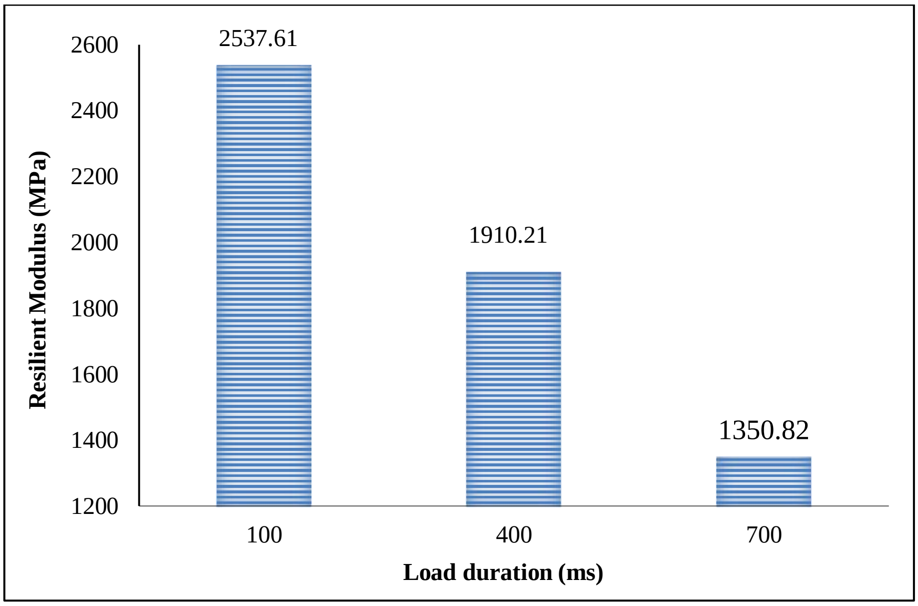

Figure 10. Effect of Load Duration on Resilient Modulus

3.4. Effect of Testing Temperature on Mr

In this study, three different test temperatures were used (15, 35, and 45°C). For all the load durations for all prepared specimens. Figure 11 displays the relationship between the average Mr values versus the increase in the tested temperature. It can be seen that the temperature greatly affected the decreasing Mr of warm mix; this effect was seen when the test temperature increased from 15 to 45, which led to the reduction of the Mr by 60%. When the temperature increased, the asphalt binder became softer and flowy. At high test temperature and low compaction for warm mix as compared to HAM, bitumen may lose its ability to bind the aggregates together thus increases the shear strain between the particle contacts, this leads to decreases the stiffness of the specimen at an applied deviator stress. The result agree with Hamzah et al. (2014) [15], Goh et al. (2008) [16], Hilal (2018) [17], Albayati (2018) [18].

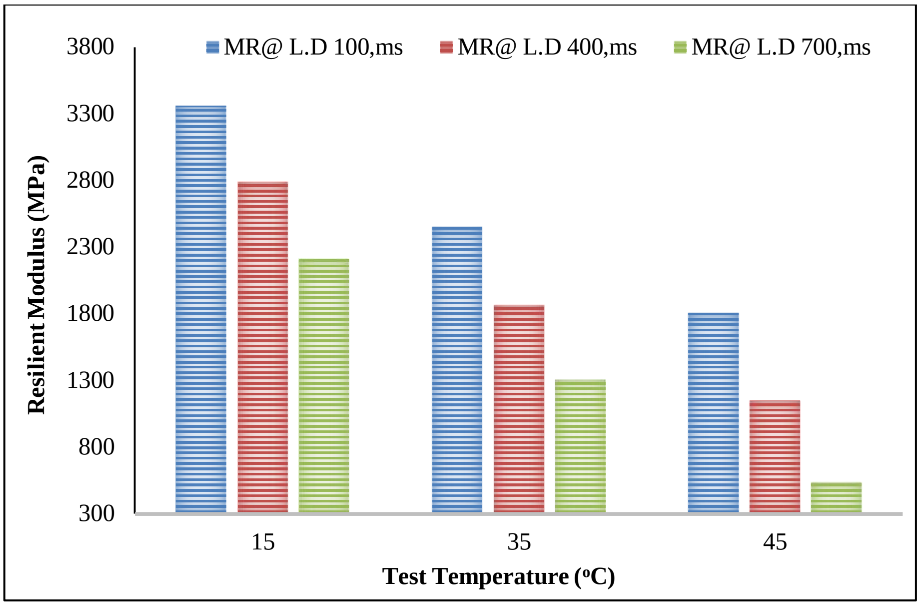

Figure 11. Effect of Test Temperature for each Load Duration on Resilient Modulus

MINITAB Vs 17 software was applied to analyze the variables considering in this study. The analysis of variance (ANOVA) for the different effects of these variables is shown in Table 6. The lower value of P or the higher value of F represents the significance of the factor. Also, all p values are lower than 0.05 this indicates that the independent variables had a good explaining the variation in the dependent variable (Resilient Modulus). Table 7 shows the resilient modulus model that predicted from different variables used in this research. It can be observed, through Table 7 the value of R2 = 0.964 was high which indicates a very good relationship obtained means an acceptable correlation between dependent and independent variables. The predicted model indicated that the resilient modulus decreases with the increase of temperature, load duration, and air voids, whereas the resilient modulus increases with the increase of asphalt content and filler types.

Table 6. ANOVA Test Results for Resilient Modulus Model

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	5	7.75544E+12	1.55109E+12	2613.33	0.000
A.c (%)	1	22919863047	22919863047	38.62	0.000
T.T (°C)	1	4.75213E+12	4.75213E+12	8006.55	0.000
Av (%)	1	3.14976E+11	3.14976E+11	530.68	0.000
L.D (ms)	1	2.32285E+12	2.32285E+12	3913.62	0.000
F.T	1	9398542855	9398542855	15.83	0.000
Error	480	2.84894E+11	593529963		
Lack-of-Fit	462	2.84089E+11	614911217	13.74	
Pure Error	18	805399730	44744429		
Total	485	8.04034E+12			

Table 7. Summary for Resilient modulus model

R-sq	R-sq (adj)	R-sq (pred)	SER	Durbin-Watson
96.46%	96.42%	96.36%	24362.5	1.06774
Regression Model	Mr (Psi) = 915411 + 19343 (A.C) - 7928.4 (T.T) - 282.24 (L.D) + 39540 (Filler Type) - 89014 (Av)			

4. Conclusions

Based on the analysis of the results, it has been concluded as below:

- Mr of WMA was developed for different test conditions and mixture properties on the PRLS.
- The Mr in the warm mix was greatly influenced by the temperature changes. When the temperature increased from 15 to 45°C, the Mr decreased by 60%.
- Mr decreased by 24.72% when the loading time increased from 100 to 400 ms, and when the loading time increased from 400 to 700 ms, the Mr decreased by 29.28%.
- When the content of asphalt increased from 4.3 to 4.8%, the average Mr increased by 10%; whereas, when the asphalt content increased from 4.8 to 5.3%, the average Mr increased by 8.66%.
- The average value of Mr increased by 6.89% when the filler content increased from 4 to 6%, and when the filler content increased from 6 to 8%, the average Mr increased by 5.88%.
- Mr increased by 10.71% with the use of Portland cement as a mineral filler rather than with the use of limestone as a filler in the mix.
- Mr decreased by 8.53% when the passing sieve no. 4 increased from 53 to 59, but it decreased by 6.72% when the passing sieve no. 4 increased from 59 to 65.
- Mr reduced by 24.72% when the loading time increased from 100 to 400 ms, and when the loading time increased from 400 to 700 ms, the Mr decreased by 29.28%.
- The result of these variables show that the Mr was strongly dependent on the temperature and moderately dependent on the load duration, while it showed low dependence on asphalt content, filler content, passing sieve no. 4, and the types of filler.
- The developed model was nonlinear, with a higher coefficient of determination of R^2 = 96.46%.

5. Conflicts of Interest

The authors declare no conflict of interest.

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