Investigating the Effect of Gradation, Temperature and Loading Duration on the Resilient Modulus of Asphalt Concrete

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Abstract

This research was carried out to assess the effect of aggregate skeleton, temperature variation, and loading duration on the resilient modulus of asphalt concrete mixtures. Two different gradation methods, i.e., the conventional method of gradation and the Bailey method of gradation, were adopted to design the aggregate skeleton. The effect of these gradation methods, with temperature and loading duration, on the resilient modulus of asphalt concrete has not been previously investigated. The Modified Marshall Test was used to determine optimum binder content against 4% air voids, and then volumetric and strength parameters were calculated against optimum binder content. For performance tests, specimens were prepared at optimum binder content using a Superpave gyratory compactor. An indirect tensile strength test on both types of mixtures was conducted, and a 20% value of indirect tensile strength was kept for peak load, whereas 10% was kept for seating load for conducting resilient modulus tests. The tests were conducted at 100 and 300 ms duration loads under two different temperatures, i.e., 25 ℃ and 40 ℃. The results declared that aggregate skeleton, temperature, and loading duration have a prominent effect on the resilient modulus of asphalt concrete mixtures. Bailey gradation mixtures disclosed higher resilient modulus values than conventional gradation mixtures. Higher values of resilient modulus were observed for both gradation mixtures at low temperatures and under small duration loads than at high temperatures and large duration loads. The results of the two-way factorial design also confirmed the above findings.

Keywords: Bailey Gradation; Modified Marshall Test; Hot Mix Asphalt; Superpave; Resilient Modulus.

1. Introduction

The design of flexible pavement depends on the appropriate representation of the stress-strain behavior of the different pavement layers [1]. The prediction of stress-strain behavior of a pavement requires the estimation of the actual field conditions, such as future traffic load and environmental factors, particularly, temperature. In the performance testing of asphalt concrete mixtures, traffic load is usually represented by a cyclic load, and the performance of asphalt concrete mixtures is analyzed on the basis of load-deformation behavior under cyclic traffic loading and temperature [2]. Resilient modulus is the ratio of deviator load to recoverable deformation. As it provides a basic relationship about the pavement stress-deformation state, it can be used to assess the quality of pavement materials and as an input parameter in the pavement design and analysis process. Consequently, it provides a notable means of relating the

response of pavement materials under different circumstances [3]. The nature of pavement materials cannot be considered completely pliable because of the indication of enduring distortions under load. In this case, if material strength is high compared with repeated load, then deformation is almost fixable and hence the material is considered pliable. In the early phase of loading, enduring deformation takes place, which indicates plastic strain. But with the increase in the number of load replications, the plastic deformation gets tapered and finally the deformation becomes fully recoverable after 100 load replications, as shown in Figure 1 [4].
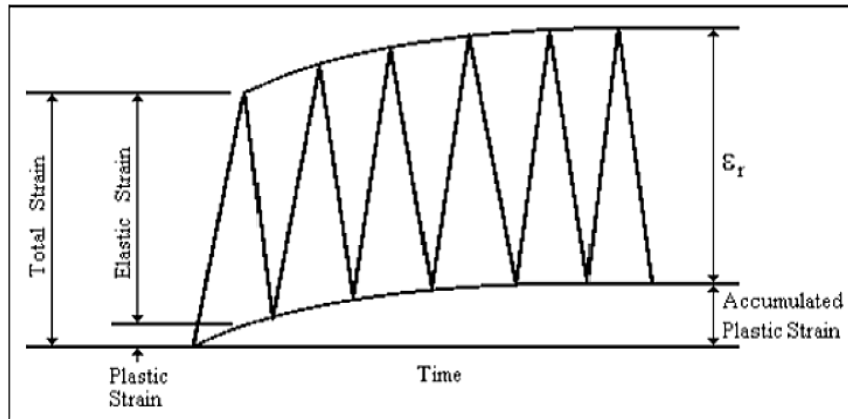

Figure 1. HMA Response during Loading [4]

In the current era, researchers are more focused on studying resilient modulus because of its usefulness in pavement thickness design and for describing the behavior of unbound aggregates and asphalt mixtures. Many factors, like material properties and environmental conditions, have a prominent influence on the behavior of the resilient modulus of asphalt mixtures [5]. Evaluation of the HMA resilient modulus designed with recycled aggregates subjected to temperatures of 0, 10, and 20 °C was carried out, and it was concluded that temperature is the most significant agent in decreasing the resilient modulus because tested specimens revealed higher stiffness values at low temperatures [6]. The resilient modulus of bituminous mixtures decreases by about 12–20% at 20 °C and about 15–40% at 35 °C [7]. In comparison with the influence of other parameters like percentage of bitumen, diameter of specimen, and duration of load, an increase in temperature from 25 to 32.5 °C revealed a significant decrease in the resilient modulus of HMA [8]. The resilient modulus model for the asphalt pavement wearing layer declared a 65.738% decrease in resilient modulus values with an increase in temperature from 10 to 25 °C and a 97.715% decrease in resilient modulus values with an increase in temperature from 25 to 40 °C [9]. Investigation of the influence of temperature on the performance of HMA revealed that resilient modulus values start decreasing above 20 °C and at 40 °C they become unrealistically low [10]. Similar effects of temperature were observed by Lavasani et al. [11].

Investigation of the influence of rest period, waveform, and duration on the resilient modulus of asphalt mixtures declared that the waveform and duration of load pulse significantly influence the resilient modulus of asphalt concrete mixtures, hence the demand for consideration in flexible pavement analysis and design [12]. Loading duration has an influence on the resilient modulus of flexible pavements due to their viscoelastic nature. It was recommended to use a loading duration of 300 ms in dynamic tests for better characterization of the nature of flexible pavements [13]. The assessment of the resilient modulus of bituminous mixtures at temperatures 15-40 °C lower than that of traditional HMA showed 60 % decrease in resilient modulus values by increasing temperature from 15 to 45 °C and 24.72 % decrease by increasing the loading time from 100 to 400 ms [14]. From the factorial design of experiment data, it was found that four parameters, namely; percentage of bitumen, diameter of specimen, loading duration, and test temperature, offset the resilient modulus of asphalt mixtures following the sequence of temperature, loading duration, and specimen diameter [15]. Investigation of the resilient modulus of Styrene-Butadiene-Styrene (SBS) polymer modified asphalt concrete mixtures showed that loading frequency has a significant effect on the resilient modulus of asphalt concrete mixtures in dry conditions and a slight influence in saturated conditions only at 40 °C. It was also noticed that the influence of loading frequency on the resilient modulus is directly linked with temperature in both conditions [16].

Investigation of the asphalt concrete mixtures designed with three gradation sets, passing above, below, and through the restricted zones of Superpave mix design, revealed loading duration and temperature as the most crucial factors affecting the resilient modulus of asphalt concrete mixtures. Furthermore, gradations passing above the restricted zone were found to be more rut prone than the other two sets of gradations [17]. A direct relation between resilient modulus values and nominal maximum aggregate size and an inverse relation between resilient modulus and air void percentage was concluded [18]. The resilient modulus of an asphalt concrete mixture is mainly affected by the morphology of coarse aggregates [19]. Research findings declared that aggregate gradation significantly influences the resilient modulus of HMA, followed by the shape and surface texture of aggregates [20].

From the above literature, following points were considered in this research. Aggregate gradation has an effect on the properties of asphalt concrete but there are no studies in which comparison of effects of Bailey and Conventional method of gradation has been done. This gap is fulfilled in this study. Effect of temperature and loading duration has also been found to significantly affect the resilient modulus so they are also studied in this research with different methods of gradation. In this research, the temperature was varied between 25 and 40 ^{0}C, while loading duration was varying between 100 to 300 ms. These limits are within the extremes values being applied in the previous studies.

2. Materials and Methods

The overall research methodology of the current study is presented by a flow chart in Figure 2. This first step of research methodology was the selection and collection of aggregate and binder. Dina source of aggregate and Attock Refinery Limited 60/70 penetration grade (ARL 60/70 Binder) binder were considered for this study. After checking the appropriateness of materials, gradation blends were developed using the concepts of Bailey method and conventional method of gradation. Conventional method of gradation is based on concept of maximum density line method, also known as mid line gradation. While Bailey method of gradation relies on the packing and interlocking characteristics of aggregate particles. It needs additional inputs parameters like loose and rodded unit weight, specific gravity and absorption of different aggregate fractions for carrying out volumetric adjustment by changing course and fine fraction of the gradation blend [21, 22]. Using these two distinct concepts, aggregate skeletons were designed for both types of gradation within the Pakistan NHA Class-B (NHA-B) gradation limits.
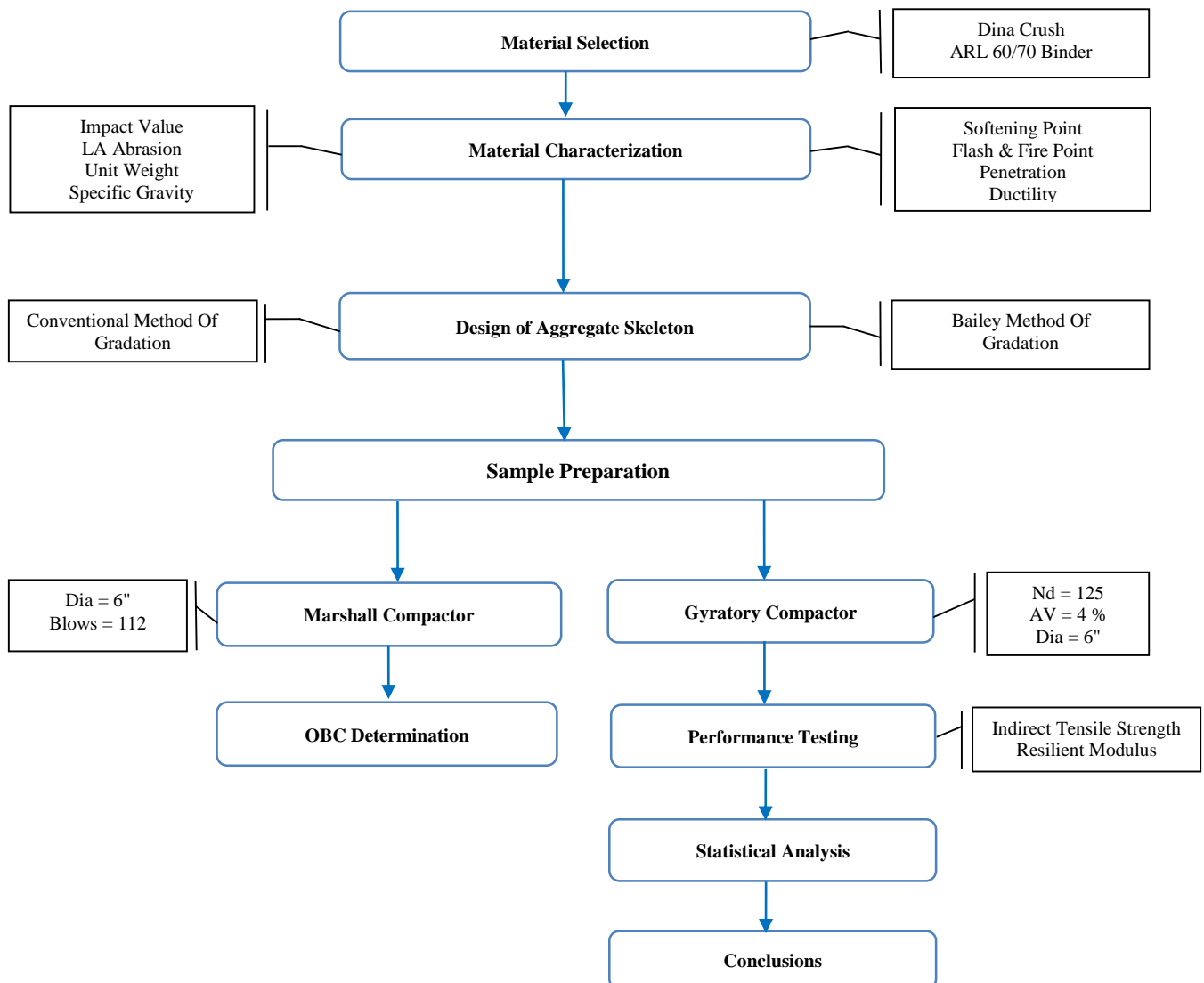

Figure 2. Research Methodology

Modified Marshal Method was practiced and Optimum Binder Content (OBC) was determined at 4 % air voids. To perform tests on each type of bituminous mix, gyratory compactor was used to prepare samples (6 inches diameter and 7.5 inches height) at optimum binder content and 125 numbers of gyration in order to simulate heavy traffic condition.

After preparation of gyratory samples, specimens of 4 inches diameter were prepared as required by indirect tensile strength test and resilient modulus test. Core cutting and saw cutting machines were put into services for this job. Finally, performance tests were performed following the standard procedures.

3. Laboratory Evaluation

Laboratory testing were carried out in two stages. The aim of the first stage of testing was to identify the different properties of aggregate and binder. In this regard impact value, Los Angeles Abrasion, flakiness and elongation index, Loose and Rodded Unit Weight (LUW & RUW), specific gravity and absorption tests were conducted on aggregates using standard procedures [23-26]. These results are compiled in Tables 1 and 2. While Attock Refinery Limited 60/70 penetration grade bitumen (penetration grade) (ARL 60/70 Binder) was characterized by penetration, ductility, softening point and flash and fire point tests as per standard procedures [27-30]. These results are presented in Table 3.

Table 1. Physical Properties of Aggregate

Type of Test	Results (%)	Specification	Standard
Impact value	17	≤ 30	AASHTO T 96
Los Angeles Abrasion	27	≤ 30	AASHTO T 96
Flakiness Index	13	≤ 15	ASTM D 4791
Elongation Index	4	≤ 15	ASTM D 4791

Table 2. Unit weight, Specific gravity and Absorption of Aggregate

Type of Test	Aggregate Sizes (mm)				Standard
	0-5	5-10	10-20	20-25	
LUW (kg/m^3)	-	1455	1426	1390	ASTM C29
RUW (kg/m^3)	1890	1632	1570	1513	ASTM C29
Specific Gravity (%)	2.95	2.66	2.64	2.57	ASTM C127
Absorption (%)	2.8	2.35	2.1	1.4	ASTM C127

Table 3. Physical Properties of ARL 60/70 Binder

Type of Test	Results	Specifications	Standard
Penetration Test (mm/10)	64	60-70	AASHTO T49
Ductility Test (cm)	129	≥ 100	AASHTO T51
Softening Test (^{0}C)	49.7	46-56	AASHTO T53
Flash & Fire Point Test (^{0}C)	328 & 362	≥ 232	AASHTO T48

The control sieve details and respective percent passing by each sieve for both methods of gradation, that is control gradation and Bailey gradation, are represented in Table 4. Moreover, the Baily designed and recommended ratios for Dina aggregate having 25 mm Nominal Maximum Size (NMS) are also presented in Table 5.

Table 4. Obtained Gradation for Conventional and Bailey Methods

Sieves (mm)	37.5	25.4	19	12.5	9.0	4.75	2.36	0.300	0.075
Specified Limits (mm)	100	75-90	65-80	55-70	Maximum 65	30-45	15-35	5-15	2-7
Gradation Type					Passing (%)				
Conventional Gradation	100	82.5	72.5	62.5	52.5	37.5	25	10	4.5
Bailey Gradation	100	84.3	79	69.8	63.6	36	26.7	8.4	4.5

Table 5. Bailey Recommended Ratios for 25 mm NMS Aggregate

Aggregate Blend Ratios	Results	Bailey Recommended Values
Coarse aggregate ratio (CA Ratio)	0.732	0.70 – 0.85
Fine aggregate ratio of fine portion (FA$_f$ Ratio)	0.470	0.35 – 0.50
Fine aggregate ratio of coarse portion (FAc Ratio)	0.468	0.35 – 0.50

The second stage of testing was conducted to measure the intended characteristics of the HMA such as Marshall stability-flow and volumetric properties, indirect tensile strength and resilient modulus.

3.1. Marshall Test

Modified Marshal was put into practice for determining the Optimum Binder Content (OBC) of both types of bituminous mixtures separately. Specimens were made at three different binder content percentages (4.0, 4.5 and 5.0 %). Each specimen was compacted by delivering 112 blows to each side of the specimen. Care was taken to maintain 145 ± 5 ^{0}C temperature during the compaction process. OBC were calculated against 4 % air voids and then other parameters (volumetric properties, stability and flow) were determined against it [31]. The mix design results are summarized in Table 6.

Table 6. Marshall Mix Design of Bituminous Mixtures

Mix Type	AC (%)	VA (%)	VMA (%)	VFA (%)	Stability (Kg)	Flow (0.25mm)
Bailey Gradation	4.70	4.00	15.522	74.189	2907	19.058
Conventional Gradation	4.930	4.00	16.143	74.827	2850	20.024

3.2. Indirect Tensile Strength Test

Indirect tensile strength test was performed at 25 ^{0}C on both type of asphalt concrete specimens [32]. Each specimen was set in the testing machine and a compressive load was applied across the perpendicular diametric plane at a controlled rate of deformation (50 mm/min). The ultimate load at which the sample collapse occurred was recorded and the average values are presented in Table 7. This test was conducted to provide the values of loading for resilient modulus test.

Table 7. Indirect Tensile Strength Test Results

Mix Type	ITS (N) at 25 ^{0}C	20 % value of ITS
Conventional Gradation	6026	1205
Bailey Gradation	7296	1459

3.3. Resilient Modulus Test

Resilient Modulus test was performed at two different temperatures (25 and 40 ^{0}C) and two different loading durations (100 and 300 ms). 20 % value of indirect tensile strength was kept for peak load whereas 10 % was kept for seating load. The Poisson ratio was taken as 0.4. All these variables were put in the UTM-25 software and the test were run [33]. The results of resilient modulus test are summarized in Table 8.

Table 8. Resilient Modulus Test Results

Mix Type	Mr (MPa) at 300 ms		Mr (MPa) at 100 ms	
	25 ^{0}C	40 ^{0}C	25 ^{0}C	40 ^{0}C
Conventional Gradation	4414	1656	6414	2710.5
Bailey Gradation	5031	1867	7311.5	3051

4. Results and Discussion

On the basis of the defined input parameters, the tests were conducted both on Conventional and Bailey gradation samples and the results were plotted in Figures 3 and 4. These plots clearly indicate that irrespective of load duration, the design of aggregate skeleton has remarkable effect on the resilient modulus of asphalt concrete. Specimens developed with Bailey method of gradation has high resilient modulus values as compared to specimens developed with conventional method of gradation. Specimens prepared with Bailey method showed approximately 11% improvement in resilient modulus.
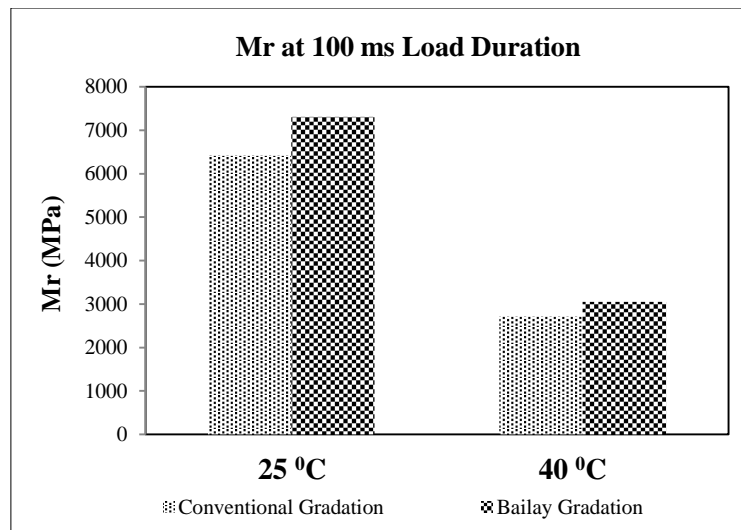
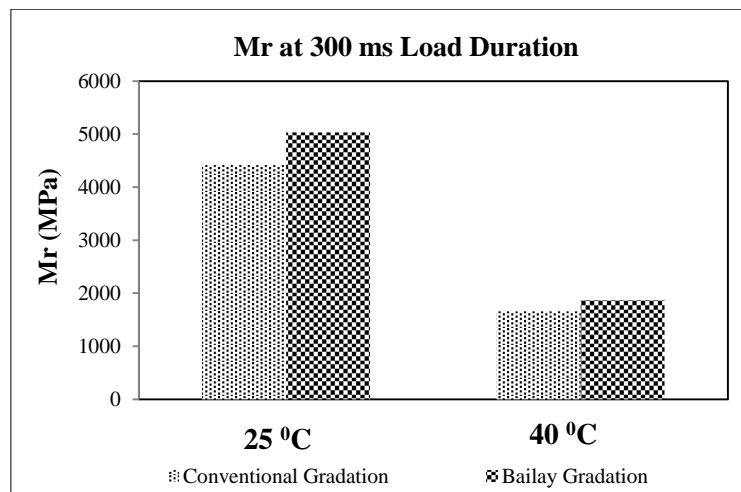**Figure 3. Effect of Gradation on the Resilient Modulus of Asphalt Concrete**

Figure 4. Effect of Gradation on the Resilient Modulus of Asphalt Concrete

4.1. Factorial Design for Resilient Modulus Test Results

Factorial design is used to know the influence of used attributes on the behavior of response variables in statistical language. In current research, two-level factorial design is carried out by considering resilient modulus as response variable and temperature and loading duration are considered as effecting factors. Table 9 presents all the factors considered for resilient modulus test along with their corresponding details. The level of significance considered for the Analysis of Variance (ANOVA), was 0.05 and the ANOVA results are compiled in Tables 10 and 11.

Table 9. Factors Considered for Conventional and Baily Gradation Mixes

Abbreviations	Factors	Levels	Units
A	Load Duration	25 and 40	^0C
B	Temperature	100 and 300	ms

Table 10. Anova for Resilient Modulus - Conventional Gradation Mixes

Source	DF	Seq. Sum of Squares	Adj. Sum of Square	Adj. Mean Squares	F - Test	P -Test	Significance at 95%
Main Effects	2	25540476	25540476	12770238	1292.13	0.000	Yes
2-Way Interactions	1	446985	446985	446985	45.23	0.001	Yes
Residual Error	4	39532	39532	9883			
Pure Error	4	39533	39533	9883			
Total	7	26026994					

Table 11. ANOVA for Resilient Modulus - Bailey Gradation Mixes

Source	DF	Seq. Sum of Squares	Adj. Sum of Square	Adj. Mean Squares	F - Test	P -Test	Significance at 95%
Main Effects	2	33562980	3362980	16781490	531.24	0.000	Yes
2-Way Interactions	1	601156	601156	601156	19.03	0.012	Yes
Residual Error	4	126357	126357	31589			
Pure Error	4	126357	126357	31589			
Total	7	34290493					

4.2. Interactions

The following hypothesis were tested by using Minitab-15 software:

- Null Hypothesis: Ho = Interactions of Load Duration and Temperature have Insignificant Effect on Resilient Modulus of HMA

- Alternative Hypothesis: Ha = Interactions of Load Duration and Temperature have Significant Effect on Resilient Modulus of HMA

From Tables 9 and 10, it is very clear that the 2-way interactions have P-test value smaller than the level of significance (LOS; $\alpha=0.05$), which rejects the null hypothesis in the favor of alternative hypothesis. In other words, the 2-way interactions of load duration and temperature have statistically significant effect on resilient modulus of HMA.

4.3. Significant Effects and Interaction Plots

Pareto Charts developed with Minitab software show the factors and interactions of factors influencing the resilient modulus of bituminous mixtures. Figures 5 and 6 illustrate separate Pareto charts for each type of bituminous mixtures, showing the influence of loading duration and temperature on the resilient modulus. From these figures, it is clear that temperature bar and loading duration crosses the reference line and hence denotes that they are significantly influencing factors for resilient modulus of bituminous mixtures.
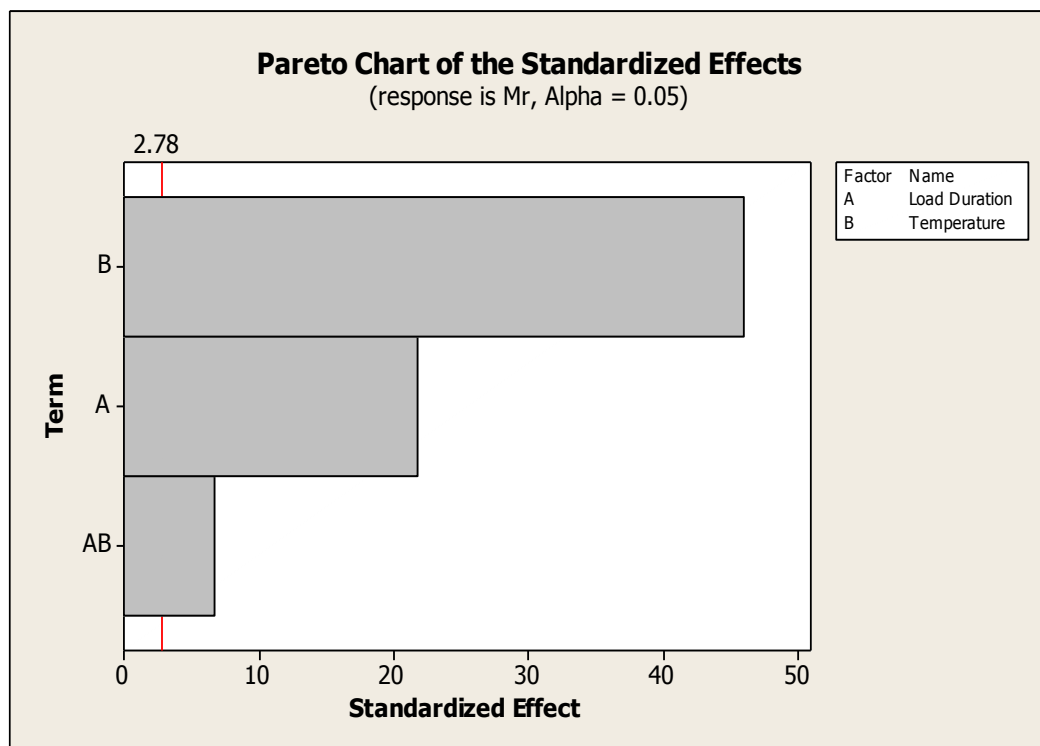
Figure 5. Pareto Chart for Resilient Modulus - Conventional Gradation Mixes
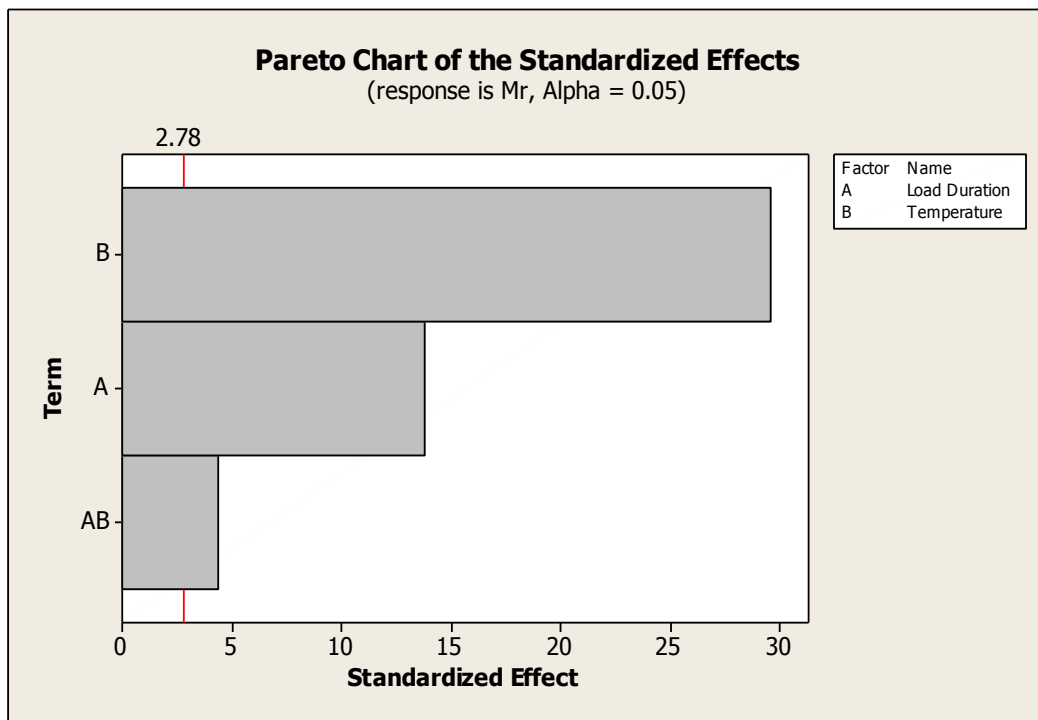
Figure 6. Pareto Chart for Resilient Modulus – Bailey Gradation Mixes

4.4. Main Effect Plots

The main effect plots for the resilient modulus of each type of bituminous mix are shown in Figures 7 and 8. The slope of the load duration and temperature lines is sharp, showing that the effect of both the factors is significant. It is important to mention that temperature and load duration both are significant parameters but affect resilient modulus inversely as suggested by the slope of the line. Moreover, temperature line has sharper slope than load duration line which means that temperature is more significant parameter than load duration parameter. This is also evident from the following. The loading duration, when decreased from 300 to 100 ms, improved the resilient modulus by 35%. On other hand, increase in temperature, from 25 to 40 ^{0}C, reduce the resilient modulus by 62%.
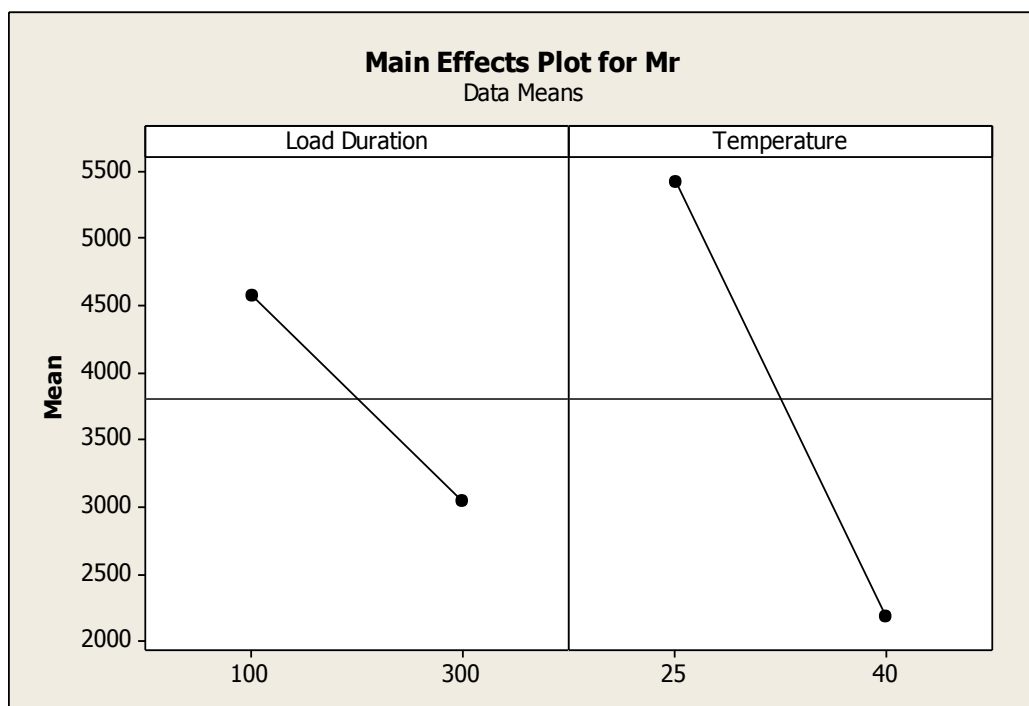
Figure 1. Main Effect Plot for Resilient Modulus - Conventional Gradation Mixes
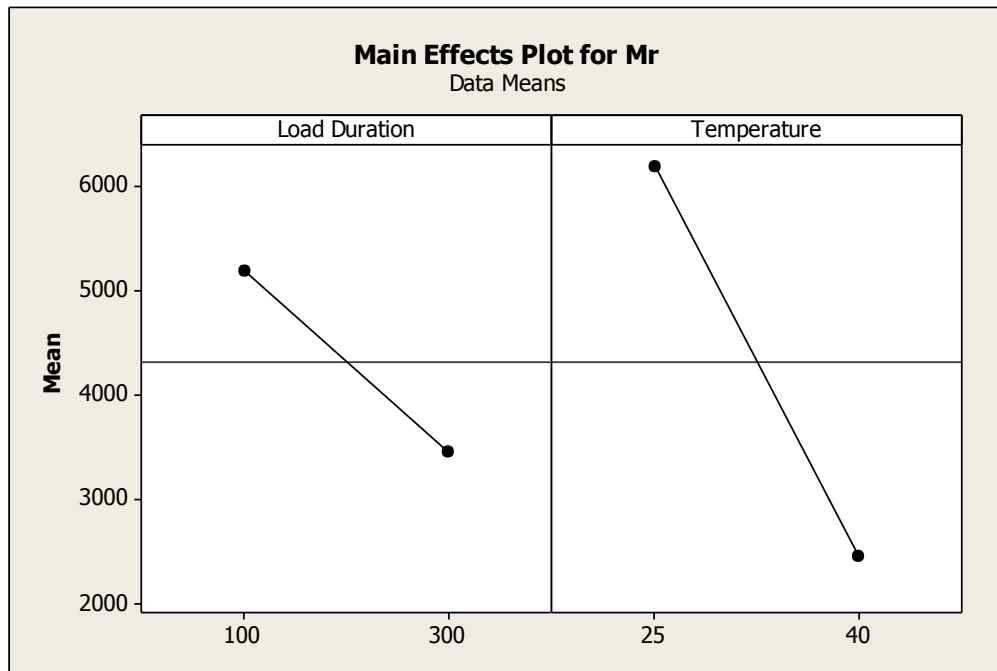
Figure 8. Main Effect Plot for Resilient Modulus - Bailey Gradation Mixes

4.5. Interaction Plots

Interaction plots are shown in Figures 9 and 10 for the resilient modulus of each type of bituminous mix. From the figures it is obvious that temperature and loading duration has prominent influence on the resilient modulus of both types of gradation. The significant effect of these factors can be judged from the parallel lines for these factors, while in case of insignificant factors parallel lines can be observed.
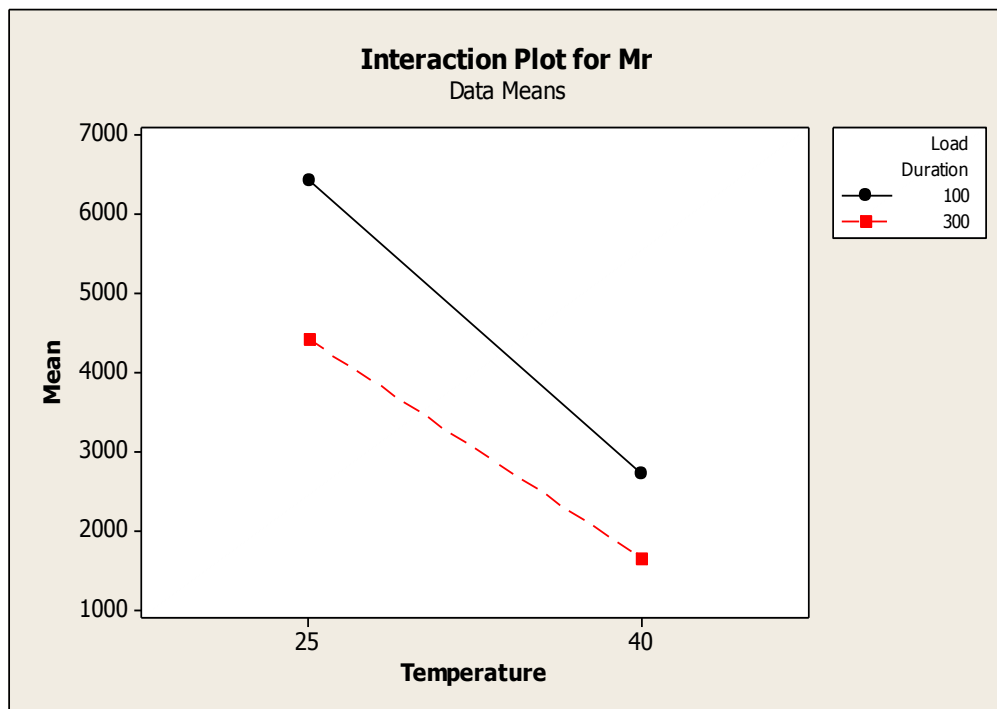

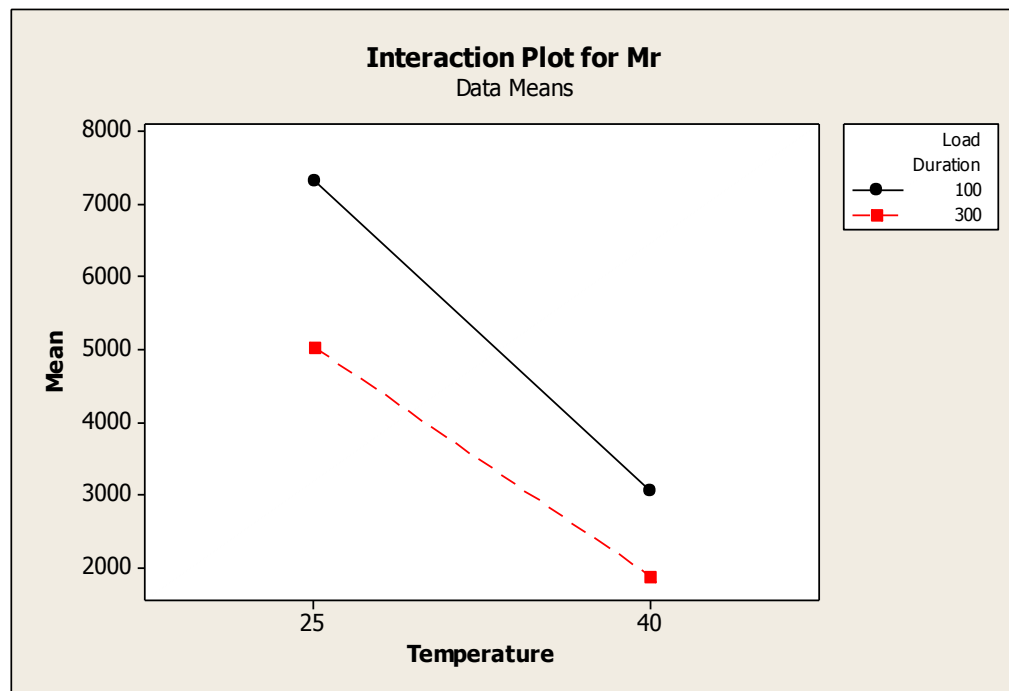**Figure 9. Interaction Plot for Resilient Modulus - Conventional Gradation Mixes**

Figure 10. Interaction Plot for Resilient Modulus - Bailey Gradation Mixes

5. Conclusion

The objectives of this research were to evaluate the effects of different parameters, including; aggregate gradation method, temperature, and loading, on the resilient modulus of asphalt concrete. Statistical analysis was used to measure the significance of these impacts. As shown in Figure 3, the aggregate skeleton has shown an obvious influence on the resilient modulus of asphalt concrete mixtures. Asphalt concrete mixtures developed with the Bailey method of gradation showed 12 and 11% higher resilient modulus values than conventional gradation mixtures, at temperatures of 25 and 40 ⁰C respectively. The better performance of Bailey gradation mixtures is mainly due to the strong interlocking and packing mechanisms of the aggregate particles. Therefore, it is recommended to use the Bailey gradation method for the design of HMA to achieve better performance.

From factorial design, it was concluded that loading duration and temperature are remarkably effective factors in the resilient modulus of asphaltic concrete mixtures. Against a 300 ms duration load, a 100 ms duration load showed an average increment of 35% in resilient modulus values for both gradation mixtures. This reflects that slow-moving vehicles cause more damage than fast-moving vehicles, and the reason is that when a load is applied for a longer duration, asphalt concrete experiences high strain due to its viscoelastic nature.

The evaluation of the temperature effect on the resilient modulus of asphalt concrete mixtures showed an inverse relationship between temperature and resilient modulus. For both gradation mixtures, an average decrease of 62% in resilient modulus values is noted due to the change in temperature from 25 to 40 ⁰C. The drop in resilient modulus versus the rise in temperature is mainly due to the fact that, at high temperatures, asphalt concrete becomes soft, its stiffness decreases and recoverable strain increases. It is recommended that future research be aimed at developing prediction models for resilient modulus incorporating these factors.

6. Declarations

6.1. Author Contributions

Conceptualization, M.J., M.Z.A.S. and G.Y.; methodology, M.J., M.Z.A.S. and G.Y.; software, M.J., M.Z.A.S. and G.Y.; formal analysis, M.J., M.Z.A.S. and G.Y.; data curation, M.J., M.Z.A.S. and G.Y.; writing—original draft preparation, M.J. and H.H.A.; writing—review and editing, M.J., D.K. and M.J. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in article.

6.3. Funding

6.4. Acknowledgements

6.5. Conflicts of Interest

The authors declare no conflict of interest.

7. References

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