Comparing Factors Affecting Resilient Modulus in Asphalt Mixtures

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Abstract. The present study attempts to investigate different factors affecting the resilient modulus of hot mix asphalt. So a fractional factorial analysis of experiment was carried out considering five factors, each at two different levels. These factors were the maximum nominal aggregate size, specimen diameter and thickness, the load pulse form and duration. During the course of analysis, two types of hot mix asphalts with different maximum aggregate sizes were taken into consideration, while Marshall compaction method was used to prepare the specimens. Furthermore, measuring the resilient modulus, sinusoidal and triangular load pulse forms were applied. Finally, our investigation examined the different factors interactions which affect the resilient modulus. Analysis of the factorial experimental design showed that the maximum nominal aggregate size was the most important factor affecting the resilient modulus, then the load duration, the specimen geometry (thickness and diameter), and finally the interactions between the different factors.

Keyword: Resilient modulus; Specimen’s geometry; Load factors; Factorial experimental; Asphalt mixtures.

INTRODUCTION

The resilient modulus is an important parameter that is used in the mechanistic pavement design. It is being used as an input to the multi-layer elastic theories or finite elements models to compute pavement response under traffic loading. Resilience is the property of a material to absorb energy when it is deformed elastically and then, upon unloading, to have this energy recovered. For the sake of simplicity and easy application to test laboratory compacted specimens and field cores, the indirect tensile test is the most common repeated load test to measure the resilient modulus of bituminous mixture. This test involves preparing a compacted cylindrical asphalt mixture subjected to diametrical repeated loading. This test is standardized under the Australian standard AS 2891.13.1 and ASTM D4123. Although it was first believed that stiffer pavements had greater resistance to permanent deformation, it has been concluded that resilient modulus at low temperatures is somehow related to cracking. Stiffer mixes (higher \( M_r \)) at low temperatures tend to crack easier than more flexible mixtures (lower \( M_r \)) [1]. However, there are lots of factors affecting resilient modulus of asphalt when subjected to indirect tensile test. These include the geometric factors of the test specimen, maximum nominal size of aggregates, the load waveforms and pulse durations applied to the specimen, the preset strain measurement that is to be met during the test, and the type of compaction. This research aims to consider the effects of these factors except compaction methods, their interactions, and significance on the resilient modulus through a fractional factorial design of experiment.

The resilient modulus is defined as the ratio of the deviator stress to the recoverable strain. It is known that the bituminous material is not elastic, but it experiences some permanent deformation after each load application. However, if the load is small compared to the strength of the material and is repeated for a number of times, the deformation under each
load repetition is nearly completely recoverable and proportional to the load and can be considered as being elastic [2].

Under a repeated load test, there is considerable plastic strain at the initial stage of load applications and by increasing load repetition, the plastic strain decreases due to each load repetition. After about 100 to 200 cycles of repetitions, the strain is almost all recoverable; thus the elastic modulus is defined as the resilient modulus which is the deviator or axial stress over the recoverable strain (Figure 1). The resilient modulus test is the most common method of determining the stiffness modulus for hot mix asphalt and as such it involves preparing a compacted cylindrical asphalt mixture subjected to a diametrical repeated loading [3].

The test procedures consist of two parts: the preconditioning and test setting determination, and the resilient modulus determination. So far as the preconditioning and test setting determination is concerned, the range of the recovered horizontal strain must be specified and thus the peak load that is required to deform the specimen within that range of recovered horizontal strain is determined by the following equation:

$$P_r = \frac{ED\varepsilon_r}{(v + 0.27)}$$

(1)

where $P_r$ is estimated peak load, $E$ is estimated resilient modulus of the specimen, $D$ is an average diameter of the cylindrical specimen, $h_e$ is an average height of the specimen, $\varepsilon$ is recovered horizontal strain, and $v$ is Poisson ratio (it depends on temperature and can be estimated as 0.35). A single pulse within a specified rise time is applied to the estimated peak load calculated above and then removed. At the end of the pulse, the recovered horizontal deformation is measured and then the recovered horizontal strain is calculated through the following equation:

$$\varepsilon = \frac{H}{D},$$

(2)

where $\varepsilon$ is recovered horizontal strain, $H$ is recovered horizontal deformation and $D$ is an average diameter of the cylindrical specimen. If the recovered horizontal strain is within the specified range, further preconditioning pulses must be applied at the same estimated peak load until five pulses of preconditioning have been completed. But, if the recovered horizontal strain is not within the specified range, the estimated peak load must be adjusted so that the recovered horizontal strain will fall within the specified ranges. Following the above preconditioning procedures, five load pulses were applied with the specified rise time to the peak load determined before. The recovered horizontal deformation after each pulse is measured and recorded. Equation 3 determines the resilient modulus.

$$M_r = \frac{P(v + 0.27)}{Hh_e},$$

(3)

where $M_r$ is resilient modulus, $P$ is peak load, $v$ is Poisson ratio, $H$ is recovered horizontal deformation of specimen and $h_e$ is height of the specimen.

**LITERATURE REVIEW AND INVESTIGATING FACTORS**

**Diameter of Specimen**

Louizi et al. [4] conducted the comparative evolution of resilient modulus and dynamic modulus of hot mix asphalt as material properties for flexible pavement design. They found that the size of the specimen statistically affected the measured resilient modulus value. Resilient modulus values obtained in the 100 mm diameter specimens were higher than those obtained in the 150 mm diameter specimens in all testing temperatures. It is concluded that the dynamic modulus test provides a better characterization of HMA than the resilient modulus test because it provides full characterization of the mix over temperature and loading frequencies. Kandhal and Brown [5] carried out a comparative evaluation of 4- and 6-inch diameter specimens and found that the tensile strength (resilient modulus) of the latter was always lower than the former. Under the same loading, the strain rate for the 6-inch diameter was lower than that of the 4-inch specimen. Lim et al. [6] also conducted a study to evaluate the specimen size effects on the results of diametrical mechanical testing methods, namely the resilient modulus test and the indirect tension test. The diameter/height ratio of specimen was constant at 1.6 and it was observed that the resilient modulus decreases as the diameter of the specimen increases. Therefore, they came to the conclusion that the specimen size does affect the resilient modulus and the resilient modulus decreases with the increase of the size of the specimen. In this paper, specimens were made at two different diameters, i.e. 100 mm and 150 mm, to investigate the effect of diameter on resilient modulus.
Thickness of Specimen

According to Australian Standard AS 2891.13.1, the thickness of the specimen is to be between 70 and 35 mm and 75 ± 15 mm for the 100 mm and 150 mm diameter specimens, respectively. Using static indirect tensile test, Hugo and Schreuder evaluated the influence of the specimen thickness on the tensile strength and related engineering properties [7]. They found that the indirect tensile strength increases as the specimen thickness increases. The specimens thicker than 20 mm experience stress concentrations at the top and bottom contact points. The stress along the remainder of the vertical diameter would be reduced far below the average calculated stress level. This could be the cause of an increase in tensile strength considering the fact that the unequal stress distribution causes the specimen strength to be stress-dependent. This indicates that the middle portion of the specimen commences once the top and bottom contact points (highly stressed points) on the outside begin to fail. Consequently, required failure load increases. In this study, specimens were prepared in two different thicknesses of 35 mm and 65 mm to investigating the effects of thickness on resilient modulus.

Maximum Nominal Aggregate Size

Based on Australian Standard AS 2891.13.1, the particle size of up to 40 mm can be used for the resilient modulus specimen test. An investigation by Lin et al. [6] on the effect of diameter/maximum nominal stone size ratio shows that the resilient modulus decreases as the ratio increases. Another investigation directed by Brown and Bassett [8] on the relationship between asphalt mixture properties and maximum aggregate size shows good correlation between the resilient modulus and the maximum aggregate size. Accordingly, the resilient modulus increases as the aggregate size increases. Tongyan et al. [9] conducted a laboratory study aimed at investigating the effects of the material properties of the major component on the resilient modulus of asphalt mixes with the coarse aggregate morphology considered as the principal factor. With modulus tests performed at a temperature of 25°C, using coarse aggregates with more irregular morphologies substantially improved the resilient modulus of asphalt mixes. They found that the changes in aggregate gradation did not significantly affect the relationship between the coarse aggregate morphology and the resilient modulus. Decreasing the nominal maximum aggregate size from 19 mm to 9.5 mm indicated an improvement on the resilient modulus of asphalt mixes according to aggregate morphology. This study used two different gradations by maximum nominal 12.5 mm and 20 mm to investigate the effect of aggregate size.

Loading Factors

For the load duration and the strain level, the standard values are 100 and 50 micro strain, respectively. Also, the test pulse period was set at 3000 ms, i.e. the frequency of the test was 1/3 Hz. The loading factors considered in this study are the duration, waveforms and the strain level. For load duration, it is expected that the plastic strain becomes bigger as the duration gets higher and thus the resilient modulus gets smaller. For load waveforms, however, the standard did not specify the waveform to be used in the test. As a matter of fact, this study included haversine and triangular shaped waveforms and deduced whether load waveform had any significant effect either by itself or other factors on resilient modulus. Moreover, for the strain level, the standard states that the recovered horizontal strain has to be 50 ± 20 micro strain. This study investigates the effect of a low (20 micro strain) and a high (60 micro strain) recovered horizontal strain on the resilient modulus.

Compaction Methods

Compaction methods affect the air void content and friction between the aggregate particles and bond which is between the bitumen and the aggregates. Harvey and Erilson [10] showed that different compaction methods produce different permanent deformation responses to the repeated shear loading. He also indicated that each method of compaction gives a particular type of aggregate orientation and binder aggregate film. Fwa and Low [11] conducted a study on density profile of asphalt mixture specimens compacted by four methods (drop hammer compactor, kneading compactor, single plunger compression and double plunger compression), showing that different methods make non-uniform density profiles and probably produce different resilient modulus. In this study, the comparative methods are not considered and Marshal method is used to compact all specimens.

FACTORIAL EXPERIMENTAL DESIGN

The normal procedure to investigate the effects of factors is the “one factor at a time” strategy, and it fails to consider the interaction between factors. Therefore, the best approach in multiple factors problems is factorial experiment and it is the only way to understand interactions between variables [12, 13]. The most basic factorial design is the $2^k$, where ‘2’ denotes the two levels of experiment (high and low), and $k$ denotes the number of factors. In this paper, there are totally six factors that are shown in Table 1, so
Table 1. Factors in factorial analysis.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Factors</th>
<th>Level</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometric</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Diameter of specimen</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>B</td>
<td>Thickness of specimen</td>
<td>35</td>
<td>65</td>
</tr>
<tr>
<td>C</td>
<td>Maximum nominal aggregate size</td>
<td>12.5</td>
<td>20</td>
</tr>
<tr>
<td>Loading</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Load duration</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>E</td>
<td>Strain level</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>F</td>
<td>Wave form</td>
<td>Haversine</td>
<td>Triangular</td>
</tr>
<tr>
<td></td>
<td>Compaction methods</td>
<td>Marshal method</td>
<td></td>
</tr>
</tbody>
</table>

there will be about $2^6 = 64$ tests. Furthermore, three replicates will be considered, bringing the total tests to 192. This number of test is too great to be conducted; therefore, by neglecting the high order interactions, the next most sensible design of experiment option that is the $2^{6-1}$ One Half Fractional Factorial Experimental Design (OHFFED) will be achieved. This results in 96 tests including three replicates. The $2^{6-1}$ OHFFED is an ideal objective of identifying those factors that have significant effects which are confounded. This study used Minitab (a program specializing in statistical process control and Design of Experiment) to generate the OHFFED. Inputting the factors with high and low levels as well as the number of replicates, statistical analysis was done and significant affects were estimated.

**LABORATORY INVESTIGATION**

**Materials**

The aggregates used in this study were crushed limestone and physical properties of both coarse and fine aggregate and mineral filler which are indicated in Table 2. Two different gradations with maximum nominal of 12.5 mm and 20 mm were used to investigate the aggregate size effect. The particle size distributions for both gradations are illustrated in Figures 2 and 3. Bitumen was 60/70 (ASTM D) penetration grade whose properties are shown in Table 3.

**Sample Preparation**

To prepare the uniform asphalt samples, several parameters such as the maximum theoretical specific gravity, the optimum compaction temperature, and the bulk specific gravity of the compacted mix samples needed to be measured. The percentage of air voids was maintained at 5% ± 0.5% for all specimens regardless of their geometry. Since certain levels of viscosity needed to be ensured that the asphalt binder was sufficiently fluid for mixing and compacting, the optimum compacting temperature for the asphalt mix was determined using a rotational viscometer. More details can be found in ASTM D4402. It is shown that the optimum temperature should be between 140°C and 145°C to achieve the viscosities between 170 ± 20 centistokes (cSt).

Table 2. Aggregate properties.

<table>
<thead>
<tr>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Bulk specific gravity, g/cm³</td>
<td>Bulk specific gravity, g/cm³</td>
<td>Apparent specific gravity, g/cm³</td>
</tr>
<tr>
<td>2.698</td>
<td>2.683</td>
<td>2.743</td>
</tr>
<tr>
<td>Apparent specific gravity, g/cm³</td>
<td>Absorption, %</td>
<td>L.A. abrasion, % (ASTM C131)</td>
</tr>
<tr>
<td>2.714</td>
<td>0.33</td>
<td>23.57</td>
</tr>
<tr>
<td>Absorption, %</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Figure 2. Aggregate grading (maximum nominal 12.5 mm).](www.SID.ir)
pending on these factors, variation of void by blow compaction was determined as a curve compaction. Each curve is defined by three points, and each point consists of two replicates to increase the accuracy of the air voids determinations. Due to high surface area, compaction of 150 mm diameter specimen has much greater heat dissipation than the smaller diameter specimen. With a manual modified Marshall hammer, the amount of time taken to compact a specimen increases causing greater heat loss and inconsistency in the percentage of air voids. Thus, trial and error were used to prepare the 150 mm diameter Marshall compacted specimens at 5% ± 0.5% air voids.

### ANALYSIS OF THE EXPERIMENTAL RESULTS

MINITAB and Design Expert software were applied to analyze all six factors considering their high and low levels and the number of replicates. Further, using the $P$-value and level of significance of 0.05, the important effects or interactions were identified. The analysis of variance for the different effects is shown in Table 4. The higher value of $F$ or the lower value of $P$ represents the significance of the factor.

The validity of the results has been investigated by residual analysis to confirm the normality of data. Figure 4 shows the probability plot and it is clear that there is approximately a straight line, and Figure 5 shows the result verified by the Pareto chart. It displays the interactions in terms of their significance. It is clear that the maximum nominal aggregate size is the most important factor affecting the resilient modulus, then load duration, the specimen geometry (thickness and diameter) and finally the interactions between different factors.

![Figure 3. Aggregate grading (maximum nominal 30 mm).](image_url)

![Figure 4. Normal probability plot of residual analysis.](image_url)
Table 4. Analysis of variance of signification of factors.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Sum of Square</th>
<th>Mean Square</th>
<th>F Value</th>
<th>P-Value, Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4852695</td>
<td>4852695</td>
<td>201.13</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>B</td>
<td>6923433</td>
<td>6923433</td>
<td>323.45</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>C</td>
<td>26965632</td>
<td>26965632</td>
<td>1296.32</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>D</td>
<td>12063553</td>
<td>12063553</td>
<td>502.36</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>E</td>
<td>201136</td>
<td>201136</td>
<td>12.32</td>
<td>0.0034</td>
</tr>
<tr>
<td>AB</td>
<td>2203723</td>
<td>2203723</td>
<td>101.2</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>AC</td>
<td>3245263</td>
<td>3245263</td>
<td>157.25</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>BC</td>
<td>1185236</td>
<td>1185236</td>
<td>57.36</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>ABC</td>
<td>2123659</td>
<td>2123659</td>
<td>95.36</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>BCD</td>
<td>212365.2</td>
<td>212365.2</td>
<td>11.23</td>
<td>0.0025</td>
</tr>
<tr>
<td>Model</td>
<td>39976695</td>
<td>3215261</td>
<td>152.36</td>
<td>&lt; 0.0001</td>
</tr>
</tbody>
</table>

Figure 6 shows the effect of the maximum nominal aggregate size on resilient modulus. It is clear that the coarser the aggregate gradation, the higher the resilient modulus of the asphalt mix. This is expected because of the fact that larger aggregates have higher particle-to-particle contact in the coarser aggregate structure. The analysis of variance of Table 4 shows that maximum nominal aggregate size has the largest F value, reflecting the importance of the aggregate gradation on the resilient modulus. This is further verified by the Pareto chart shown in Figure 5.

Figure 7 shows the effect of the load duration on the resilient modulus. It is evident that the longer the load duration, the smaller the resilient modulus. The longer duration meant that the asphalt sample experienced higher strain for a longer period of time, thus reducing the resilient modulus. This effect can be attributed to the viscoelastic nature of bituminous materials, causing these mixes to be rate dependent. It is known that slow traffic has the most damaging effect on the asphalt pavement, causing severe rutting and distortions in the structure. Therefore, while measuring the resilient modulus in the laboratory,
appropriate load duration should be selected in order to measure a representative resilient modulus for the in situ conditions.

Figures 8 and 9 show the effect of specimen thickness and diameter. It is observed that smaller diameter and thinner specimens yield higher resilient modulus than the larger diameter and thicker specimens. This may be due to the higher confinement of the aggregate particles in the smaller dimension. Apart from the larger diameter and thicker specimens, the probability of higher percentages of microcracks is higher than that of the smaller specimens. Therefore, the rate of energy released in the larger specimens is higher than that of the smaller ones. A similar effect is noticed in Portland cement specimens. Smaller cylinders always yield a higher strength than that of the larger specimens. Therefore, a representative geometry should be selected to have a resilient modulus that matches the actual field conditions.

Figure 10 displays the effect of the interaction between the aggregate size and specimen diameter on resilient modulus. It is found that the effect of coarser gradation is very prominent in the smaller diameter specimen, while it is less in the larger diameter specimen. This shows that using the 100 mm diameter mould or smaller in the laboratory is very sensitive to the aggregate gradation compared to the 150 mm diameter specimens. It is probably owing to the fact that there is a higher degree of confinement in the smaller diameter mould compared to the larger one.

Figure 11 shows the effect of the interaction between specimen diameter and thickness on the resilient modulus. The effect of the diameter is pronounced for the thinner specimen, while this effect is minute for the thicker specimen. It is also observed that thickness has significant effect on the smaller diameter specimen, while not much on the larger diameter specimen.

Figure 12 shows the interaction between the specimen thickness and aggregate size. It is found that the coarser gradation is providing slightly higher effect on the resilient modulus for the thin specimens (35 mm) which is reduced for the thick specimens (65 mm).

Figure 13 shows the interaction between the specimen diameter, thickness and aggregate size. It is clear that the smallest dimension cylindrical specimen with

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**Figure 8.** Effect of specimen thickness.

**Figure 9.** Effect of specimen diameter.

**Figure 10.** Effect of interaction between aggregate size and specimen diameter.

**Figure 11.** Effect of interaction between aggregate specimen diameter and thickness.
coarser aggregate gradation has the highest resilient modulus. This is due to the confinement that occurred during compaction of a small-sized sample with the strong aggregate interlock resulted from aggregate contact by using 20 mm aggregate size. The lowest resilient modulus occurred when the diameter, thickness and aggregate size were 150 mm, 65 mm and 12.5 mm, respectively. This again could be attributed to the less confinement effect compared to smaller samples and to the high probability of the existence of micro cracks which will lead to the reduction of resilient modulus. The smaller 12.5 mm aggregate size also meant that there was less aggregate contact, hence lower aggregate interlocking strength, resulting in a lower resilient modulus.

CONCLUSION AND RECOMMENDATIONS

The results of the $2^{k-1}$ half factorial experimental design of the factors affecting the resilient modulus of a cylindrical sample indicated that it influenced not only the individual factors, but the interactions between these factors as well. It was found that the maximum nominal aggregate size was the most significant factor influencing the resilient modulus, then the load duration, specimen thickness, and specimen diameter. The most significant 2-level interaction was the diameter aggregate size interaction, and the most significant 3-level interactions were the diameter thickness aggregate size interaction. This means that the geometry of the specimen size for a resilient modulus test is critical for it to be a representative of insitu condition. Another research finding was that the effect of the confinement during compaction for 100 mm diameter and 35 mm thick specimens were large, highlighting the need for a suitable geometry for a resilient modulus test with small confinement effect.

REFERENCES

