The effect of aggregate and compaction method on the physical properties of hot mix asphalt

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Abstract. Developing countries such as Malaysia have increased the traffic density in commercial vehicles and overloading trucks which cause tire pressure on the roadway and result into rutting and fatigue cracking in roadways. Aggregate plays an important role in influencing the performance of the flexible pavement. This study aimed to determine the effect of aggregates in terms of types and gradation together in compaction of methods on the resulting prop of laboratory performance to compare the various in term of aggregate types, gradations and compaction methods based on the physical properties and resilient modulus. As a comparative study, the study attempted to compare two types of aggregate (granite and limestone) with the two gradations (upper and lower) for each kind of the mentioned aggregates using Marshall and Gyratory Compaction Methods for asphalt mixtures. Two phases were carried out in this research: determining the optimum asphalt content and comparing the mixtures in different type of aggregate, gradation and compaction. The results of the study on the performance of the mixtures indicated that the granite upper mixtures achieved the best results of Marshall stability, fatigue cracking resist and rutting resist for compacted samples by gyratory compactor.

1. Introduction

Hot mix asphalt (HMA) basically consists of an asphalt cement binder and mineral aggregates. The binder works as a cohesive agent that binds the aggregate particles into the adherent mass. The mineral aggregates represent a stone structure that provides strength and hardness to the hot mix asphalt. The behavior of hot mix asphalt depends on the properties of the individual components and how they react to each other in the system [1]. The temperature mostly plays a significant role in the hot mix asphalt, particularly in binder asphalt and aggregate. The asphalt binder and aggregate are heated together to obtain a fluidity of asphalt binder to cover the aggregate and to dry the aggregate, respectively. A construction project has a type of mixture based on the site conditions. There are many methods used in designing hot mix asphalt such as Marshall, Hveem, and Superpave method [2].

Aggregate type and gradation play an important role in reducing intergranular void spaces. Such reduction reflects the amount of bituminous cement used as a lubricant for mineral aggregates. Moreover, the increase of the voids in the mineral aggregates, and the air voids in the mixture make it porous and water permeability [3].

Gradation is probably the most significant property of aggregates. It affects almost all the important characteristics of an HMA, including strength, stability, durability, permeability, operability, fatigue resistance, friction resistance, moisture resistance and damage [4]. It is considered a key factor in the
resistance of mixture to permanent deformation. The most important concept is that gradation provides
the greatest structural strength (resistance to rutting) for any given type and quality of aggregates [5].
The way aggregates are assessed influences all stability characteristics of mixtures. In addition, it was
pointed that aggregate grading controls the void structure, and therefore, aggregate properties in HMA
pavements oblige such aggregate mixture to drop within a specified range of gradation values. The
result of a previous related study indicated that the value of maximum stability was obtained with the
dense mixture was higher than the open-grain mixture [6]. The study aimed to evaluate two types of
aggregates such as limestone and basalt on three varieties of aggregate gradations in hot mix asphalt
(HMA). The results revealed that the mixture that was exposed to long periods of wetting and/or
freezing/thawing cycles in field preferred to use basalt in preparing HMA, especially for roads, it was
expected to be exposed to heavy axle loads in arid regions [7]. The purpose of this latter study was to
compare the aggregates such as limestone, sandstone and granite in hot mix asphalt. The results have
shown that the reduction of VMA in dens hot mix asphalt leads to increase both longitudinal and
alligator cracking which influence the performance of the mixtures. Moreover, the lower VMA led to
a decrease in the effective asphalt content which in turns reduced the binder film thickness. Asphalt
mixtures of relatively low film thickness are mostly considered to have a lower resistance to cracking.
Thereby, low VMA in asphalt mixtures is used with lower traffic volumes [8].

The compacting characteristic of hot mix asphalt (HMA) blends with different nominal maximum
aggregate size (NMAS) and different gradation at different compaction temperatures. The results
showed that the stability and volumetric properties of Marshall were significantly influenced by the
compaction temperature, which increased the stability of Marshall presented due to the increase in the
compaction temperature. In addition, mixtures with different types of gradations but with the same
NMAS require different compaction energy to reach the predicted density [9]. The influence of
compaction procedures using Superpave gyratory compactor (SGC) and Marshall compactor on
volumetric and mechanical properties of asphalt mixture indicated that it is wrong to set up a number
of gyrations with SGC to compact the specimens with a density that is similar to the obtained one
through Marshall compactor because the number of cycles varies depending on the mixture type. In
addition, it is not certain to use the air-void content to compact specimens with similar characteristics
in-place mixtures. As observed, the mechanical properties are affected by the temperature more than
the compact ability with both procedures. On the other hand, the different SGC in density of
specimens between 80°C and 160°C was about 1-2 % while modulus reduction was between 25 % - 30
%. A higher variation in density reduction was appreciated by the Marshall compactor, which is
estimated between 3% - 5 % when passing from 80°C - 160°C and a modulus loss 30% - 35% [10].
The air void content and the mechanical properties of compacted mixtures were evaluated using both
Marshall and Superpave mixture design methods. Furthermore, the Superpave gyratory compactor
observed better reproduction of compaction that occurs in the field than the Marshall compactor.
However, the specimens that compacted using the Marshall compactor and Superpave compactor
resulted into similar values of resilient modulus. Moreover, the optimum asphalt contents in
Superpave and Marshall proved to be more technically reliable with better fatigue behavior, without
compromising permanent deformation compaction [11]. Previous research also compared between
traditional Marshall Design method and Superpave system design methods in the wearing course
mixes in flexible pavements by evaluating the volumetric, mechanical properties and moisture
susceptibility. The outcomes pointed out the estimated asphalt content for the Superpave mix design
was lower than that of the Marshall Mix Design method. Therefore, the Superpave mix design was
described to be more economical. Furthermore, modified asphalt played a role in improving the
asphalt mixture against rutting by using a trial field section [12].

HMA mixture was also investigated with the fine and filler particles sizes of limestone aggregates
with granite in coarse sizes through laboratory tests. The HMA was submitted by Marshall and
Superpave methods. The results presented better mechanical behavior and gain of mechanical
resistance mainly to permanent deformation [13]. Aggregate properties and filler play a significant
role in asphalt mixtures behavior. In this research, three types of aggregate (limestone, gravel and
basalt) with three types of mineral filler (limestone powder, cement and hydrate limestone powder) were examined. The results illustrated that the use of basalt provided the highest values of Marshall stability, stiffness modulus and indirect tensile strength of the mixture. Yet, for each flow, density and air voids were the lowest values. Likewise, the use of 4% or less of cement content as a mineral filler showed better results than those of other types of mineral fillers [14].

This paper reports a study into comparing mixtures in various type of aggregate, gradation and compaction in term of physical properties and mechanical properties for evaluating the performance of asphalt mixtures capability on resistance to permanent deformation and fatigue cracking.

2. Experimental

The main objective of this research is to compare the granite mixtures with limestone mixtures in their own gradations (upper, and lower) by two laboratory compaction techniques. It also attempts to identify the condition in types of mixture, gradations, and laboratory compaction methods that achieves the best resistance to rutting and fatigue cracking. The laboratory work was divided into two phases. In the first phase, the optimum asphalt content for each mixture was determined (Figure 1). In the second phase, the various compaction methods, different types of aggregate mixtures and gradations were compared in term of the physical properties and mechanical properties (Figure 2).

Fig. 1: The flow chart for first phase
2.1 Materials
The materials used in this study were aggregates, bituminous binders, and fillers. All materials were prepared in accordance with the Standard Specification for Roadworks (JKR, 2008).

2.1.1. Aggregates. The aggregates used in this study are granite and limestone. Some tests such as Los Angeles Abrasion, aggregate impact value and specific gravity were also performed in the study. The aggregates were separated by a sieve analysis into different sizes to obtain the required proportion of the aggregates in each sieve accordance to ASTM C136. Moreover, blending of the aggregates was conducted to achieve the desired gradation which is within the range of ACW14 in accordance to specifications (JKR, 2008).

2.1.2. Bituminous binder. The bituminous binder for asphalt mixtures was 60-70 according to the expected climatic conditions in Malaysia. Some tests were prepared for bituminous binder, including penetration test, viscosity test, softening point test and flash and fire test. The procedures for these tests were carried out according to ASTM specifications.

2.2 Mix design
In this study, the Marshall and Superpave mixed designs were utilized for hot mix asphalt properties.

2.2.1. Marshall mix design. The mixtures in the first phase were accomplished using the Marshall mix design for determination of the optimum asphalt content. In this regard, 60 samples prepared were subjected to 75 blows that are considered for the mix design for heavy traffic.

2.2.2. Superpave mix design. The Superpave mix design was used in this phase. A total of specimens which were prepared in this procedure were 84 samples to compare between the Marshall compactor and the Gyratory compactor using different types of aggregate in mixtures such as granite and limestone in the two gradations (upper and lower). The parameters which were considered to control
the compaction effort of the Superpave machine were 600 KPa of vertical pressure and the angle of the gyration was set up to 1.25. In addition, the gyrations were applied for a rate of 30 revolutions per minute. Thereby, the number of gyrations was simulated for heavy traffic and the settings of the gyratory compactor were adjusted to stop when achieving 4 % air voids.

3. Results and discussion
The results of the laboratory tests were conducted in order to compare the physical properties of mixtures such as bulk density and air voids as well as the mechanical properties of mixtures such as resilient modulus, stability and flow, permanent deformation and fatigue cracking.

3.1. Aggregates tests
The aggregates properties play an important role in affecting the performance of hot mix asphalt (HMA) such as fatigue cracking and rutting which are caused by the poor selection of misuse of aggregates. In this research, some aggregate tests such as Los Abrasion Test, Aggregate Impact Value, Absorption and Specific Gravity conducted are reported in Figure 3.

![Fig. 3: Aggregates test results for granite and limestone](image)

3.2. Bitumen tests
There are a number of tests for evaluating the properties of bituminous materials. These tests presented in Table 1 were generally conducted in order to estimate the properties of bituminous materials.

**Table 1: Bitumen 60/70 Test Results**

| Penetration (mm) | Softening point (°C) | Flash Point (°C) | Fire Point (°C) | Viscosity (cP) at 135 °C | Viscosity (cP) at 165 °C |
|------------------|----------------------|------------------|-----------------|------------------------|------------------------|
| 64.83            | 48.25                | 230              | 260             | 300.8                  | 1531.82                |

3.3. The first phase
This approach was used to find out the optimum asphalt content (OAC) of each type of mixture as shown in Figure 1. The prepared specimens were analyzed to determine OAC based on the density, 4% air voids, stability and Resilient Modulus [15]. The results of the optimum asphalt content were achieved for the procedure as shown in Table 2 according to the UPM method.
Table 2: The Optimum Asphalt Content (OAC)

| Type of aggregate       | OAC (%) for Density | OAC (%) for Stability | OAC (%) for VTM | OAC (%) for Resilient Modulus | Average Optimum Asphalt Content |
|-------------------------|---------------------|-----------------------|-----------------|------------------------------|---------------------------------|
| Granite upper gradation | 5.3                 | 4.7                   | 4.5             | 4.5                          | 4.8                             |
| Granite lower gradation | 6                   | 5                     | 6.8*            | 4.5                          | 5.2                             |
| Limestone upper gradation | 5.1              | 4.3                   | NA              | 4.3                          | 4.6                             |
| Limestone lower gradation | 4.8             | 4.3                   | 5.5             | 4                            | 4.7                             |

* Value not considered in calculation. NA: Not applicable

Based on the optimum asphalt content, it was observed that the granite mixtures in upper and lower gradations scored taken a higher percentage of asphalt content comparing with limestone mixtures in upper and lower gradations. In addition, the percent asphalt content of the lower gradation mixtures was higher than that of the upper gradation mixtures.

3.3.1. Marshall tests analysis for OAC. The Marshall properties were examined based on the optimum asphalt content and Marshall test analysis that were obtained in first phase using the Marshall procedure. The results are presented in Table 3.

Table 3: The Marshall Test Result

| Type of Mixture       | OAC (%) | Density (Kg/cm³) | Stability (KN) | Flow (mm) | VTM (%) | VFA (%) | Resilient Modulus (MPa) |
|-----------------------|---------|------------------|----------------|-----------|---------|---------|-------------------------|
| JKR/SPJ/2008 Spec.    | 4 - 6   | -                | > 8 KN         | 2 - 4     | 3 - 5   | 70 - 80 | > 2000                  |
| Granite upper gradation | 4.8    | 2.401            | 24.23          | 2         | 3.05    | 75.5    | 6200                    |
| Granite lower gradation | 5.2    | 2.298            | 12.49          | 6.9       | 5.92    | 64.1    | 3100                    |
| Limestone upper gradation | 4.6    | 2.469            | 16.1           | 3.5       | NA      | 98.6    | 3800                    |
| Limestone lower gradation | 4.7    | 2.442            | 12.53          | 3.8       | 5.9     | 56.7    | 3845                    |

NA: Not applicable

The above results of stability and stiffness showed that the values are in accordance with the range stated in the JKR specifications. As for the flow, the obtained results showed that all values are in the range except for granite lower gradation mixture. In term of VTM and VFA, the granite upper gradation mixture values were also in the range.

3.4. Second phase
The aim of this approach was to compare the granite mixtures with limestone mixtures in terms of physical properties such as density and air voids and mechanical properties such as resilient modulus, stability and flow, rutting and fatigue cracking of mixtures based on the results obtained from the preliminary approach. These factors showed a relatively good comparison between granite mixtures.
and limestone mixtures including the Marshall Compaction Method and the Gyratory Compaction Method.

3.4.1. Bulk density and air voids. The most important factor that affects the long-term durability of the hot mix asphalt (HMA) is the mix density, especially when it is accomplished with compaction. Furthermore, the density of the HMA material increased when the air void content of the mixture decreased, which implies that they are inversely proportional to each other. Therefore, the air voids of HMA in order to properly design should be within the range (3% - 5%) [16]. The results obtained from our comparison based on density and air voids are shown in Table 4.

| Type of aggregate          | Density (kg/m³) | Air voids (%) |
|----------------------------|-----------------|---------------|
|                            | Marshall        | Superpave     | Marshall | Superpave |
| Granite upper gradation     | 2.381           | 2.368         | 2.3      | 2.83      |
| Granite lower gradation     | 2.344           | 2.374         | 3.34     | 2.1       |
| Limestone upper gradation   | 2.482           | 2.439         | 0.92     | 2.63      |
| Limestone lower gradation   | 2.484           | 2.478         | 0.72     | 0.96      |

From Table 4, it is evident that the high-density value resulted into low air voids. In addition, the air voids were less than the range (3% - 5%) except for the granite lower gradation mixture compacted by the Marshall Compactor Method. Furthermore, all of the mixtures appeared susceptible to permanent deformation, thus excluding the granite lower gradation mixture used to the Marshall Compactor. As seen, the limestone mixtures resulted into lower values of air voids compared with granite mixtures. Therefore, the limestone mixtures need improvement to resist the rutting.

3.4.2. Height & compaction. Compaction is one of the main factors significantly affecting the asphalt mixtures. In this research, the results were observed based on the height of samples in different compaction methods such as the Marshall compactor and the gyratory compactor for each mixture as shown in Table 5.

| Type of aggregate          | Average Height (mm) | Compaction (%) |
|----------------------------|---------------------|----------------|
|                            | Marshall (actual)    | Superpave (actual) | Marshall (actual) | Superpave (actual) |
| Granite upper gradation     | 65.7                | 68.3            | 97.7              | 97.17             |
| Granite lower gradation     | 67.4                | 68.9            | 96.66             | 97.9              |
| Limestone upper gradation   | 62.5                | 66.7            | 99.08             | 97.37             |
| Limestone lower gradation   | 62.6                | 66.7            | 99.28             | 99.04             |

The above results for the height of samples indicate that the samples compacted using the Marshall compactor yielded less height comparing with the specimens compacted utilizing gyratory compactor. On the other hand, the granite mixtures were higher than the limestone mixtures. These results are in line with results of some previous studies, which indicate that the granite is stiffer than the limestone. In addition, a decrease in the height of the samples was observed, and it could be attributed to increasing the compaction of specimens except for granite lower gradation mixture. Based on the
results of compaction, the mixtures containing limestone of aggregate obtained a higher value than mixtures containing granite of aggregate.

3.4.3. Marshall stability & flow. The Marshall stability and the flow test represent a real experimental and they are not substantially correlated with the performance. However, they aid in evaluating the properties of the performance of the HMA mixtures. The differences between the stability and flow test in granite mixtures with limestone mixtures in various compaction methods are highlighted in Table 6.

| Type of Mixture            | Stability (KN) | Flow (mm) |
|----------------------------|----------------|-----------|
|                            | Marshall       | Superpave  | Marshall | Superpave |
| Granite Upper Gradation     | 27.48          | 22.87     | 3.56     | 3.9       |
| Granite Lower Gradation     | 16.47          | 17.54     | 3.59     | 4.24      |
| Limestone Upper Gradation   | 16.12          | 15.84     | 4.19     | 4.13      |
| Limestone Lower Gradation   | 13.23          | 11.55     | 5.36     | 4.16      |

In terms of the assessed performance, the aggregate upper gradation mixture gave the highest value of stability over other mixtures when it was subjected to compact using the Marshall compactor and the gyratory compactor. As far as the flow is concerned, all the limestone mixtures provided values above the range of specification using the Marshall compactor and the gyratory compactor whereas the granite mixture values were within the range of specification except for the granite lower gradation mixture using the gyratory compactor. The range of flow is normally between 2 and 4 mm.

3.4.4. Resilient modulus results. The resilient modulus test was performed using the Universal Asphalt Testing Machine, MATTA, according to the ASTM test method D4123 (ASTM, 1995). Each sample was tested at 25 C° after 4 hour-conditioning. The peak load was applied 1200 N along the vertical diameter of the sample. The test sequence containing a 5 count of conditioning pulses was followed by 5 loading pulses. The pulse period and pulse width were 3000 ms. The rise time was measured at the points of 10 % and 90 % of the peak force and force pulse. The results of resilient modulus are illustrated in Figure 4.

![Fig. 4: Marshall versus Suprpave in Resilient Modulus](image)
Figure 4 provides a summary of comparison in Resilient Modulus for whole mixtures in this research. The results showed that the mixtures conducted by the Marshall compactor obtained higher values of Resilient Modulus than those mixtures which were performed utilizing the gyratory compactor except for the granite lower gradation mixture as well the granite upper gradation mixtures as both demonstrated a higher Resilient Modulus than the limestone upper gradation mixtures. In contrast, the granite lower gradation mixtures have a lower value of Resilient Modulus than the limestone lower gradation mixtures. The results indicated specimens compacted at a low density normally have lower Resilient Modulus than those compacted at a higher density. Moreover, the magnitude of difference was a function of some parameters, including the particle shape and fines content.

3.4.5. Permanent deformation results. The permanent deformation of the pavement occurs by the passage of heavy vehicles as each wheel passes the pavement deflects downwards and then bounces, thus leaving an irrecoverable downwards deformation. Such deformation accumulates and after millions of passes and the pavement requires rehabilitation. The test was conducted using the Asphalt Universal Testing Machine (MATT). The parameters relied on a haversine waveform with 200 kPa stress levels. Thereby, test temperatures of 40 °C were selected. The load was applied for 0.5 s followed by a rest period of 0.1 s. The sample was terminated after 3600 load cycles or until the accumulated deformation reached 10%. The outcomes are shown in Figure 5.

![Fig. 5: The Permanent Deformation Test Results](image)

As it can be seen from Figure 5, the samples were compacted using the gyratory compactor achieved a lower displacement than specimens compacted utilizing the Marshall compactor. Otherwise, the limestone mixtures demonstrated a higher displacement than granite mixtures. In brief, these results indicated that the stiffness and resistance to permanent deformation of asphalt mixtures strongly depend on the mixture composition and the degree of compaction. In addition, the mixtures containing a lot of coarse aggregates have shown more resistance to permanent deformation except for the granite mixtures which were compacted by the gyratory compactor.

3.4.6. Fatigue cracking. The fatigue cracking test was accomplished utilizing the Universal Testing Machine (MATT). The tests were set out under the following conditions as100 N seating force, 0.12s loading time,1.5s rest time, 1000 N cyclic loading and the conditioned temperature 20°C c was selected. Furthermore, the tests were terminated when they reached a maximum cycle count of 3600 (1 hour) or a maximum axial displacement of 9 mm. The method for determining the fatigue characteristics of mixtures was used in this study by employing the Indirect Tensile Fatigue. The
specimens were divided into two types based on their thickness. The first type was performed using approximately 40 ± 5 mm of the middle of the sample and the second type was conducted utilizing the entire sample. The results of tests are presented in Table 7.

Table 7: Indirect Tensile Fatigue Results

| Type of Mixture                  | Thickness (mm) | Displacement (mm) | Thickness (mm) | Displacement (mm) |
|----------------------------------|----------------|-------------------|----------------|-------------------|
| Granite upper gradation Marshall | 37             | 0.67              | 66             | 0.23              |
| Granite upper gradation Superpave| 35             | 0.53              | 68             | 0.66              |
| Granite lower gradation Marshall | 35             | 1.43              | 68             | 0.33              |
| Granite lower gradation Superpave| 37             | 0.93              | 68             | 0.69              |
| Limestone upper gradation Marshall| 35           | 1.1               | 63             | 0.82              |
| Limestone upper gradation Superpave| 36            | 0.95              | 66             | 1.3               |
| Limestone lower gradation Marshall| 37            | 1.19              | 63             | 0.81              |
| Limestone lower gradation Superpave| 37            | 1.32              | 66             | 1.05              |

Based on the results of Table 7, the displacement of fatigue cracking for full samples compacted by the Marshall compactor was significantly lower than the displacement of full samples compacted using the gyratory compactor. Furthermore, compaction seemed to play a significant role in determining the indirect tensile strength in the asphalt mixtures as proved by previous studies. Thereby, high compaction yielded a lower displacement of fatigue cracking. On the other hand, the type of aggregate in mixtures is one of the parameters that cause immediate fatigue cracking. Therefore, the weak aggregate such as limestone indicated a higher displacement than granite. However, as noticed from the results in Table 7, when the thickness of approximately 40 ± 5 mm in the middle of the sample was considered to investigate the indirect tensile fatigue, the results indicated that using the Marshall compactor resulted into a higher displacement than the gyratory compactor except for limestone lower gradation mixtures.

3.4.7. Summary of results. Several tests such as density, air voids, Marshall stability, flow, resilient modulus, permanent deformation and fatigue cracking were performed in the second phase of this study. These tests were performed to compare compaction methods: the Marshall compactor and the gyratory compactor in four mixtures: granite upper gradation mixtures, granite lower gradation mixtures, limestone upper gradation mixtures and limestone lower gradation mixtures. The results of the study obtained from these various tests are summarized in Figure 6.
4. Conclusions
The most important findings of this study are summarized based on the research objective that can aid in future as follows:

The results of comparison of the physical properties in the mixtures show the highest values of the Marshall stability achieved with the granite upper gradation mixtures as well as the flow of the granite upper mixtures and the granite lower mixtures compacted by the Marshall compactor are within the range (2-4) mm. On the other hand, the limestone lower gradation mixtures resulted into the lowest values of air voids. Otherwise, the granite lower mixtures gave the lowest values of resilient modulus compared to other mixtures.

Based on our comparison of the compaction methods, the mixtures compacted by the Marshall compactor achieved the highest values of Marshall stability except for the granite lower gradation mixtures and the flow which are not within of the range (2 – 4) mm and the granite upper gradation mixtures and granite lower gradation mixtures compacted by the Marshall compactor. All mixtures compacted by the gyratory compactor gave a higher percentage of air voids and resilient modulus values than the mixtures which were subjected to the Marshall compactor except for the granite lower mixtures.

The results of permanent deformation and fatigue cracking indicated that the granite upper gradation mixtures compacted by the gyratory compactor and the granite lower mixtures compacted by Marshall compactor fulfilled the best result of rutting resist. In addition, the granite upper gradation mixtures provided the best resistance of fatigue cracking with both compaction methods: the Marshall compactor and the gyratory compactor.

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