Effect of Compaction Methods on the Morphology of Aggregates in Hot Mix Asphalt

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Abstract  Hot mix asphalt plays a very important function in determining a pavement’s capacity with regard to major failures, such as fatigue, permanent deformation, and thermal-associated cracking. Hot mix asphalt's behaviour is affected by the mechanistic attributes and shape of its constituent aggregates, alongside the geometric properties of those aggregates such as position and orientation. This paper focused on characterising the aggregates used in producing hot mix asphalt and their allocation within such asphalt mixes using digital image processing (DIP) methods. Additional laboratory tests were also performed in order to match compaction methods used in the laboratory with those occurring in the field. The results provided evidence that this methodology offers simpler and faster ways to provide a full indication of the behaviour of aggregates during compaction and to determine their tendency to randomise throughout the compaction process. ImageJ Fiji software was found to be competent to characterise aggregates’ constituent forms and orientations; randomness, represented by vector magnitude, is determined in an aggregate directional array as an orientation factor (Δ) and used as a reference for better interlocking where heavy compaction is used. This factor ranges from 0 to 100%, where 0% indicates completely random particles and 100% indicates that particles are exactly within a single array. Mixes compacted with a Superpave gyratory compactor (SGC) and roller compactor had aggregate particles with relatively higher numbers of contact points and randomness than those mixes compacted using a Marshall Hammer. The results also showed that vector magnitude is an approach to determining field compaction, with results of 82.6, 67.43, and 90.7% for SGC, Marshall Hammer, and roller compactor compaction, respectively. This makes it clear that SGC and roller compaction are the nearest types of compaction to those used the field. DIP also showed that the percentage of contact points in various types of compaction were 63.6 and 92.9% for Marshall and roller compacters, respectively, while field core was found to have 88.4% contact points when produced by SGC.

1. Introduction

Hot mix asphalt (HMA) is a complex material composed of an asphalt binder, mineral aggregates, and air voids. The performance of the asphalt mixtures is influenced by the type of compaction process used during production [1], which can change many of the considerations that affect the performance of asphalt mixtures such as aggregate orientation and contact points [2]. The existence of a contact point between two adjacent aggregate constituents is formulated when they are isolated individually at a fixed distance, as shown in Figure 1. Contact points are a very important issue in terms of the mechanical properties of hot mix asphalt, affecting the enhancement of mixture stiffness to withstand external load or internal stresses.
that might otherwise lead to cracks and other distortions such as fatigue and permanent deformations [3]. However, Tashman noted that the numbers of contact points seen among adjacent particles follow the parameters (angle, stress, temperature and thickness of specimen) developed during compaction[4]. Another study by Sousa reported that samples manufactured and compacted via kneading compaction showed large numbers of contact points as well as higher performance with regard to permanent deformation compared with those produced by other compaction methods [5]. Masad further highlighted that rising the gyration numbers up to 100 generated a propensity to more disparate orientations for particles, and that gyration numbers exceeding 100 caused aggregate skeletons to exhibit wider random orientation [6, 7]. Hunter reported that fabricating samples with plate compaction provided small orientation angles for aggregates in comparison with other compaction methods such as gyratory or vibratory [8]. These results show that this affects the strength of permanent deformation. Masad and Hunter concluded that a higher number of gyrations was necessary to realise the equivalent orientation level to that existing in reality.

Figure 1. Contact between aggregates

Aggregate shape properties can be obtained using Superpave methodological methods, including the use of a calliper gauge to reveal the constituents’ dimensions and visual detection for aggregate constituent angularities [9, 10]. Traditional procedures such as these are costly and time-dependent, though they can help characterise aggregates shape; they also present further disadvantages such as inadequacy to distinguish between fine and coarse aggregates’ characteristics, and the fact that aggregate attributes captured through indirect measurements may be affected in one or more property by such measurement [11]. The arrays of an aggregate constituent may be defined by the angle of confinement of the aggregate constituent's major axis with the horizon of the digital image [12, 13]. This axis can also be identified as the largest separated distance amidst two parallel coordinates in the particle's body [14, 15].

2. Objectives

The objectives of this paper are to characterise the aggregates used in producing hot mix asphalt, including examining the distribution of aggregate within asphalt mixes using DIP methods, matching compaction methods in the laboratory with those occurring in the field, and the quantitative realization of the two-dimensional (2-D) orientations of coarse aggregate particles (D ≥ 1.18 mm) in AC mixtures.

3. Materials and Methodology

Two types of gradation mixes were used in this study, as shown in Figure 2, to determine aggregate orientation detection limits; these are referred as coarse and fine mix, as specified by the State Commission of Road and Bridges (SCRB), Iraq [16]. The aggregates were bought from Al-Nebae quarry. Optimum
asphalt content of coarse and fine mixes (4.6% and 4.8%, respectively by weight of aggregate) were then determined. Eight asphaltic samples of 15 cm in diameter with thicknesses of 8.7 cm were then compacted using a Superpave gyratory compactor according to AASHTO designation T-312.

Furthermore, alternate AC specimens (coarse and fine) were also fabricated by using two different compaction modes (Marshall and roller compactor) to examine the influence of compaction mode on particle orientation within hot mixes. Twelve samples (10 cm diameter by 6.5 cm thick) were fabricated using a Marshall compactor according to AASHTO designation R 68, and six field cores of 10.16 cm diameter and 6.25 cm thick were recovered according to ASTM D5361, from a section of roadway pavement compacted using a conventional vibratory steel roller followed by a rubber-tire roller by the project department of the university of Al-Nahrain. In addition, six specimens of slabs (40 by 30 cm) were also fabricated using a roller compactor according to ASTM D8079, to detect the effect of confinement on the morphological properties of aggregate and its particle orientations.

The DIP system used in this study consisted of a Nikon D5300 Camera with 24.1 megapixels and a Microlens of 50 mm; no specific lighting considerations applied throughout the process. In the laboratory, prepared AC specimens and field core specimens were cut, utilising a masonry rotary saw, into multiple vertical or horizontal sections as illustrated in Figure 3. The specimen cross-sections were photographed with a tape measure fixed behind the sections in order to calibrate the digital images processing. All images were treated with image editing and analysis software called ImageJ that makes it possible to find a value representing the uniformity of the distribution of particles within the observed section of the sample. To quantify the directional array of aggregate, an orientation factor called the vector magnitude (Δ) was determined according to Equation.1 [17, 18]:

$$\Delta = \frac{100}{N} \times \sqrt{\sin(\theta_k)^2 + \cos(\theta_k)^2}$$

where:
- Δ: vector magnitude;
- θk: the enclosed angle amidst the horizontal line with respect to the digital image and aggregate particle [13]; and,
- N: the number of aggregates constituents that appear in the image subjected to analysis. The orientation factor (vector magnitude) represents the aggregate consistent distribution; which fluctuates with a range of 0 to 100%: the value of 0% suggests totally random particles allocation, while 100% indicates that the particles are arranged wholly in a single array.
3.1 Digital images Analysis

3.1.1 Aggregates properties

Figure 2. Mixes gradation

Figure 3. Specimen's Preparation
The properties concerning aggregate shape, such as percentage of elongated/flat particles, contact points, and angularities, were detected using DIP techniques. Before processing, a picture on a plane surface was captured, converted into a grayscale and passed through restoration, filtration, and segmentation to allow border detection, as shown in Figure (4).

![Figure 4. Digital images of a gyratory compacted horizontal sections (a: digital image; b: filtered image; c: grayscale image and d: binary image)](image)

3.1.2 Aggregate morphological properties and Hot Mix Asphalt Microstructure characterisation.

Aggregates in hot asphalt mixes constitute approximately 80 to 85 percent by weight of the mixes [19], making it very important to characterise the properties of the aggregates used. There are many specifications for this purpose, but the Superpave specifications classify aggregate properties as consensus properties and source properties.

Elongated or flat particles, those having a ratio of length to thickness greater than a specified value, were selected according to ASTM D 4791, and three sources of aggregate were chosen (Nibaai, Dyala, and Karbala) with two length to width gauges of aggregate particles and width to thickness gauges. Elongated and flat particles in hot asphaltic mixtures may reduce workability, as well as could exposing the substance to fritter on compaction and under traffic loads. The designations of Superpave thus indicate that the morphology of aggregate with regard to its elongated and flat constituents of a ratio of 5 to 1 should not exceed 10%, based on an intensity of traffic volume of moderate or high level. Figure (5) shows the laboratory results of flat and elongated particles for each local aggregate; it is clear that the aggregate from the Nibaa area contained the lowest proportion of flat and elongated particles by around 25% and 14.2% in comparison with Dyala and Karbala respectively, suggesting that the Nibaa area has good consensus properties among its quarries.
Figure 5. Flat and Elongated Particles for each Source Aggregate

The other issue associated with the geometry of the particle is angularity. Angularities refer to the magnitude of variations in the sand or gravel corners [2]; these formations’ parameters are referred to as surface textures and they can cause a increase inner friction amidst particles, placing leverage on HMA performance. Manual inspection of each aggregate particle according to ASTM D 5821 is extremely important in order to determine the presence of shattered faces. However, these tests do not assess angularity levels (sharpness) or texture. Superpave designations clearly demonstrate that the smallest rate of fractured faces in association with traffic volumes or to the proximity of particles to surface level is required. Figure (6) shows the angularities for the three types of coarse aggregate, which illustrates that Nibaai's aggregate had more fractured faces than Dyala and Karbala, by 35.9% and 77.9%, respectively.

Figure 6 Fractured Faces for Selected Sources

3.2 Analyses of Criteria Adopted for Aggregate Cross Sections

Digital image processing procedures can reveal further morphological factors which identify the geometry of particles’ cross sections. Figure (7) shows several parameters of a constituent cross-section as found and analysed this study:
Area: the total of the selected object in square units (e.g., mm$^2$, cm$^2$) or square pixels.
- The centroid: the x and y coordinates for all pixels in the image, selection, or object in terms of the brightness-weighted average such pixels, referred to using the YM and XM headings.
- Perimeter: the measurement of the outside circumference of selected objects (particles).
- Feret Diameter: defined as the distance joining the two parallel planes restricting the object perpendicular to that direction [19].

\[
\text{Feret diameter} = \left( \frac{4 \times \text{area}}{\pi} \right)^{\frac{1}{2}}
\]

- The Major Axis: the greatest distance between two points on the boundary contour.
- The Minor Axis: the perpendicular to the major axis.
- Shape signifiers: many shape signifiers are used to describe the morphology of aggregates; the following shape signifiers were adopted in this study:
  a. Aspect ratio: the aspect ratio of a particle’s fitted ellipse can be defined as the ratio between the major axis and the minor axis length [20]:

\[
\text{AR} = \frac{\text{Major Axis}}{\text{Minor Axis}}
\]

b. Roundness: Aggregate sphericity and orientation are determined through this parameter, which is the inverse of aspect ratio and calculated as [18]

\[
\text{Roundness} = 4 \times \frac{\text{Area}}{\pi \times \text{[Major Axis]}^2}
\]

Roundness not only reflects the form of particles but also provides an important indication of the orientation of aggregates.

4. Testing and Results

As soon as specimen fabrication and imaging analysis were accomplished, considerable information was available. Table 1 shows the contact point numbers per cross section for each mix and compaction type. It is immediately obvious that the Superpave gyratory compactor process produces the most contact points in comparison to other types of mixing, and it is clear that compaction type affects the number of contact points significantly, with SGC specimens showing higher numbers of contact points by 53% and
6% than Marshall and roller compactor specimens, respectively, for the same gradation; this is due to the effect of the shear force produced in SGC, which makes particles more dispersed.

Table 1. Numbers of Contact points in Mix Cross Sections

| Type of compaction | Coarse Mix | Fine Mix | Field Core |
|--------------------|------------|----------|------------|
| Gyratory           | 300        | 308      |            |
| Marshall           | 196        | 181      | 276        |
| Roller Compactor   | 290        | 300      |            |

Figure 8 illustrates a comparison between aggregate roundness using different types of compaction and fields, which approaches the results obtained by traditional techniques of angularity; the results of roundness testing show that adapting Superpave traditional tests suggests that more than 80% of particles had non uniform shapes (not rounded), which can be explained by the position of the cut particles in the cross sections. The gravel tends to sit regularly while placed in the mould, but the impact of the shear forces generated in the SGC and the roller compactor tilt it to an angle which could reduce roundness.

Table 2 shows the vector magnitude by type of compaction, which shows that most orientations tend to randomness, with gyration compaction exacerbating this in comparisons of Marshall, roller compactor and field compaction. It is clear that the vector magnitude in vertical sections is larger than in horizontal sections in SGC, Roller, and field compaction by around 40 to 75% for many reasons, including temperature of compaction, which decreases the viscosity of the asphalt binder, enhancing the lubricant effect which allows the sliding of particles on each other, and the thickness of the sample, which prevents the particles from re-orientating in the vertical direction as much as in the horizontal due to their small diameter. The Marshall Samples showed results contrary to those reported under the effects of diameter/thickness ratio, however, with vector magnitudes in the vertical sections less than in horizontal sections by 30 to 35%.

![Figure 8. Comparison between Aggregate Roundness Using Different Types of Compaction](image-url)
Table 2. Average Vector Magnitude According to Type of Compaction

| Compaction type      | Coarse Mix | Vector Magnitude | Fine Mix | Field Core |
|----------------------|------------|------------------|----------|------------|
|                      |            | H                | V        | H          | V          |
| Gyration             | 13.49      | 23.89            | 15.34    | 26.85      | 15.3       | 28.9      |
| Marshall             | 54.29      | 38.31            | 40.22    | 31.2       |            |           |
| Roller compactor     | 17.6       | 26.22            | 21.7     | 35.12      |            |           |

Figure (9) and Figure (10) illustrate the variation in average vector magnitude for horizontal and vertical sections related to type of compaction for coarse mix and fine mix, respectively, in comparison with field core; these show that the gyration compactor creates the least vector magnitude in horizontal and vertical sections, approaching zero, which indicates a high degree of randomness in comparison with mixes produced by Marshall, roller compactor, and field core compaction.

Figure 9. Average Vector Magnitudes for Horizontal Sections of Coarse and Fine Mixes in Comparison with Field Core

It is clear that gyratory compactor samples have non-uniform orientation, that is, lower vector magnitudes, in comparison to Marshall and roller compactor samples. In addition, the vector magnitude for horizontal cross-sections of SGC samples was simulated in the field as 90.7%, while Marshall and roller compactor samples were 82.6% and 67.43% respectively. In the vertical cross-sections, the vector magnitude for SGC samples approached 93%, while Marshall and Roller compactors achieved convergence at 82% and 92%, respectively.

Plate 1 shows an illustration of a sample of the digital image outputs of the aggregate attributes in an AC horizontal cross section compacted with SGC.
By examining the results obtained from the digital image analysis of the asphalt sections, it can be observed that gyratory and roller compactor allow spreading through the section more than Marshall compacting by around 50 to 60% for the former and 10 to 20% for the latter, as illustrated in Table 3.

**Table 3.** Statistical results from digital image processing

| Mix      | Compaction Method | Section Orientation | Dimension >1.18 mm | No. Of Aggregate Per cm² | Average Area Per Aggregate (mm²) | Ratio |
|----------|-------------------|---------------------|--------------------|--------------------------|---------------------------------|-------|
|          |                   | H V H V              | H V                | H V                      |                                 |       |
| Gyratory | 4 3               | Major               | 6.55 7.42          | 45.36 26.57              | 1.7                             |       |
|          |                   | Minor               | 4.22 3.83          | 42.12 22.2               | 1.89                            |       |
|          |                   | Feret               | 3.64 3.571         | 44.87 27.3               | 1.643                           |       |
|          |                   | Major               | 3.84 4.32          | 29.3 26.88               | 1.09                            |       |
|          |                   | Minor               | 3.01 2.74          | 24.42 23.7               | 1.03                            |       |
|          |                   | Feret               | 3.66 3.52          | 27.5 25.9                | 1.06                            |       |
|          |                   | Major               | 6.21 6.89          | 44.52 26.65              | 1.67                            |       |
|          |                   | Minor               | 3.87 3.78          | 42.74 34.74              | 1.23                            |       |
| Roller  | 2 2               | Minor               | 3.87 3.78          | 42.74 34.74              | 1.23                            |       |
| Compactor|                   | Feret               | 3.21 3.44          | 43.6 27.94               | 1.56                            |       |
| Mix 2    | Gyratory | Major               | 5.8 6.2            | 38.98 23.91              | 1.63                            |       |
|          | 4 3               | Minor               | 4.1 3.6            | 37.2 25.65               | 1.45                            |       |
| Material                      | Feret 1 | Feret 2 | Feret 3 | Major 1 | Major 2 | Major 3 | Minor 1 | Minor 2 | Minor 3 | Ratio |
|-------------------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|-------|
| Marshall                      | 2.9      | 3.1      | 38.4     | 25.43    | 1.51     |          | 3.31     | 2.84     | 23.2     | 22.97  | 1.01  |
| Roller Compactor              |          |          |          | 3.54     | 2.14     | 24.1     | 23.62    | 1.02     |          |       |
| Field core                    |          |          |          | 6.6      | 5.44     | 43.5     | 28.06    | 1.55     |          |       |
| Steel roller & tire compactor |          |          |          | 5.4      | 3.59     | 42.7     | 32.59    | 1.31     |          |       |
|                               |          |          |          | 5.9      | 4.89     | 43.4     | 28.55    | 1.52     |          |       |
|                               |          |          |          | 5.8      | 5.21     | 41.25    | 28.25    | 1.46     |          |       |
|                               |          |          |          | 4.32     | 4.22     | 38.9     | 27.39    | 1.42     |          |       |
|                               |          |          |          | 4.85     | 3.76     | 40.16    | 27.69    | 1.45     |          |       |
Plate 1. Sample: Digital Analysis Results of Aggregate Properties
5. Results and Discussion

The digital image processing methodology offers an easier and faster way to develop a full indication of the behaviour of aggregates during compaction and their tendency to randomness throughout the compaction process. Image analysis can supply accurate detail comparisons to those realised by laboratory tests in terms of shape descriptors. Image analyses also present statistical distributions while laboratory (traditional) techniques present only an average magnitude for all parameters. Roundness results, captured via DIP, illustrate a good match with results obtained in the laboratory. The software used in this work, ImageJ Fiji, has readily able libraries to describe aggregate constituent orientation and shape; furthermore, the DIP techniques can capture the parameters of internal structures related to HMA, including contact points, interlock, and even orientation, as better interlocks between aggregate constituents could be an indication of distribution randomness.

Mixes compacted with SGC and roller compactor showed higher randomness levels and contact point numbers for aggregate particles in comparison with mixes compacted by Marshall Hammer. Statistical results from the digital image processing and analyses as seen in Figures (10) and (11), Table 1 and Table 2, show that samples compacted with SGC had the lowest vector magnitudes for horizontal cross-sections of SGC samples simulated the field at 90.7%, while Marshall and roller compactors had 82.6% and 67.43%, respectively. In the vertical cross-sections, the vector magnitude for SGC samples approached to field measurements, at 93%, while the Marshall and Roller compactor types achieved convergence of 82% and 92% respectively. Figure 9 illustrates the comparison between aggregate roundness using different types of compaction with field results. According to the observations, shape factors and the sizes of aggregate constituents on vertical cross sections are less varied than in the horizontal cross-sections of the asphaltic concrete mixes. The difference in shape factors represents the fact that the aggregate particles on the vertical AC cross-section are more elongated than in the horizontal AC cross sections.

Table 3 summarises the ratio of aggregate coverage by specimen cross-section, and this indicates that Gyratory and roller compactor allow spreading out through the section more than Marshall compacting by a range of 50 to 60% and 10 to 20% for SGC and roller compactor, respectively.

6. Conclusions

This paper inspected aggregates’ attributes, distributions, and orientations within prepared local asphalt mixtures samples by utilising DIP procedures. This allows summarisation of the following facts:

- The digital image process approach reduces time and effort required as well as permitting aggregate characterisation, constituent orientation, and shape identification; using ImageJ software thus reveals the internal structure of HMA, such as segregation, contact points, and orientation.
- The results show that average vector magnitudes are 13.49 to 26.85 for Gyratory compactor, 31.2 to 54.29 for Marshall Hammer, and 17.6 to 35.12 for roller compactor compaction, in comparison with field core vector magnitude of 15.3 to 28.9. This indicates more random orientations for particles compacted with SGC or Roller compacters, which simulate field compaction, than those formulated by Marshall hammer.
- The Digital Image processing analysis illustrates that the number of contact points were 308, 196, and 312 in SGC, Marshall, and roller compactor specimens, respectively, while field core showed 276 contact points. The specimens fabricated with SGC and roller compacter may thus show higher levels of mechanical properties.
- SGC samples had the lowest average vector magnitudes for horizontal cross-sections of SGC samples at 90.7%, while Marshall and roller compactor samples were 82.6% and 67.43% respectively.
- In the vertical cross-sections, the vector magnitude for SGC samples matched the field sample by 93%, while Marshall and Roller compactor samples achieved convergence of 82% and 92%, respectively.
• Gyratory and roller compactors can spread the aggregate particles throughout the sections more than the Marshall Hammer by a range of 50 to 60% and 10 to 20% for SGC and roller compactor, respectively.

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