Influence of Asphalt Concrete Internal Structure on their Packing and Mixture Properties

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Abstract: Hot Mix Asphalt (HMA) pavement is most used in road construction in Iraq due to its economic benefits and ease of maintenance. Several factors are affecting the performance of HMA in the field. One of the major factors is aggregate gradation. The Universal Specification for Roads and Bridges in Iraq (SCRB) specifies limits for the different types of asphalt layers and allows tolerance for the designed aggregate gradation. In the current asphalt industries, it quite difficult for contractors to achieve the required job mix due to difficulties in sieves control. This study concentrates on the effect of aggregate gradation deviations on the required specification performance. A mid gradation of the binder asphalt mixture was selected as a reference mix and more than 20 deviated mixtures were then prepared. Typical Marshall routine trials were performed on the prepared admixtures to evaluate the mixture properties. Bailey packing theory for mixture evaluation (Coarse Aggregate Ratio CA, Coarse Portion of Fine Aggregate F\textsubscript{Ac} ratio) was also used to understand the impact of these deviations on the particle arrangement and mixture performance. Results showed that minor aggregate deviations do not greatly affect the mixture performance, however, a large deviation in coarse aggregate results in a drop in Marshall properties. Results showed that the Bailey method for performance evaluation is a good tool to understand the mixture performance. This paper aims to study the influence of aggregate gradation deviations on the mixture performance.

Keywords: Aggregate gradation; asphalt concrete mixtures; packing theory; Bailey ratios.

1. Introduction

Hot mixtures of asphalt (HMA) are complex materials consisting of asphalt binder, mineral components, and air voids [1]. As known, asphalt performance is determined by the type of aggregate gradation [2,3]. Any changes in aggregate gradation result in a change in many factors that in turn affect the performance of asphalt mixtures such as directions and points of contact [4,5]. Golalipour et al. [6] studies the effect on the performance of rutting in asphalt pavements by the aggregate gradation. They have chosen aggregate gradations with a nominal size of 19mm and used three different gradations, the maximum limit, the minimum limit, and a middle gradation according to The Asphalt Institute. The Marshall test results showed that the maximum gradation limit was of the highest stability and that the minimum gradation limit was the lowest. While Ahmed and Attia [7] showed that coarser aggregate combats permanent deformation better than fine aggregate by using four types of aggregate gradation and conducting a wheel tracking test. The combinations are referred to as coarse gradations, fine gradation, open gradation, and dense gradation according to the Egyptian requirements. Since it was established there have been a lot of efforts to validate the basic concept and Bill Pine, the Heritage Research Group, has promoted its approach in recent years [8].
The "Bailey gradation method" is primarily a tool to develop and analyze mixing gradations in the laboratory and the field. It provides a better grasp of aggregate packaging and its influence on compatibility and volumetrics for designers and contractors [9-11]. Aggregate packing is the focus of the Bailey approach. The particles that form the coarse aggregate structure and fit in the voids within that structure must be established to better understand aggregate packing. The packaging properties are based on various factors: aggregate shape, strength, and texture, combined mixture gradation, and the compact stress type and amount [12-14].

For example, cubic particles are denser than flat, extended particles. Smooth particles more easily slide along than raw surface texture [15,16]. The gradation, the mix between different sizes influences also the way the mixture fills the voids created by larger particles. Similarly, aggregates of varying strength compact differently depending on how they behave when compacted [17]. For example, a fine blend plays a much more important role in the strength of the fine aggregate than a coarse mixture [18]. Finally, with the Bailey method, the designer chooses a skeleton that can withstand continuous deformation, and adjust the VMA by modifying the packages for coarse and fine aggregates to provide an adequate asphalt binder for the mixture [19-21]. Maybe this has led to some of Iraq's concerns. Field Compaction has inherently stressed the need to design mixes with enough VMA, which has enhanced the need to better understand the overall design of mixes.

This research aims to understand the asphalt mixture performance when aggregate gradation has deviations which greatly affects its packing. The objectives of this research are to make a mixed design of the binder course control mixture according to the SCRB specifications and apply deviation on aggregate gradation. The samples will then be tested to examine the mixture performance and apply the Bailey ratios to understand the mixture performance.

2. The Bailey method principles

A further part with a detailed background and fundamental principles of the Bailey method can be found [22]. Vavrik et al. [22] recommended sieve size No. 8 as the primary control sieve (PCS) for admixture with 12.5 mm NMAS. The proportion passing sieve size No. 8 (P8) was preserved constantly at 32% and 29% for Plant 1 and 2 materials respectively. However, The VMA values shown in bold do not fulfill the minimum 15 percent requirement. The values for OAC and VMA of Plant 2 compared to those of Plant 1 compounds are higher. Garcia et al. [23] concluded in this study that the mix of design information and paving materials were collected for two typical Superpave mix designs of a nominal 12.5 mm maximum aggregate size. Mainly the volumetric properties of the mixtures were evaluated concerning the voids in mineral aggregates, while with the Hamburg wheel-tracking and indirect tension testing, the rutting potential and strength of the blends were assessed.

The Bailey method was initially designed to design and adjust aggregate proportions based on aggregate packaging and its impact on HMA blend performance. The method can also be used to assess the characteristics of the aggregate packaging. The Bailey method is based on a grading curve, which determines the ratios indicating the total efficiency of packaging using certain control strands. The first control sieve is the Nominal Maximum Particle Size (NMPS), which is usually defined as a sieve bigger than the sieve, which retains more than 10% of the total [24]. From the NMPS, another control sieve can be estimated. These control sieves include the half sieve (HS), which is the sieve closest to the half of the NMPS, the principal control sieve (PCS) which is defined as the sieve closet of 22% of the NMPS, the Secondary Control Sieve (SCS), which is defined as the sieve armchair at 22% of the PCS and the Tertiary Control Sieve (TCS), which is defined as the sieve closet of 22% of the SCS. With the Bailey method, there are four key principles, see Figure 1:

- Determine which of the structures of the aggregate (i.e. the coarse aggregate) are in control, what generates and fills the voids.
- Coarse fraction packaging has an impact on fine fraction packaging.
- The fine coarse aggregate fraction concerns the packing in the combined blend of the total fine fraction.
- The fine aggregate fine fraction concerns fine gradation packaging in the mixture.
The two Bailey ratios CA and FAc can be calculated from the following equations:

\[ CA = \frac{\%\text{Passing HS} - \%\text{Passing PCS}}{100 - \%\text{Passing HS}} \]  

(1)

\[ FAc = \frac{\%\text{Passing SCS}}{\%\text{Passing PCS}} \]  

(2)

The CA ratio represents the description of coarse aggregate in the mixture and its void structure, while the FAc represents the interlock of coarse particles in the fine portion. The ratios introduced by Al-Mosawe [25] and used in this research are:

\[ \frac{C}{F} = \frac{\%\text{Passing PCS} - \%\text{Passing SCS}}{\%\text{Passing HS} - \%\text{Passing PCS}} \]  

(3)

This ratio defines the fine-coarse particles interlock.

\[ \frac{F}{C} = \frac{\%\text{Passing PCS}}{100 - \%\text{Passing PCS}} \]  

(4)

This ratio is to give the percent of the fine particles to coarse particles for the mix as a whole.

3. Materials and methodology

Crushed quartz aggregates, which are routinely used in the production of HMA mixes, were sourced from Al-Nabai quarries in Al-Taji. One aggregate gradation was used in this study as shown in Figure 2 for aggregate’s orientation detection, referred to as coarse and fine mix which was specified by the State Commission of Road and Bridges (SCRB)/Iraq [25]. A (40-50) penetration graded asphalt cement was used. The asphalt was brought from the refinery at Al-Duarah, south-west of Baghdad. In particular, optimum asphalt contents were found to Binder course mixes (4.5%) by weight of aggregate. Asphaltic samples of 10.16 cm in diameter with an approximate thickness of 6.35 cm, was compacted by Marshall Hammer to fabricate twenty samples of different mixtures (for two types of deviations), see Figure 3. The binder course exceeding the tolerance of the Iraqi specifications (named as T) and beyond the upper and lower limit of these specifications (named as S) as shown in Table 1 and Table 2. To detect the effect of aggregate gradation and degree of packing on asphalt mixtures performance, Bailey ratios were calculated and other ratios were introduced by Al-Mosawe [25] were also calculated.
4. Experimental data analysis

The binder course mixture was evaluated using the requirements considered in Iraq which is the Iraqi Specifications for Roads and Bridges (SCRB). The required tests are Marshall stability and flow and their volumetric properties, see Figures 4 and 5. The samples with the two different types of deviations which are beyond the tolerance limit but within SCRB limits and the second are beyond the SCRB limits were tested and referenced with their control mixtures. The control mixtures were selected as the mid gradation of the mixture using the SCRB limitations. It can be seen in Figure 6 that most of the deviations caused a reduction in Marshall stability. However, stability for mixes 1, 2, 4, 6, and 8 are kept within the required limits which are greater than 7 kN. Other mixes are reduced by less than 15% of the required stability, such as T3 and T4. The other mixtures performed a higher reduction in stability except that for T9 where the deviations made it much stronger. It can be noticed that the deviations that come closer to the coarse part (lower limit) make no big effect on the mixture performance which is represented by its stability and flow. On the other hand, most of the other deviated mixtures that are beyond the SCRB limits suffered from a severe reduction in stability. S1, S6, and S9 resisted the deviations and achieved stability values within the limits (as shown in Figure 7).
Figure 4. Marshall stability of the control and tolerance deviated asphalt mixtures for binder course.

Table 1. Mixture Gradations for tolerance deviations and Results for binder course.

| Mix | T1 | T2 | T3 | T4 | T5 | T6 | T7 | T8 | T9 | Control | Tolerance | SCRB |
|-----|----|----|----|----|----|----|----|----|----|---------|------------|------|
| Sieve mm | %Passing | %Passing | %Passing | %Passing | %Passing | %Passing | %Passing | %Passing | %Passing | %Passing | %Passing | %Passing |
| 25 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 19 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 |
| 12.5 | 88* | 72* | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| 9.5 | 68 | 68 | 68 | 68 | 68 | 68 | 68 | 68 | 68 | 68 | 68 | 68 |
| 4.75 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| 2.36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 |
| 0.3 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| 0.075 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |

Volumetric Properties

| Density (kg/m³) | 2.25 | 2.24 | 2.23 | 2.26 | 2.24 | 2.27 | 2.23 | 2.27 | 2.30 | 2.0 | 2.307 |
| % AV | 6.01 | 6.51 | 6.77 | 5.69 | 6.40 | 5.24 | 6.82 | 5.03 | 3.89 | 7.65 | 3.9 |
| Stability (kN) | 7.32 | 7.77 | 6.66 | 7.7 | 6.77 | 7.66 | 5.55 | 7.77 | 10.55 | 5.77 | 7.9 |
| Flow (mm) | 2.5 | 3 | 2.4 | 3.15 | 2.75 | 2.8 | 2.2 | 2.9 | 3 | 2.8 | 3.4 |
| % VMA | 14.59 | 15 | 15.28 | 14.3 | 14.54 | 14.3 | 15.33 | 13.7 | 12.66 | 16 | 13.44 |

Gradation Ratios

| CA | 0.562 | 0.562 | 1.083 | 0.25 | 0.312 | 0.812 | 0.562 | 0.562 | 0.562 | 0.562 | 0.562 |
| Fac | 0.445 | 0.445 | 0.445 | 0.445 | 0.383 | 0.529 | 0.496 | 0.393 | 0.513 | 0.387 | 0.618 |
| Cf/Fc | 1.541 | 1.541 | 1.067 | 2.775 | 3.575 | 0.759 | 1.399 | 1.683 | 1.35 | 1.7 | 0.982 |
| F/C | 1.111 | 1.111 | 1.111 | 1.111 | 1.111 | 1.567 | 0.792 | 1.111 | 1.111 | 1.111 | 1.111 | 0.818 |

(*) refers to deviation
Figure 5. Marshall stability of the control and tolerance deviated asphalt mixtures for base course.

The SCRB deviations, as shown in Table 2, are formed as eliminating one of the sieves. The gap that is made in the mixture highly affected the results.

Table 2. Mixtures gradations deviations beyond SCRB requirements.

| Mix Sieve mm | S1 (%) | S2 (%) | S3 (%) | S4 (%) | S5 (%) | S6 (%) | S7 (%) | S8 (%) | S9 (%) | S10 (%) | Control (%) | Tolerance (%) | SCRB (%) |
|--------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------------|---------------|----------|
| 25           | 100    | 100    | 100    | 100    | 100    | 100    | 100    | 100    | 100    | 100    | 100          | 100           | 100      |
| 19           | 95     | 95     | 95     | 95     | 95     | 95     | 95     | 95     | 95     | 95     | 95-100       | 90-100        | 90-100   |
| 12.5         | 68*    | 83     | 80     | 80     | 80     | 80     | 80     | 80     | 80     | 80     | 74-86        | 70-90         | 70-90    |
| 9.5          | 68     | 82*    | 70*    | 68     | 68     | 68     | 68     | 68     | 68     | 68     | 62-74        | 56-80         | 56-80    |
| 4.75         | 50     | 50     | 70*    | 55*    | 50     | 50     | 50     | 50     | 50     | 50     | 44-56        | 35-65         | 35-65    |
| 2.36         | 36     | 36     | 60     | 54*    | 36     | 36     | 36     | 36     | 36     | 36     | 32-40        | 23-49         | 23-49    |
| 0.3          | 12     | 12     | 12     | 12     | 12     | 12     | 12     | 12     | 12     | 12     | 8-16         | 5-19          | 5-19     |
| 0.075        | 6      | 6      | 6      | 6      | 6      | 6      | 6      | 6      | 6      | 6      | 4-8          | 3-9           |          |

Volumetric Properties

| Density (kg/m³) | 2.24  | 2.26  | 2.23  | 2.26  | 2.26  | 2.25  | 2.23  | 2.24  | 2.27  | 2.22  | 2.307         |
| %AV            | 5.28  | 5.39  | 6.67  | 5.54  | 5.63  | 5.81  | 6.93  | 6.46  | 5     | 7.45  | 3.9          |
| Stability (kN) | 7.11  | 6.44  | 6.55  | 6.33  | 5.22  | 7.88  | 5.99  | 4.55  | 7.77  | 4.88  | 7.9          |
| Flow (mm)      | 2.6   | 2.2   | 2.6   | 2.5   | 2.1   | 3.7   | 1.95  | 1.8   | 2.5   | 1.75  | 3.4          |
| %VMA           | 13.9  | 14.03 | 15.19 | 14.2  | 13.23 | 15.32 | 15.17 | 14.99 | 13.67 | 15.9  | 13.44        |
| CA             | 0.56  | 0.522 | 1.777 | 0.04  | 0     | 1.125 | 0.406 | 0.562 | 0.562 | 0.56  | 0.28         |
| Fb             | 0.45  | 0.445 | 0.445 | 0.45  | 0.317 | 0.615 | 0.544 | 0.282 | 0.582 | 0.44  | 0.618        |
| Cf/Fc          | 1.54  | 1.541 | 0.867 | 13.9  | -     | 0.341 | 1.927 | 1.992 | 1.16  | 1.54  | 0.982        |
| F/C            | 1.11  | 1.111 | 1.111 | 1.11  | 2.8   | 0.507 | 1.375 | 1.111 | 1.111 | 1.11  | 0.818        |

(*) refers to deviation.

Bailey ratios and those introduced by Al-Mosawe [25] were calculated and it can be seen that in Table 1 for example, mixes T5 and T6 the difference between them is the percent of passing in sieve No.4. T5 has a deviation that makes the number of fine particles much more than that in T6. This is reflected in the ratio Cf/Fc which has great change between them and compared to the control mix. The explanation
to this is compatible with the finding of reference [25] which states that the interceptor particles are supported by a large number of fine particles as in T5.

Figure 6. Aggregate gradation for asphalt mixtures (tolerance limit).
Figure 7. Aggregate gradation for asphalt mixtures (out of specification).
5. Conclusions
The combined gradation has an important effect on the performance of the asphalt mixture. This study focused on the effect of the mixture internal structure on the performance and particle packing. The following conclusions can be summarized:

- Binder course mixture properties were selected for this study and the mid gradation was selected as the control mix.
- Two types of deviations were applied to the designed mixture to represent the out-of-control sieving that occurred in the asphalt concrete industry.
- The two deviation types are: beyond the tolerance but within the SCR limits and the second is beyond the SCR limits.
- It was found that the first type of deviations has less effect on the mixture performance represented by Marshall properties.
- The deviations that exceed the lower limit (coarser) do not negatively affect the performance of the mixture unlike that exceeds the upper limit (finer) for the first type of deviations (tolerance deviated samples).
- The second type of deviation shows, in general, deterioration in the mixture performance.
- Packing ratios showed a good tool to understand the packing of aggregate and in turn the mixture performance.
- The study suggests to re-consider the deduction rates that are used in Iraqi projects for the first type of deviations.

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