SIIV - 5th International Congress - Sustainability of Road Infrastructures

An application to the European practice of the Bailey Method for HMA aggregate grading design

Andrea Graziani, Gilda Ferrotti, Emiliano Pasquini*, Francesco Canestrari

*Università Politecnica delle Marche, via Brecce Bianche, 60131 Ancona, Italy

Abstract

The Bailey Method provides a set of tools for the design and the evaluation of aggregate packing and voids of asphalt concrete grading while maintaining appropriate mixture workability and durability. In this study, concepts, procedures and parameters of the Bailey Method, that is strongly based on sieves and aggregate sizes adopted in the USA, were applied in the European perspective. To this aim, two sets of asphalt mixtures were designed applying the Bailey Method. The study shows that the European practice for aggregate grading design allows the application of the Bailey Method criteria confirming the validity of its basic principles.

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Keywords: Mix-Design, aggregate packing, Bailey Method, volumetric properties

1. Introduction

Aggregate grading is an essential property of bituminous mixtures, because it can be related to many aspects of mixtures performance in the field, such as compactability, durability and resistance to permanent deformation. Grading curves are obtained by blending single size aggregates and mineral fillers, mostly by trial and error procedures. Provided that empirical-type specifications are in use, the grading of mixtures needs to meet specification bands usually derived from well established national or local practices; conversely, if performance specifications are employed, the mix designer focus shifts from grading to mixture requirements, particularly volumetric properties.

In the European Standard EN 13108 the term Asphalt Concrete (AC) identifies continuously graded or gap-graded hot mixtures where aggregate particles form an interlocking structure. Grading curves of AC mixtures, commonly refer to the 0.45 power equation to produce the densest aggregate packing, while allowing the

* Corresponding author. Tel.: +39 071 2204507; fax: +39 071 2204510.
E-mail address: e.pasquini@univpm.it
necessary voids for bituminous binder [1]. Aggregate packing can be evaluated using Voids in the Mineral Aggregate (VMA). For a given mixture, this parameter is mainly a function of compaction energy shape, surface texture and strength of aggregate particles.

In this context, the Bailey Method [2] provides a set of tools that can be used to analyze aggregate size distribution, using the degree of particles interlock as a design input. The method, developed in the early 1980’s by Robert D. Bailey of the Illinois DOT, has been subsequently improved by additional studies and field trials [3, 4]. It can be used to design and evaluate aggregate blends within any mix design method, such as Marshall or Superpave. It provides empirical rules that allow to control mixture volumetric properties, and to achieve compactability and performance in the field.

The basic principles of the Bailey Method have been empirically developed, therefore its parameters and rules are strongly based on sieves and aggregate sizes typically adopted in the United States. In this study principles, procedures and parameters of the Bailey Method were first reviewed in the perspective of European practice and specifications, then an experimental analysis was carried out to verify its practical validity. Two families of AC mixes, characterized by different maximum aggregate sizes and levels of particles interlock were designed and compacted using a GC. Volumetric properties and compactability of the mixtures were evaluated and related to aggregate packing parameters defined by the Bailey Method.

2. The Bailey Method

Coarse and fine aggregate particles are commonly separated using a conventional sieve dimension, customarily placed between 4.75 mm and 2 mm. In the Bailey Method a different definition of “coarse” and “fine” is adopted, with reference to their volumetric function inside an aggregate blend. Specifically, when packed together in an aggregate blend, coarse particles create the voids, whereas fine particles fill the voids. This definition is therefore related to the overall grading of the mixture, and particularly to its Nominal Maximum Aggregate Size (NMAS). The break sieve between coarse and fine, named Primary Control Sieve (PCS), is defined as:

\[
PCS = NMAS \times 0.22
\]

In this relationship, NMAS is used to represent the size of the coarse particles, whereas PCS represents the size of the inter-granular voids, that is proportional to that of the coarse particles. Equation (1) was found to represent average conditions of AC mixtures which are composed by particles having different shape, texture and strength.

Single aggregate sizes are classified as “coarse” or “fine” whether their PCS passing is below or above 50%, respectively. Their packing characteristics can be measured by their bulk density or “unit weight”: the mass of a unit volume of bulk aggregate, including the inter-granular voids. The Loose Unit Weight (LUW) is measured without the application of any compactive effort and therefore, in the LUW condition, only a minimum level of particle-to-particle contact is present. The compact bulk density is determined using a rodding procedure, obtaining the so-called Rodded Unit Weight (RUW); in the RUW condition aggregate particles are closely packed together.

If the coarse aggregate volume in a mixture falls below the value corresponding to the LUW condition, the level of coarse particle-to-particle contact will be minimal or even absent. On the other hand, reaching or even exceeding the RUW condition, the volume of coarse aggregate will be so great that mixture compaction will result difficult.

In the Bailey Method the desired level of coarse aggregate interlock is selected by choosing the unit weight of coarse aggregate (Chosen Unit Weight, CUW), usually expressed as percent of the LUW. After the CUW has been selected, the coarse aggregate weight and the volume of inter-granular voids can be calculated. Multiplying
the latter volume by the RUW of the fine aggregate, the weight of fine aggregate needed for the blend is obtained. The RUW of fine aggregate is used to ensure stability and strength of its structure inside the mixture.

If CUW is in the range from 95% to 105% the resulting blend is named “coarse-graded” as the coarse fraction controls VMA. If the CUW is less than 90%, the volume of fine aggregate in the mix is so high that coarse particles are spread apart and the fine fraction controls VMA; therefore the resulting blend is named “fine-graded”. Values of CUW between 90% and 95% should be avoided because mixture behavior in the field could be controlled either by the coarse or the fine fraction, due to the normal construction tolerances on grading. On the other hand, CUW above 105% leads to coarse-graded mixtures that are usually difficult to compact and as a consequence the desired volumetric properties (VMA, air voids) may be difficult to achieve in the field.

The packing characteristics of the coarse fraction of an aggregate blend, can be analyzed defining the Half Sieve (HS) as one half of the NMAS. The HS separates particles retained on the PCS, into “pluggers” (larger particles retained on the HS) and “interceptors” (smaller particles passing on the HS). To control the balance of these two fractions the Coarse Aggregate ratio is defined as:

$$CA = \frac{P_{HS} - P_{PCS}}{100 - P_{HS}}$$

where P indicates the percent passing to the specified sieve. Increasing the CA ratio, that is increasing the interceptors, generally leads to an increase of VMA because interceptors are too large to fit into the voids created by larger particles.

The packing characteristics of the fine fraction of an aggregate blend, can be analyzed considering the PCS passing itself as a “new” blend of coarse and fine particles. Generally the PCS can be considered as the NMAS of the new blend and therefore a new break, the Secondary Control Sieve (SCS), can be defined as the closest sieve matching the value 0.22 times PCS. This principle can be iterated again as the fine fraction of the fine aggregate can be broken down into a coarse and a fine part. Therefore, the Tertiary Control Sieve (TCS) can be defined as the closest sieve matching the value 0.22 times SCS. Balance between the different fractions that compose the fine aggregate is evaluated using the Fine Aggregate Coarse ratio ($FAC$) and the Fine Aggregate Fine ratio ($FAf$) defined as:

$$FAC = \frac{P_{PCS}}{P_{PCS}}$$

$$FAf = \frac{P_{TCS}}{P_{TCS}}$$

where P indicates the percent passing to the specified sieve. An increase of the FA ratios generally brings to decrease of VMA and air voids ($V_m$) in the mixture because the fine fraction increases its packing potential. For the evaluation of fine-graded mixtures (CUW < 90%), where only the fine aggregates carries the load and controls VMA, only the passing to the original PCS is evaluated. Therefore, the characteristic sieves as well as the ratios must be redefined assuming the original PCS as the new NMAS.

3. **Procedures and parameters of the Bailey method in the European perspective**

The application of the Bailey Method to the European practice requires some adjustment of its definitions mainly related to the different approaches employed to classify aggregate sizes and mixture grading requirements. The main issues arise from the use of different sieve sizes; even if this could appear a minor difference, the consequences of “small” sieve changes should not be overlooked, especially because the Bailey principles were empirically derived.
The EN 13043 designation system for single aggregate sizes requires the definition of lower (d) and upper (D) sieve sizes. Limits of oversize and undersize fractions are declared as grading categories. Respect to US specifications (ASTM D 692, ASTM D 448, AASTHO M43, ASTM D 1073), the EN 13043 gives larger freedom of product designation. In the EN 13043 and EN 13108 designation systems, the upper sieve size D represents a concept analogous to NMAS. For example, EN 13108-1 requires that the total passing on the sieve size D of AC mixes should always be above 90%, which is identical to the Superpave definition of NMAS as one sieve larger than the first sieve that retains more than 10%. In the context of the Bailey Method, the NMAS was redefined as one sieve larger than the first sieve that retains more than 15% [5]. This new definition helped to fix some issues mostly related to fine-graded mixes. However, for a first application in the European perspective, maintaining the 10% definition seems reasonable.

As the Bailey control sieves can be obtained from the NMAS of the mix, the same concept could be applied using the upper dimension D of European mixes. Table 1 summarizes the control sieves calculation for AC mixes specified in accordance with EN 13108-1; in this case the closest sieve size to the corresponding formula has been selected. In the EN 13108-1 empirical specification system, the target grading composition of an AC mixture needs to be expressed in terms of a grading envelope, using maximum and minimum passing values at the following sieves: 1.4D, D, a characteristic coarse sieve, 2 mm, a characteristic fine sieve, and 0.063 mm. In addition, when required, an optional coarse sieve and an optional fine sieve can be added. As shown in Table 2, the principles of the Bailey Method can be used as a guide to choose characteristics and optional sieves; for each mixture size D, the control sieves are highlighted, showing that EN 13108-1 allows to specify Asphalt Concrete grading that can be easily analyzed using the Bailey packing principles.

An additional aspect to be considered is the determination of loose and compacted aggregate bulk densities. For the loose condition, European Standard EN 1097-3 describes a test method that is very similar to the AASHTO T-19 procedure for LUW.

Table 1. Control sieves of the Bailey Method for European mixes (EN 13108-1)

| D [mm] | HS (0.5×D) [mm] | PCS (0.22×D) [mm] | SCS (0.22×PCS) [mm] | TCS (0.22×SCS) [mm] |
|--------|----------------|-------------------|---------------------|---------------------|
| 32     | 16 (16)        | 8 (7)             | 2 (1.76)            | 0.5 (0.44)          |
| 20     | 10 (10)        | 4 (4.4)           | 1 (0.88)            | 0.25 (0.22)         |
| 16     | 8 (8)          | 4 (3.5)           | 1 (0.88)            | 0.25 (0.22)         |
| 12     | 6 (6)          | 2 (2.6)           | 0.5 (0.44)          | 0.125 (0.11)        |
| 10     | 4 (5)          | 2 (2.2)           | 0.5 (0.44)          | 0.125 (0.11)        |

Table 2. Sieves for aggregate grading definition for both Bailey approach and EN 13108-1

| 1.4×D [mm] | Mixture designation D [mm] | Characteristic coarse sieve [mm] | Optional sieve [mm] | 2 [mm] | Characteristic fine sieve [mm] | Optional sieve [mm] | 0.063 [mm] |
|------------|---------------------------|---------------------------------|--------------------|-------|-------------------------------|--------------------|-----------|
| 63         | 32                        | 16 (HS)                         | 8 (PCS)            | 2 (SCS) | 0.5 (TCS)                     | 0.25 (TCS)         | 0.063     |
| 32         | 20                        | 10 (HS)                         | 4 (PCS)            | 2 (S)   | 1 (SCS)                       | 0.25 (TCS)         | 0.063     |
| 32         | 16                        | 8 (HS)                          | 4 (PCS)            | 2 (S)   | 1 (SCS)                       | 0.125 (TCS)        | 0.063     |
| 20         | 12                        | 6 (HS)                          | 4                  | 2 (PCS) | 0.5 (SCS)                     | 0.125 (TCS)        | 0.063     |
| 14         | 10                        | 8                               | 4 (HS)             | 2 (PCS) | 0.5 (SCS)                     | 0.125 (TCS)        | 0.063     |

For the compacted condition, a specific procedure is not specified by EN 1097-3, therefore the rodding procedure described in the AASHTO T-19 may be employed. However, it must be noticed that bucket capacities required by the two test methods are different and this could have an impact on results because of the “wall-effect”.

4. Experimental program

In the previous section, some concerns deriving from the application of the Bailey Method to the European practice have been remarked. To clarify these potential issues and verify the overall validity of the grading analysis approach, an experimental investigation has been carried out blending typical Italian aggregate sizes in accordance with the Bailey principles. Two Asphalt Concrete mixes with different upper sieve sizes (AC12 and AC20) were designed at five different CUW, from 90% to 110% of the LUW, and the volumetric properties of the resulting ten mixes were evaluated preparing cylindrical specimens by means of a GC.

4.1. Materials

This section summarizes the geometrical and physical properties of the employed materials, especially aggregates, and the grading characteristics of the combined blends. Three coarse aggregate sizes (4/8, 8/12 and 12/20), one fine aggregate size (0/4) and a mineral filler were employed. All aggregates came from crushed limestone rock, and were designated according to EN 13043. Sieve analysis and classification tests results are shown in Table 3 and Table 4.

In the second part of Table 4 the bulk densities and inter-granular voids in the loose and compacted conditions (LUW and RUW) are also indicated (the average value of three repetition is reported). Tests were carried out using procedures and apparatus described in EN 1097-3 except that, as previously noted, the rodding procedure described by AASHTO T-19 was employed for the compacted unit weight. For coarse aggregates the ratio RUW/LUW is around 110%, which is important when considering the CUW of the combined blend. Inter-granular voids of coarse aggregates range from 47.6% to 50.6% in the LUW condition and from 42.7% to 43.8% in the RUW condition, resulting in a difference of 5% to 7% from LUW to RUW conditions. These values are inside the normal ranges obtained using the AASHTO T-19 procedure [5].

Two Asphalt Concrete mixtures characterized by different upper sieve size, AC12 and AC20, were designed by selecting various levels of coarse aggregate interlock. The following CUW values were selected: 90%, 95%, 100%, 105% and 110%. For each blend, the volume of the inter-granular voids was calculated, and the amount of fine aggregate was determined using its RUW (Table 4). This allowed to determine the dosages of each aggregate size (Table 5) and the grading of the mixture (Figure 1). Finally, passing percentages to the control sieves listed in Table 1 were used to calculate the aggregate ratios reported in Table 5.

Table 3. Sieves for aggregate grading definition for both Bailey approach and EN 13108-1

| Sieve [mm] | Total passing [%] |
|------------|-------------------|
| 32         | 100               |
| 20         | 96                |
| 16         | 81                |
| 12         | 39                |
| 10         | 6                 |
| 8          | 1                 |
| 6          | 11                |
| 4          | 5                 |
| 2          | 3                 |
| 1          | 2                 |
| 0.5        | 100               |
| 0.25       | 99                |
| 0.125      | 90                |
| 0.063      | 75                |
A 70/100 pen paving grade bitumen was used to produce the AC mixes. The total binder content was determined by previous experience as 4.7% for the AC12 mix, and 4.1% for the AC20 mix.

4.2. Test procedures

For each mixture, two 1000 g specimens were used for the measurement of maximum density ($\rho_m$) (EN 12697-5) and three 150 mm diameter specimens were prepared with a Gyratory Compactor (EN 12697-31), applying 180 gyrations. After cooling, the bulk density ($\rho_b$) of the specimens were measured by the hydrostatic method (EN 12697-6). Finally the void characteristics of the specimens (air voids, $V_m$; voids in mineral aggregate, VMA; voids filled with bituminous binder, VFB) were calculated at 100 gyrations, according to EN 12697-31 and EN 12697-8 and the values were corrected using the bulk density measured by the hydrostatic method.

![Grading of the tested AC mixes](image-url)
Table 5. Aggregate dosages and ratios for the aggregate blends

| Aggregate size dosages | Aggregate ratios |
|------------------------|------------------|
| CUW [%] | 0/4 [%] | 4/8 [%] | 8/12 [%] | 12/20 [%] | Filler [%] | CA | FA | FAf |
| AC12-90 | 90 | 55.2 | 2.2 | 41.3 | 1.3 | 0.60 | 0.42 | 0.37 |
| AC12-95 | 95 | 51.6 | 2.4 | 44.5 | 1.6 | 0.54 | 0.42 | 0.38 |
| AC12-100 | 100 | 47.9 | 5.1 | 45.1 | 1.9 | 0.56 | 0.43 | 0.40 |
| AC12-105 | 105 | 44.4 | 7.1 | 46.4 | 2.1 | 0.56 | 0.44 | 0.41 |
| AC12-110 | 110 | 40.9 | 8.6 | 48.0 | 2.4 | 0.55 | 0.45 | 0.42 |
| AC20-90 | 90 | 41.7 | 13.7 | 11.5 | 31.6 | 1.6 | 0.65 | 0.44 | 0.40 |
| AC20-95 | 95 | 38.7 | 14.3 | 12.0 | 33.1 | 1.9 | 0.65 | 0.44 | 0.41 |
| AC20-100 | 100 | 35.9 | 14.9 | 12.6 | 34.5 | 2.1 | 0.64 | 0.44 | 0.42 |
| AC20-105 | 105 | 33.0 | 15.6 | 13.1 | 36.0 | 2.3 | 0.64 | 0.45 | 0.44 |
| AC20-110 | 110 | 30.2 | 13.6 | 13.6 | 37.4 | 2.6 | 0.64 | 0.45 | 0.45 |

5. Results and discussion

5.1. Densification curves

The densification curves obtained from the GC (average of three specimens) are reported in Figure 2, and the volumetric properties of the mixtures are summarized in Table 6. The curves clearly show that for both AC12 and AC20, mixes prepared with a CUW between 95% and 105% were characterized by better compaction behavior respect to the 90% and 110% mixes. This is in accordance with recommendations provided by the Bailey Method that, for dense coarse-graded mixtures, explicitly suggests the use of a CUW ranging from 95% to 105% in order to obtain coarse aggregate interlock. In mixtures with CUW as low as 90% the behavior is no more controlled by the coarse fraction, whereas in mixtures with CUW as high as 110% the volume of coarse aggregate is around the RUW condition and therefore compaction was difficult. This behavior is also showed plotting the VMA at 100 gyrations as a function of the CUW (Figure 3a): these curves show a minimum around the LUC condition (i.e. CUW = 100%) where the employed aggregates reached an optimal packing.

Table 6. Particle densities and volumetric properties of tested AC mixes

| Mixture | $\rho_s$ [kg/m$^3$] | $\rho_b$ [kg/m$^3$] | $V_p$ [%] | VMA [%] | VFB [%] |
|---------|---------------------|---------------------|------------|---------|---------|
| AC12-90 | 2508 | 2264 | 9.73 | 19.35 | 49.70 |
| AC12-95 | 2506 | 2355 | 6.01 | 16.06 | 62.64 |
| AC12-100 | 2506 | 2348 | 6.30 | 16.30 | 61.38 |
| AC12-105 | 2505 | 2353 | 6.07 | 16.10 | 62.32 |
| AC12-110 | 2504 | 2254 | 9.97 | 19.56 | 49.28 |
| AC20-90 | 2523 | 2234 | 11.79 | 19.96 | 41.74 |
| AC20-95 | 2521 | 2353 | 6.65 | 15.31 | 56.54 |
| AC20-100 | 2520 | 2339 | 7.16 | 15.78 | 54.91 |
| AC20-105 | 2518 | 2336 | 7.25 | 15.84 | 54.25 |
| AC20-110 | 2516 | 2174 | 13.58 | 21.59 | 37.15 |
Even though completing a mix design process was not an objective of this study, some considerations can be made from a mix-designer point of view. For both AC12 and AC20 mixes the minimum VMA at 100 gyrations was obtained for CUW = 95%. These values (16.1% and 15.3% respectively for AC12 and AC20) are above the target values recommended by Superpave specifications (15% for NMAS = 12.5 mm and 14% for NMAS = 19.0 mm), but still close to the maximum of the allowable VMA range (16% for NMAS = 12.5 mm and 15% for NMAS = 19.0 mm). This suggests that small corrections to the aggregate blends should be made to lower the VMA. For example in the AC12 mix eliminating the 4/8 size would lead to a reduction of “interceptors” and therefore an increase of the CA ratio which generally leads to a reduction of VMA. Moreover, for both AC12 and AC20 mixes the air voids level is higher than the design value recommended by Superpave for surface and binder courses \( V_m = 4\% \). This indicates that an increase of bitumen content should be made, later in the mix design process.

Two compaction parameters were calculated from the densification curves to evaluate further compaction properties of the tested AC mixes. First, an adapted version of the \textit{GC Locking Point} \cite{6} was defined as the number of gyrations after which the rate of change in height for the following five gyrations was equal to or less than 0.25 mm. This parameter can be interpreted as the degree of compaction at which the aggregate skeleton “locks” together and further gyrations results in aggregate degradation and little additional compaction; it can also be used as a conservative way to estimate the ultimate density of the pavement \cite{6}. Second, the \textit{Compaction slope}, \( k \) \cite{7} was obtained from a linear regression of the densification curve (in a semi-log plane) up to the GC locking point.

Results showed that the locking points of AC12 and AC20 mixes (Figure 3b, continuous lines) were reached for a similar number of GC gyrations (about 105) and were not visibly influenced by the degree of aggregate interlock within the studied range of CUW (90% to 110%).

The compaction slope \( k \), that is generally related to mixture workability (Figure 3b, dotted lines) was analyzed as a function of the Bailey aggregate ratios \( CA, FAc, \) and \( FAf \). The linear regression lines reported in Figure 4 were obtained excluding mixtures characterized by CUW = 110%, for which the coarse aggregate is almost at the RUW condition. Results clearly showed that increasing the CA ratio mixes workability decreased, as the amount of “interceptor” particles led to an unbalanced coarse aggregate structure. On the other hand, Figure 4 shows that an increase of the FA ratios leads to an increase of mixtures workability due to the fact that fine aggregate packs together tighter.
Fig. 3. (a) VMA @100 gyrations (b) GC compaction parameters

Fig. 4. Workability vs. gradation ratios
6. Conclusions

The results of an experimental study for the application of the Bailey Method for aggregate gradation analysis of bituminous mixtures compliant with EN 13108-1 standard are presented. In the first part of the study, the Bailey parameters were reviewed to account for differences between the US and the European specifications. Specifically, the nominal maximum aggregate size (NMAS) was identified with the upper sieve size (D), and differences in the procedures for the measurement of bulk densities were highlighted. Moreover, it was shown that the characteristic sieves required by Bailey Method (PCS, HS, SCS, TCS) can be used to guide the selection of the sieves required to specify mixtures grading in accordance to EN 13108-1. In the second part of the study two dense-graded AC mixes with different upper sieve size dimensions (AC12 and AC20) and five levels of coarse aggregate interlock (CUW from 90% to 110% of the LUW) were designed using the Bailey Method and compacted with a GC. The densification curves showed that mixes prepared with CUW between 95% and 105% were characterized by better compaction behavior, aggregate structures with minimum VMA values and optimal level of coarse aggregate interlock. When the volume of coarse aggregate employed in the mix was well below the LUW condition (CUW = 90%) or reached the RUW condition (CUW = 110%) the VMA rapidly increased, as suggested by the Bailey principles. Some typical mix design consideration for the VMA optimization, relative to the Superpave specifications, were suggested. From the densification curves, the GC Locking Point and the compaction slope were also determined. Results showed that the locking point was reached at about 105 gyrations and was not influenced by the mixture type or the degree of aggregate interlock. The compaction slope, that is generally linked to mixture workability was related to the Bailey aggregate ratios (CA, FA_c, and FA_f) confirming the overall validity of the grading analysis methodology.

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