

**The Bailey Method
Achieving Volumetrics and HMA Compactability**

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ABSTRACT

After decades of use, we have gained a lot of valuable experience with the Marshall mix design method. Accordingly there is a degree of comfort in working with the Marshall method in designing mixes. While there has been some guidance on the use of coarse and fine Superpave mixes, at this time, designers are still struggling with mix designs and have to conduct numerous trials to select the proper aggregate blend. A better way to speed up the process and understand the mixes that are being produced is needed.

The Bailey method was originally developed by Robert D. Bailey of the Illinois Department of Transportation in the early 1980s. It is a practical tool that has been successfully utilized for developing and analyzing hot asphalt mixes in the lab and field. The Bailey method provides a good starting point for mix design and an invaluable aid when making adjustments at the plant to improve air voids, VMA and the overall workability of the mix, whether you are using Marshall or Superpave. The paper describes the methodology in detail with some real life examples to help mix designers and contractors better understand the mixes that are currently being used across Canada.

RÉSUMÉ

Après des décades d'utilisation, nous avons acquis beaucoup d'expérience valable avec la méthode Marshall de formulation des enrobés. Par conséquent, il existe un certain degré de confort à travailler avec la méthode Marshall pour la formulation des enrobés. Bien qu'il y ait eu certaines directives dans l'utilisation des enrobés Superpave grossiers et fins, à ce jour, les concepteurs ont encore de la difficulté avec les formulations d'enrobés et doivent faire plusieurs essais pour choisir le bon mélange de granulats. On a besoin d'un meilleur moyen pour accélérer le processus et comprendre les enrobés qui sont produits.

La méthode Bailey a été développée par Robert T. Bailey du Ministère des Transports de l'Illinois au début des années 1980. C'est un outil pratique qui a été utilisé avec succès pour développer et analyser les enrobés bitumineux à chaud en laboratoire et au chantier. La méthode Bailey constitue un bon point de départ pour la formulation des enrobés et une aide inestimable pour faire les ajustements à la centrale pour améliorer les vides, le VAM et la maniabilité générale de l'enrobé, que l'on utilise Marshall ou Superpave. L'article décrit en détail la méthodologie avec des exemples réels pour aider les concepteurs et les entrepreneurs à mieux comprendre les enrobés qui sont couramment utilisés à travers le Canada.

1.0 INTRODUCTION

The move to Superpave™ (Superpave) in Ontario over the last few years has had a real impact on the mix design process and some concerns have been raised regarding the overall speed of implementation. At a glance these issues may be somewhat surprising given that designers have worked with Marshall mixes for many years and have gained a wealth of experience with the methodology. The general thought was that most of the mixes in Ontario would meet the Superpave criteria and the transition would be relatively easy. A limited study conducted in 2002 by the Ontario Ministry of Transportation (MTO) indicated that this would likely be true for the more conventional mix types but that it would be more onerous to achieve the desired volumetric properties for the premium mixes used for high traffic applications [1]. However, and for what ever the reason, relating that understanding to Superpave has had its share of trials and tribulations. In many instances, designers have had to complete numerous trials (in some cases too many to mention) to produce a good mix. This has become an extremely inefficient process and frustrating for a designer working with Superpave for the first time.

To get a better understanding of these concerns, the Ontario Hot Mix Producers Association (OHMPA) conducted a survey of its members in 2005 [2]. Some of the mix problems encountered with respect to meeting the Superpave requirements are shown in Figure 1. Other concerns related to factors such as limiting aggregate use (primarily natural sands) and/or changes to aggregate production/properties were also expressed. The excessive time to complete mix designs was also raised as a common problem. From the responses, it was quite clear that not everyone was at the same level and that further education/training was necessary. This has lead to an increased focus on Superpave courses and Bailey method workshops in Ontario.

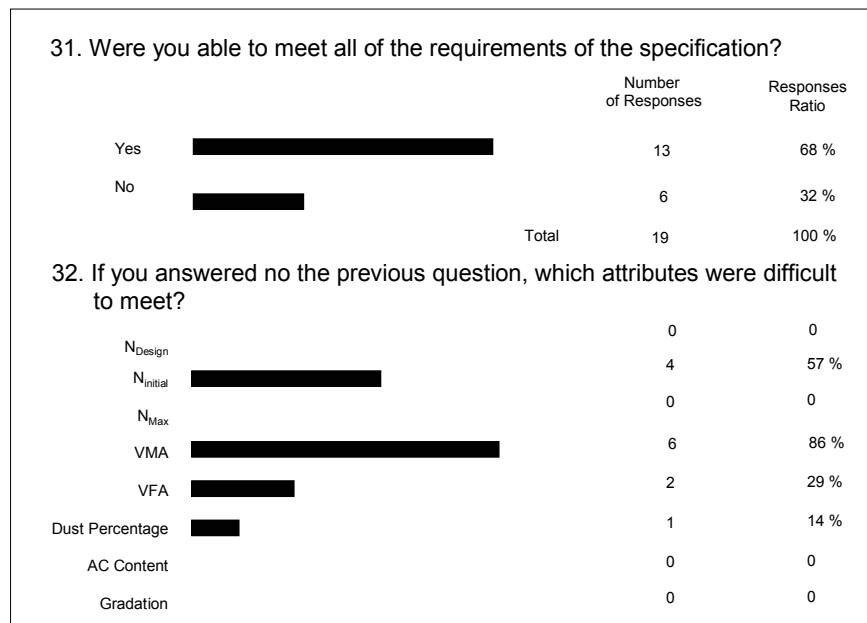


Figure 1. Excerpt from 2005 Ontario Hot Mix Producers Association Superpave Survey

Nevertheless, while there has been some guidance on the use of coarse and fine mixes, the process has been largely trial and error. The reality is that many designers are still on the low end of the learning curve and consequently, there are still a lot of questions yet to be answered. For example, should the mix be designed on coarse or fine side? How will this mix work in the field (will it segregate, will it be difficult to compact, or difficult to achieve sufficient Voids in Mineral Aggregate (VMA)?) and more importantly, how will the mix perform?

The Bailey method provides this much needed assistance to the designer to ensure that mixes are designed to provide resistance to rutting and long durability or long term performance with the aggregates available. Congruently, the mix must be fairly simple to produce and workable in the field to facilitate achieving good density. It is also envisioned that the Bailey method will provide some insight into aggregate production to further improve this process in Ontario.

2.0 BACKGROUND

Since its inception a lot of work has been done to validate the basic concept and in recent years the methodology has been greatly advanced by the efforts of Bill Pine, Heritage Research Group [3]. Essentially, the “Bailey Method of Gradation Selection” is a tool for developing and analyzing blend gradations in the lab and field. It gives designers and contractors a better appreciation of aggregate packing and its influence on mix volumetrics and compactability. The method includes guidelines for evaluating aggregates and the aggregate blend by volume, as well as by weight, and makes provision for the use of Reclaimed Asphalt Pavement (RAP). It is also should be noted that the Bailey Method is not just for Superpave. It works just as well for designing Marshall mixes.

The focus of the Bailey method is aggregate packing. In order to better understand aggregate packing, we need to determine what particles form the coarse aggregate structure and which ones fit into the voids created within that structure. The packing characteristics are determined by several factors: the shape, strength and texture of the aggregates, the combined blend gradation, and the type and amount of compactive effort (e.g. Marshall vs. gyratory compaction).

Cubical particles, for example, form a denser configuration than flat and elongated particles. Smooth particles slide together more easily than those with a rough surface texture. The gradation, the mix between various size particles, also influences how a mix packs since the smaller particles fill the voids created by bigger particles. Similarly, aggregates of varying strength compact differently depending on how they behave when compacted. For instance, in a fine mix the strength of the fine aggregate plays a much more important role than in a coarse graded mix.

Ultimately, the Bailey method allows the designer to select an aggregate skeleton that will be more resistant to permanent deformation and to adjust the VMA by changing the packing of the coarse and fine aggregates to ensure that the mix has sufficient asphalt binder. Perhaps this has lead to some of the concerns in Ontario. Inherently, Superpave has reemphasized the need to design mixes with sufficient VMA and this has heightened the need for a better understanding of the overall mix design process.

3.0 THE BAILEY METHOD PRINCIPLES

There are four key principles to consider with the Bailey Method:

- 1) Determine what is coarse and fine, what creates voids and what fills them, and which one is in control of the aggregate structure (i.e., the coarse aggregate or the fine?).
- 2) The packing of the coarse fraction influences the packing of the fine fraction.
- 3) The fine aggregate coarse fraction relates to the packing of the overall fine fraction in the combined blend.
- 4) The fine aggregate fine fraction relates to the packing of the fine portion of the gradation in the blend.

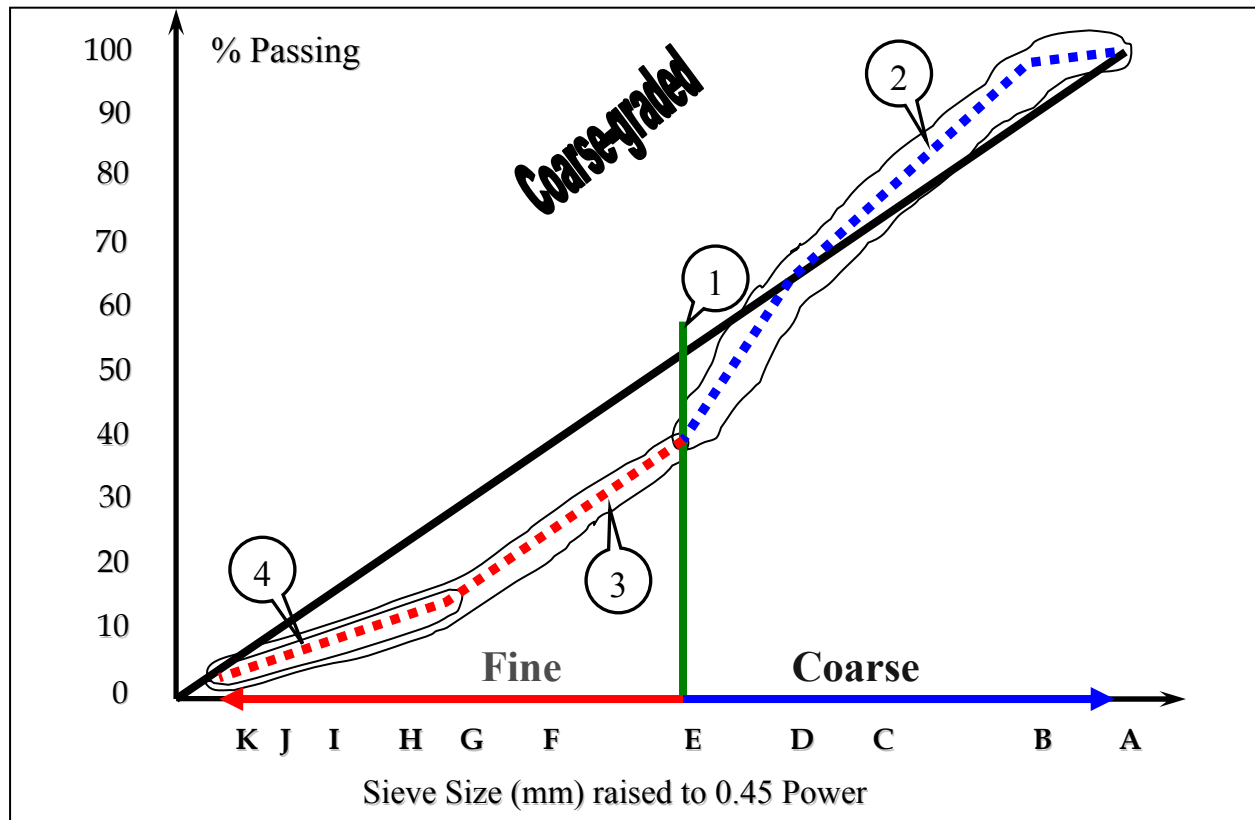


Figure 2. The Four Bailey Method Principles

Figure 2 depicts the four principles on a typical gradation curve for a coarse-graded mix. The process of evaluating the mix or combining the aggregates looks at each portion (fraction) of the gradation curve separately. Each of these four principles plays a specific role in aggregate packing or VMA. These principles also relate to compactability and segregation susceptibility in the field and to estimate expected changes in VMA or air voids from one design trial to the next, or from one Quality Control (QC) sample to the next.

The first step is to determine what is considered coarse and fine for a given blend. The 4.75 mm sieve size has been commonly used to differentiate between the coarse and fine aggregate. This is commonly referred to as the "split". However, the Bailey Method defines the average void size as 0.22 times the Nominal Maximum Particle Size (NMPS). It should be noted that NMPS is equivalent by definition to the Nominal Maximum Aggregate Size (NMAS) used in the Superpave system. The value of 0.22 was

determined by analyzing the packing of different particle shapes with two and three-dimensional models similar to Figure 3. This is the equation used in the Bailey Method to determine the break between coarse and fine in a combined blend gradation and is also used to determine the break between coarse and fine in an individual aggregate.

The Primary Control Sieve (PCS) that we will use is the closest sieve to the result of $0.22 \times \text{NMPS}$ as shown in Table 1. This is a very important relationship to remember.

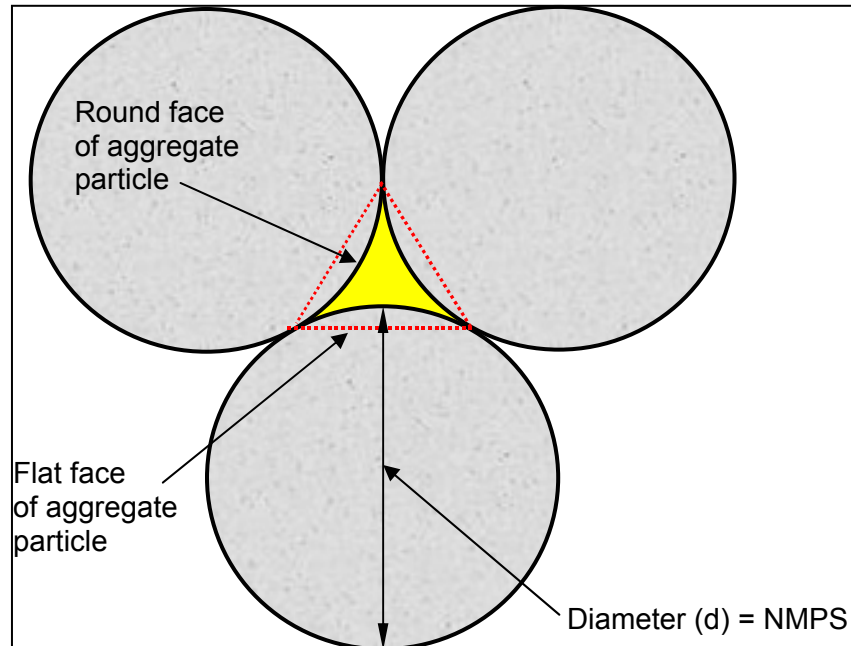


Figure 3. Two-Dimensional Aggregate Packing Model
(NMPS = Nominal Maximum Particle Size)

Table 1. Primary Control Sieve Sizes

<u>Mixture NMPS</u>	<u>NMPS x 0.22</u>	<u>Primary Control Sieve</u>
37.5mm	8.250mm	9.5mm
25.0mm	5.500mm	4.75mm
19.0mm	4.180mm	4.75mm
12.5mm	2.750mm	2.36mm
9.5mm	2.090mm	2.36mm
4.75mm	1.045mm	1.18mm

Note: NMPS = Nominal Maximum Particle Size

The next step is to evaluate the coarse and fine fractions by volume. This allows the designer to control the volumes of coarse and fine fractions according to the mix type (i.e., fine-graded, coarse-graded, or Stone Mastic Asphalt (SMA)). This starts by first evaluating the individual aggregates by volume. This provides the designers additional information about the volume of solids in the coarse fraction and the volume of voids it contains. Keep in mind that the coarse fraction or larger particles in the blend create the voids and the smaller particles or the fine fraction fills the voids.

The Bailey method uses the unit weight test based on the American Association of State Highway and Transportation Officials (AASHTO) T 19 to determine the Loose Unit Weight (LUW) and the Rodded Unit Weight (RUW) of each individual stockpile used in the mix. For each material the entire gradation, of a representative, oven dried sample is used to determine the volume of voids. A unit weight metal bucket with a 0.00708 cu. m (1/4 cu. ft.) volume is used to determine the loose voids, (i.e., with no compactive effort) of the coarse aggregate as shown in Photograph 1. The RUW is conducted with the same unit weight bucket and applying a standard compactive effort to the sample. For this test, the sample is placed in the bucket in three equal lifts and each layer is rodded 25 times. The LUW and RUW voids typically range between 43-49 percent and 37-43 percent, respectively, for coarse aggregate stockpiles.



Photograph 1. Bill Pine in Action - Demonstrates Fine Aggregate Unit Weight Test at the First Bailey Course Held in Ontario

The LUW and RUW for a fine aggregate (4.75 mm NMPS or smaller) is conducted using the same general procedure except with a standard Proctor mold with a 0.00094 cu. m (1/30th cu. ft.) volume. Typical ranges for the LUW and RUW voids are 35-43 percent and 28-36 percent, respectively, for fine aggregate stockpiles.

Unit weight tests are not performed on RAP (including recycled shingles), Bag House Fines (BHF), Mineral Filler (MF), or hydrated lime. RAP is typically continuously graded. Therefore, it normally doesn't contribute the majority of its gradation to one fraction of the combined blend (coarse or fine). Also, it would require a significant amount of extractions or ignition oven burns to produce enough RAP aggregate for the unit weight tests. The RAP aggregate would likely also have to be fractionated at the PCS of the combined blend so that one fraction could be treated as coarse and the other as fine. Additionally, determining an accurate Bulk Specific Gravity (G_{sb}) of either fraction would be questionable due to changes to the aggregate characteristics from either the extraction or burn process. As far as BHF's, MF, and hydrated lime the amount used within a combined blend is typically minimal, along with the fact that an Apparent Specific Gravity (G_{sa}) is typically determined rather than a G_{sb} , which would alter the void calculations for the unit weight tests.

3.1 Defining the Mix Type

Having determined the coarse and fine fraction of the mix, we now need to determine the volume of voids within the coarse aggregate. This will dictate the appropriate volume of fine aggregate to use for the type of mix we are designing. The Loose Unit Weight (LUW) is the minimum density required (with no compactive effort) for particle-to-particle contact and is considered the beginning of coarse aggregate interlock for coarse-graded mixes. From this we can calculate the volume of voids at the loose condition.

The Rodded Unit Weight (RUW) represents an increase in the amount of coarse aggregate in a unit volume after compaction. This represents a reference point for coarse-graded SMA mixes. Under most conditions, a coarse graded dense mix should not be designed with this high a coarse aggregate volume due to possible compactability problems. Again, we can use the RUW to calculate the volume of voids at the rodded condition.

The LUW and the RUW are the references used to pick the Chosen Unit Weight (CUW), which establishes the volume of coarse aggregate in a blend. A fine-graded mix has a volume of fine aggregate that exceeds the volume of voids in the coarse aggregate structure. Since the load is primarily carried by the fine aggregate, the strength of the fine aggregate becomes much more important. For fine-graded mixes we suggest 90 percent or less LUW.

A coarse-graded mix uses the coarse aggregate skeleton to carry more of the load but also uses some of the strength from the fine aggregate. For coarse-graded mixes we suggest a CUW in the range of 95-105 percent LUW.

Stone Mastic Asphalt relies almost completely on the coarse aggregate skeleton for its structural capacity with the fine aggregate, asphalt cement, mineral filler, and fibres acting as mastic to fill the voids for durability. For SMA mixes, we want to design above the RUW to ensure a Coarse Aggregate (CA) skeleton. Our experience to date has found a range of 110 to 125 percent RUW generally works well. The suggested ranges for each mix type are shown in Figure 4. Note that SMA references the RUW condition of the coarse aggregate, while coarse-graded and fine-graded mixes reference the LUW condition.

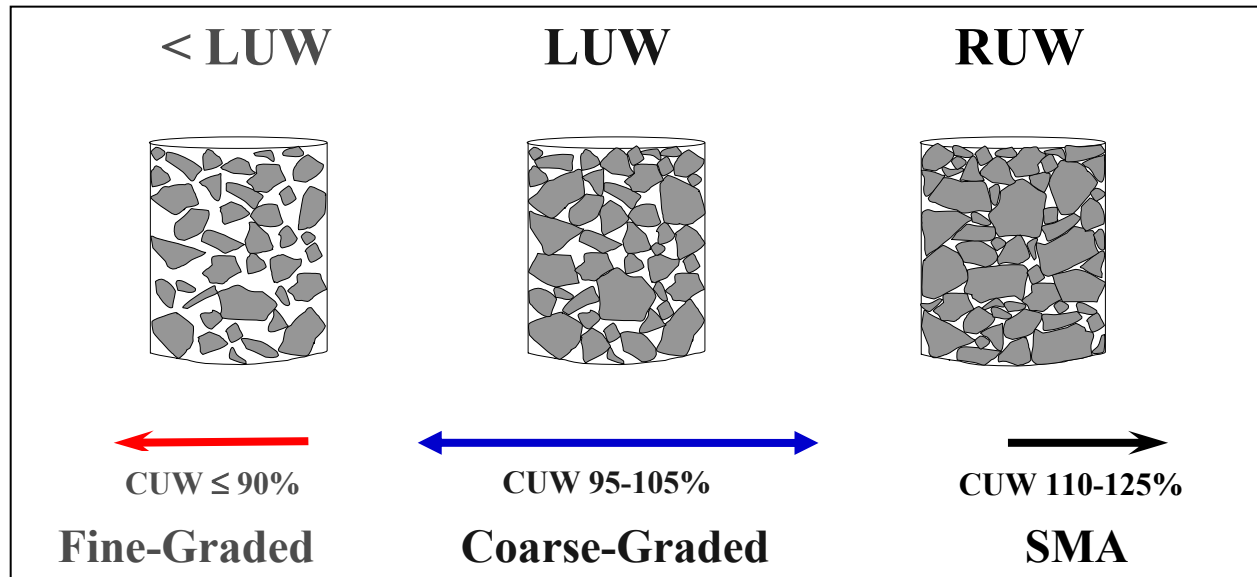


Figure 4. Chosen Unit Weight Ranges by Mix Type
(LUW = Loose Unit Weight, RUW = Rodded Unit Weight, CUW = Chosen Unit Weight)

3.2 Developing the Combined Aggregate Blend

After gathering the typical information for the individual aggregates (gradation, specific gravity, etc.) and performing the unit weight tests, a combined blend can be developed and evaluated with respect to the four main principles of the Bailey Method, prior to actually blending the mix in the laboratory. The following steps [4] outline the general procedures for developing and evaluating a trial blend:

3.2.1 Step 1: Determine the Mix Type and NMPS

The NMPS is typically a function of the specification requirements. Mix type (coarse-graded or fine-graded) may also be a function of the specifications (i.e., gradation bands) but is typically up to the designer. There are several things to consider when determining mix type, such as lift thickness in the field, material characteristics, and past experience. If the designer feels either type is appropriate, a combined aggregate blend of each type can be developed and evaluated to determine which one will better fit within the suggested ranges for each of the four principles, respective to the given type.

3.2.2 Step 2: Chose the Volume of Coarse Aggregate (i.e., CA Chosen Unit Weight)

The CA volume, expressed as a percentage of the CA Loose Unit Weight condition, should be within the suggested range for the corresponding mix type (coarse-graded or fine-graded). The CA volume for SMA mixes is expressed as a percentage of the CA Rodded Unit Weight condition.

3.2.3 Step 3: Blend the Individual Coarse Aggregates by Volume

A stockpile is considered to be coarse if the majority of its gradation is retained on the PCS of the combined blend. If multiple coarse aggregates are being used, the designer picks the blend by volume, as

100 percent, for the various CA stockpiles. The CA blend by volume is determined mathematically and a theoretical volume of voids is determined. Unit weight tests are not performed on the blended CA. The CA volume blend is the primary factor, along with the gradation of each CA stockpile, in determining and altering the CA Ratio.

3.2.4 Step 4: Blend the Individual Fine Aggregates by Volume

A stockpile is considered to be fine if the majority of its gradation passes the PCS of the combined blend. If multiple fine aggregates are being used, the designer picks the blend by volume, as 100 percent, for the various Fine Aggregate (FA) stockpiles. The FA blend by volume is determined mathematically and a theoretical unit weight is determined. Unit weight tests are not performed on the blended FA. The FA volume blend is the primary factor, along with the gradation of each FA stockpile, in determining and altering the ratio of the fine part of the fine fraction to the total fine fraction (FA_c) Ratio achieved in the combined blend. It also plays a role in the ratio of the fine part of the fine fraction to the total fine part of the fine fraction defined as (FA_f) Ratio achieved if any of the FA's contains significantly more dust than the other virgin aggregates being used.

3.2.5 Step 5: Chose the Desired Percentage of Minus 0.075 mm (#200) in the Combined Blend

This is only necessary if the design includes Bag House Fines (BHF) or Mineral Filler (MF) as a separate aggregate in the combined blend. Generally, the purpose of including BHF's or MF is to represent the amount of degradation that is expected to take place during production. Virtually all aggregates undergo some degradation. Therefore, it is strongly suggested that the designer include this in each design. The amount of degradation is a function of things such as hardness or abrasion resistance of the various aggregates, Hot Mix Asphalt (HMA) plant characteristics, HMA plant production rate, etc. Past experience is invaluable in accurately estimating the amount of degradation to account for in the mix design process.

After completing Steps 1 to 5, the designer will have established a percentage by weight or mass of each individual aggregate, as 100 percent total aggregate and therefore, a resulting combined blend. The combined blend should then be evaluated according to the mix type and NMPS, with respect to the suggested ranges for each of the four principles of the Bailey Method.

The designer should also evaluate any similar existing blends to determine the corresponding Bailey principles for comparison to the proposed combined blend. It is not uncommon to find existing blends that have performed well, with results for one or more of the four principles that fall outside the suggested ranges. However, the designer should verify that the existing design mix formula was reproduced in the field and that acceptable results were achieved (i.e., volumetric properties, in-place density, and performance) before assuming that developing a new combined blend, outside of the suggested ranges will work.

The basic premise for suggesting ranges for each principle, based on mix type and NMPS, is to help the designer develop a combined blend that will optimize the opportunity for compaction and minimize the opportunity for segregation. However, falling outside of the suggested range for any of the principles doesn't necessarily indicate that there will be field problems. That's why it's important for the designer to evaluate similar existing combined blends that utilized virtually the same aggregate sources and sizes, and relate that information to what was achieved in the field.

3.3 Evaluating the Combined Blends

The evaluation procedures used for a combined blend, depends on which fraction is in control because the mix behaves differently. The Primary Control Sieve (PCS) determines the break between the coarse and fine fractions of a combined blend. Table 2 summarizes the mix characteristics depending on which fraction is in control. For example, if the fine fraction is in control, a 6 percent increase in the PCS (i.e., amount passing the PCS) results in a 1 percent increase in VMA and air voids. However, when the coarse fraction is in control, a 4 percent decrease the PCS results in a 1 percent change in VMA and air voids. The impacts and the sensitivity of these changes on the mix are further illustrated in Figures 5 and 6 and the corresponding Ratio guidelines for coarse and fine graded mixes are shown in Tables 6 and 7, respectively [5].

3.3.1 The 1st Bailey Principle – CA

Table 2. Comparison of Expected Changes to VMA based on Changes to the Primary Control Sieve (PCS) and Coarse Aggregate Volume for Fine and Coarse Mixes

FINE IN CONTROL	COARSE IN CONTROL
Coarse fraction spread apart and floating in the fine fraction.	Fine aggregate mainly fills voids created by coarse aggregate.
Little to no particle-on-particle contact of the coarse aggregate.	There is some degree of particle-on-particle contact of the coarse aggregate.
Fine fraction carries most of the load.	Coarse fraction carries most of the load.
Fine aggregate must have sufficient gradation, shape, texture, and strength to support the load.	Coarse aggregate must have sufficient gradation, shape, texture, and strength to support the load. However, the fine aggregate still plays a role in supporting the coarse aggregate.
6% change in PCS results in approximately 1% change in VMA and air voids.	4% change in PCS results in approx. 1% change in VMA and air voids.
Decreasing coarse aggregate volume, increases VMA and air voids (providing fine fraction characteristics remain similar).	Increasing coarse aggregate volume increases VMA and air voids (providing fine fraction characteristics remain similar).
As the coarse aggregate volume increases towards 90% CA LUW, the mix can go in and out of coarse aggregate interlock, resulting in volumetric and/or field compaction variation.	As the coarse aggregate volume increases, field compactability decreases.

Note: CA = Coarse Aggregate, LUW = Loose Unit Weight, VMA = Voids in Mineral Aggregate

3.3.2 The 2nd Bailey Principle – CA Ratio

The evaluation of this portion of the aggregate structure uses the idea of the “half sieve.” Particles retained on the half sieve are referred to as “pluggers.” Particles passing the half sieve but retained on the PCS are called “interceptors.” The interceptors are too large to fit into the voids created by the pluggers and therefore, spread them apart. The ratio of the percent interceptors to the percent pluggers is defined as the CA Ratio. The CA Ratio is further described in Table 3.

Table 3. Expected Changes to VMA Based on Coarse Aggregate Ratios for Fine and Coarse Mixes

FINE IN CONTROL	COARSE IN CONTROL
Half sieve = 1/2 the original PCS. The PCS is now looked at as the new Nominal Maximum Particle Size (NMPS).	Half sieve = 1/2 the original NMPS.
New PCS is = 0.22 times the original PCS.	PCS stays as originally defined.
The portion evaluated as the new coarse fraction is smaller than that of coarse mixes and therefore less sensitive to changes.	The portion evaluated as the coarse fraction is larger than that of fine mixes and therefore more sensitive to changes.
0.35 increase in the New CA Ratio results in approx. 1% increase in VMA and air voids.	0.20 increase in CA Ratio results in approx. 1% increase in VMA and air voids.
Too low New CA Ratio means too few interceptors and therefore VMA and air voids are lower.	Too low CA Ratio means too few interceptors and therefore VMA and air voids are lower.
By definition of fine mixes, the coarse particles are floating in the fine particles. However, the old CA Ratio of fine mixes still is not related to segregation.	Too low CA Ratio means too many coarse particles and therefore, the mix is prone to segregation.
Too high new CA Ratio means too many interceptors and therefore, the mix may be tender and difficult to compact.	Too high CA Ratio means too many interceptors and therefore, the mix may be tender and difficult to compact.
New CA Ratio suggested range is 0.6 - 1.0	CA Ratio suggested range depends on the NMPS.

Note: CA = Coarse Aggregate, PCS = Primary Control Sieve, VMA = Voids in Mineral Aggregate

3.3.3 The 3rd Bailey Principle – FA_c Ratio

The evaluation of the coarse fraction of the fine aggregate within the structure uses the idea of the “Secondary Control Sieve” (SCS). The ratio of the fine part of the fine fraction to the total fine fraction is defined as the FA_c Ratio. The FA_c Ratio is the primary factor in the controlling the VMA and air voids of the mixture. The FA_c Ratio is further described in Table 4.

Table 4. Expected Changes to VMA Based on Changes to the Fine Aggregate Coarse Ratios for Fine and Coarse Mixes

FINE IN CONTROL	COARSE IN CONTROL
New SCS = 0.22 times the new PCS.	SCS = 0.22 times the original PCS.
New PCS is = 0.22 times the original PCS.	PCS stays as originally defined.
New FA _c Ratio suggested range is 0.35 - 0.50	FA _c Ratio suggested range is 0.35 - 0.50
0.05 increase in new FA _c Ratio up to 0.50, results in approx. 1% decrease in VMA or air voids.	0.05 increase in FA _c Ratio up to 0.55, results in approx. 1% decrease in VMA or air voids.
Once New FA _c Ratio increases beyond 0.50, VMA begins to increase.	Once FA _c Ratio increases beyond 0.55, VMA begins to increase.
As new FA _c Ratio increases toward 0.50, compactability of fine fraction increases.	As FA _c Ratio increases toward 0.55, compactability of fine fraction increases.

Note: PCS = Primary Control Sieve, SCS = Secondary Control Sieve, FA_c Ratio = ratio of the fine part of the fine fraction to the total fine fraction, VMA = Voids in Mineral Aggregate

3.3.4 The 4th Principle – FA_f Ratio

The evaluation of the fine portion of the aggregate structure uses the idea of the “Tertiary Control Sieve” (TCS). The ratio of the fine part of the fine fraction to the total fine part of the fine fraction is defined as the FA_f Ratio. Therefore, the small particles passing the TCS fit into the voids created by the coarser particles found between the SCS and the TCS. The FA_f Ratio is further described in Table 5.

Table 5. Expected Changes to VMA Based on Changes to the Fine Aggregate Fine Ratios for Fine and Coarse Mixes

FINE IN CONTROL	COARSE IN CONTROL
New TCS = 0.22 times the new SCS.	TCS = 0.22 times the original SCS.
New SCS is = 0.22 times the new PCS.	SCS stays as originally defined.
New FA _f Ratio suggested range is 0.35 - 0.50	FA _f Ratio suggested range is 0.35 - 0.50
As the new FA _f Ratio increases up to 0.50, VMA decreases.	As the FA _f Ratio increases up to 0.55, VMA decreases.
Once the new FA _f Ratio increases beyond 0.50, VMA begins to increase.	Once FA _f Ratio increases beyond 0.55, VMA begins to increase.

Note: TCS = Tertiary Control Sieve, SCS = Secondary Control Sieve, PCS = Primary Control Sieve, FA_f Ratio = ratio of the fine part of the fine fraction to the total fine part of the fine fraction, VMA = Voids in Mineral Aggregate

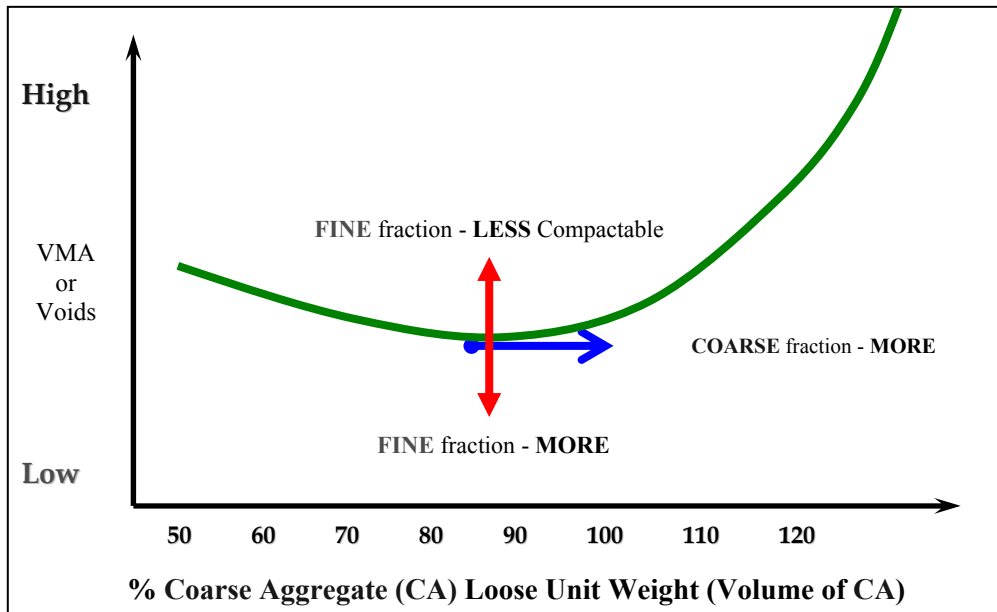


Figure 5. Expected Change in VMA and Mix Compactability due to Changes in the Volume of Coarse Aggregate

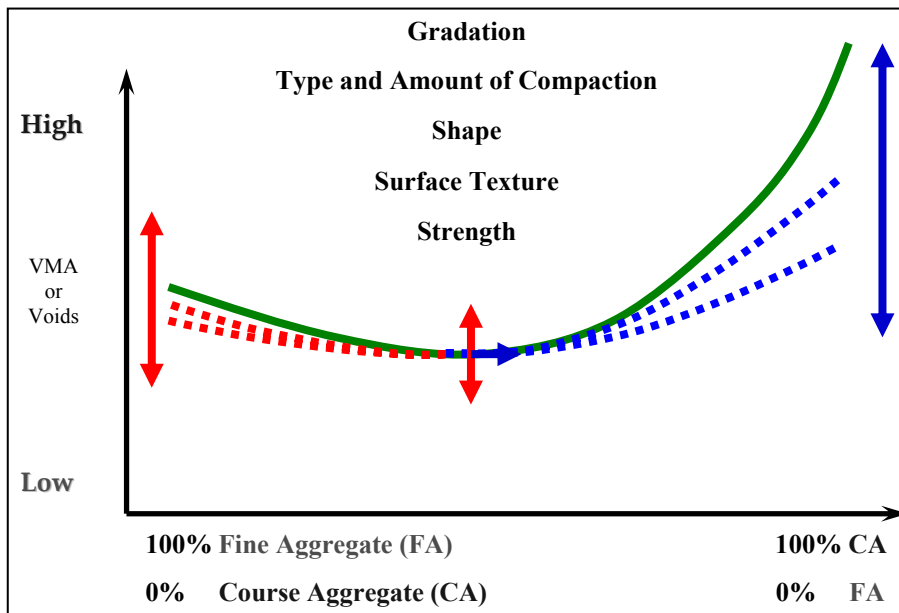


Figure 6. Impact of Changes to Aggregate Physical Properties with Varying Coarse and Fine Fractions

Table 6. Ratio Guidelines for Coarse-Graded Mixes

NMPS	37.5 mm	25.0 mm	19.0 mm	12.5 mm	9.5 mm	4.75 mm
CA Ratio	0.80–0.95	0.70–0.85	0.60–0.75	0.50–0.65	0.40–0.55	0.30–0.45
FA _c Ratio	0.35 – 0.50					
FA _f Ratio	0.35 – 0.50					

Note: NMPS= Nominal Maximum Particle Size, CA = Course Aggregate, FA = Fine Aggregate, FA_f Ratio = ratio of the fine part of the fine fraction to the total fine part of the fine fraction

Table 7. Ratio Guidelines for Fine-Graded Mixes

NMPS	37.5 mm	25.0 mm	19.0 mm	12.5 mm	9.5 mm	4.75 mm
New CA Ratio	0.6 – 1.0					
New FA _c Ratio	0.35 – 0.50					
New FA _f Ratio	0.35 – 0.50					

Note: NMPS= Nominal Maximum Particle Size, CA = Course Aggregate, FA = Fine Aggregate, FA_f Ratio = ratio of the fine part of the fine fraction to the total fine part of the fine fraction

3.0 MIX DESIGN EXAMPLES AND ANALYSIS

The *Bailey Method of Gradation Selection*[®] calculations can be done on an Excel[™] spreadsheet developed by the Heritage Research Group (HRG). Figures 9 to 12 show the details of the different worksheets used to design mixes. The first page in this example provides step-by-step direction on how to use the volume blending spreadsheets. The second sheet (Figure 10) is the main mix design calculation or blending worksheet. All the pertinent information for each stockpile is entered on this worksheet. The third worksheet includes the gradation plot for the trial blend evaluated and the last worksheet includes a table for the type of mix being designed. The program is extremely user friendly and contains advice on the amount of change and the directional change in VMA and air voids depending on the changes made to

the proportioning by the designer. This example is based on a 9.5 mm Superpave coarse graded mix. Spreadsheets for fine graded mixes, SMA, and RAP mixes have also been developed.

HRG have also developed worksheets to estimate the changes in VMA and air voids when comparing different trials of a mix design and/or comparing quality control results from sample to sample (e.g. sub-lot to sub-lot). This provides the contractor a very useful tool to monitor the mix properties or the process in the field. An example of a typical VMA estimation worksheet is shown in Table 8. A comparison of the actual versus the estimated VMA generated within the spreadsheet is shown in Figure 7. The magnitude of the difference and the directional change are also shown in Figure 8. The results show that the field VMA can be estimated with fairly good accuracy and the value of the Bailey method for tracking process control data.

The correlation graphs (VMA Graphs and Voids Graphs tabs in the spreadsheet) can also help by getting the slope of the linear regression line as close to 1.0 as possible and getting the actual line itself as close as possible to the “line of equality”. However, these graphs are significantly affected when either a shift occurs (change in aggregate shape, strength, or texture) and/or a “bad” sample occurs.

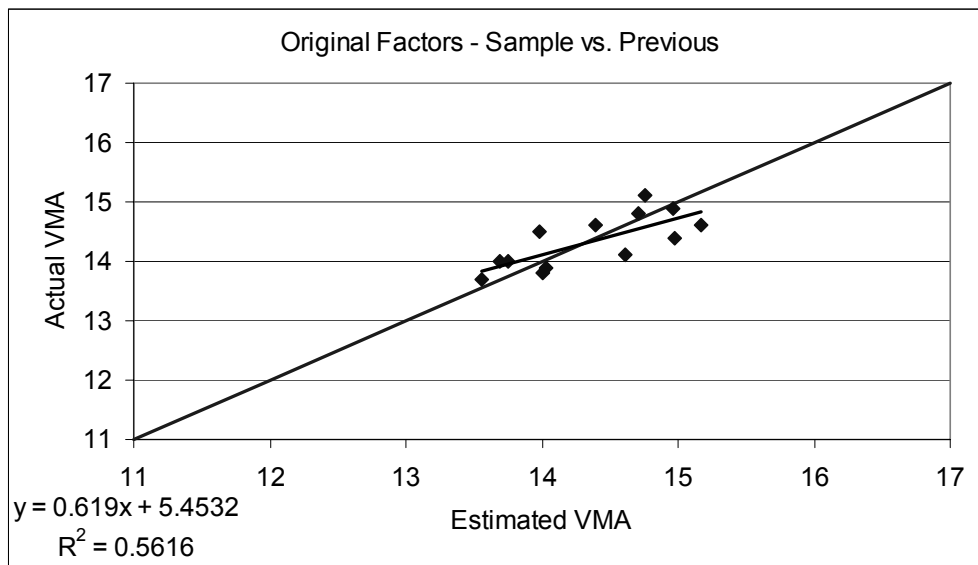


Figure 7. Typical Correlation between Estimated and Actual VMA

The estimation worksheets include an area where the Gsb, Bulk Specific Gravity of compacted Mix (Gmb), and Maximum Specific Gravity of the Mix (Gmm) data may be entered for each sample. This is used primarily to determine the Asphalt Cement Absorption (Pba) for each sample. This value can then be copied up to the row directly under the % AC. Entering the Pba significantly improves the accuracy of estimating air voids by taking the change in “effective” asphalt cement into account, rather than the change in “total” asphalt content. Through experience, HRG have found that aggregates typically absorb asphalt binder at ~ 60 percent of their water absorption (by weight). Also, you can determine an overall water absorption for a given blend, multiply by 60 percent, and generally estimate the Pba within 0.1 percent or so. If the calculated Pba values are 0 or less, either the design Gsb is suspect or the field Gsb has changed significantly.

When using the estimation worksheets, the most important thing to remember is that the gradation and AC content must accurately match the volumetric properties (air voids and VMA). If any one of these results (gradation, asphalt content, air voids, or VMA) is incorrect, the ability to accurately estimate the change in air voids or VMA decreases significantly.

When comparing a given sample to the mix design, the goal is to achieve a consistent difference between trials. When the difference varies, it typically indicates a change in aggregate shape, strength, or texture. If this is the case, you'll typically see a "shift" and the new difference will then become consistent again. However, if the difference between the following sample and the design goes back to where it was before, it generally indicates a problem with the previous sample.

When comparing a given sample to the previous sample, a minimum difference is the goal, which is considered to be between +0.5 and -0.5, ideally no difference is the real goal. However, it can't be 0.0 all the time, so it is preferred to see differences alternate from the "positive" to the "negative" side of 0.0. Being consistently one side or the other typically indicates that a factor needs adjusted.

3.1 Bailey Method Example

The application of the Bailey Method can be better explained by working through an actual mix design and the resulting HMA production. For this example a 12.5 mm SMA mix design was completed using the Bailey Method.

A 12.5 mm SMA was designed with the Superpave Gyratory Compactor using traprock coarse and fine aggregate including Performance Graded (PG) 70-28, cellulose fiber, and mineral filler. The mix design as shown in Table 8 required 79 percent traprock coarse aggregate, 12.5 percent traprock fine aggregate, 8.5 percent mineral filler, 0.3 percent cellulose fibers, and a total 5.7 percent asphalt cement by weight of mix. The resulting mix design provided 4.0 percent air voids and 17.9 percent VMA with a combined Gsb of 2.880.

It should be noted the accuracy of the estimation worksheet using the Bailey Method is predicated on the accuracy of the batching for each trial mix to the job mix formula. It has been found that fractionating the coarse and fine aggregates on each sieve down to the 2.36 mm sieve and then from the 2.36 mm sieve to the pan has improved the accuracy. This is in accordance to Asphalt Institute mix design sample preparation methodology. Others complete the fractionation on all sieves. The same would be completed on extracted RAP aggregate material.

The initial trial blend using 75.0 percent traprock coarse aggregate, 16.5 percent traprock fine aggregate, 8.5 percent mineral filler, 0.3 percent cellulose fibres, and a total 5.6 percent asphalt cement by weight of mix resulted in 3.3 percent air voids and 17.3 percent VMA. Utilizing the Bailey Method suggested a change in proportion of the CA and FA of 79.0 percent and 12.5 percent, respectively to yield 4.0 percent air voids and 18.7 percent VMA. The resulting second trial blend provided 4.0 percent air voids and 17.9 percent VMA. Well within the expected range for the estimated air voids and VMA to actual air voids and VMA. In this example, the Bailey Method process has dramatically reduced the number of mix design trials required to determine an optimum mix design.

The production tests results are summarized in Table 8. A comparison of a given production sample to the mix design indicates in most cases a consistent difference between production samples. However, there are differences that vary indicating a possible change in aggregate shape for this given traprock material.

When comparing a given production sample to the previous sample a minimum difference in air voids and VMA is generally achieved however, there are instances where the sample is significantly different from the previous.

Table 8. Example VMA Estimation Worksheet for 12.5 mm SMA

Vers. 02-27-05	VMA and Voids Estimation for 12.5 mm NMPS SMA Mix			
Sample	Mix Design	1	2	5
Identification	Hwy 401	1-1	1-4	2-5
19.0 mm	100.0	100.0	100.0	100.0
12.5 mm	98.8	95.9	95.7	98.9
9.5 mm	71.2	71.0	68.4	70.7
6.25 mm	40.1	40.6	39.4	39.4
4.75 mm	25.7	26.6	26.0	24.9
2.36 mm	21.7	21.2	20.7	20.4
1.18 mm	17.4	16.9	16.5	16.0
0.600 mm	14.8	14.1	14.0	13.1
0.300 mm	13.1	12.1	11.7	11.1
0.150 mm	10.9	10.0	9.5	9.3
0.075 mm	9.2	7.8	8.2	7.4
% AC	5.70	5.86	5.65	5.72
% AC Absorption	0.00	0.21	-0.18	-0.03
Actual VMA	17.9	17.6	17.5	18.7
Actual Voids	4.0	4.8	3.4	4.9
CA	0.307	0.327	0.308	0.313
F _{Ac}	0.682	0.665	0.676	0.642
F _f	0.736	0.709	0.679	0.710
PCS	Compares Each Sample to the Mix Design	0.17	0.33	0.43
CA		0.20	0.01	0.06
F _{Ac}		0.23	0.08	0.53
F _f		-0.36	-0.76	-0.35
Total		0.23	-0.34	0.68
Est. VMA		18.1	17.6	18.6
Act VMA		17.6	17.5	18.7
Diff in VMA		0.5	0.1	-0.1
Est. Voids		4.4	3.3	4.6
Act Voids		4.8	3.4	4.9
Diff in Voids	-0.4	-0.1	-0.3	
PCS	Compares Each Sample to the Previous Sample	0.17	0.17	0.10
CA		0.20	-0.19	0.05
F _{Ac}		0.23	-0.15	0.45
F _f		-0.36	-0.40	0.41
Total		0.23	-0.57	1.02
Est. VMA		18.1	17.0	18.5
Act VMA		17.6	17.5	18.7
Diff in VMA		0.5	-0.5	-0.2
Est. Voids		4.4	3.8	4.6
Act Voids		4.8	3.4	4.9
Diff in Voids	-0.4	0.4	-0.3	

Note: VMA = Voids in Mineral Aggregate, NMPS= Nominal Maximum Particle Size, SMA = Stone Mastic Asphalt, AC = Asphalt Content, CA = Course Aggregate, F_{Ac} = ratio of the fine part of the fine fraction to the total fine fraction, F_f Ratio = ratio of the fine part of the fine fraction to the total fine part of the fine fraction, PCS = Primary Control Sieve

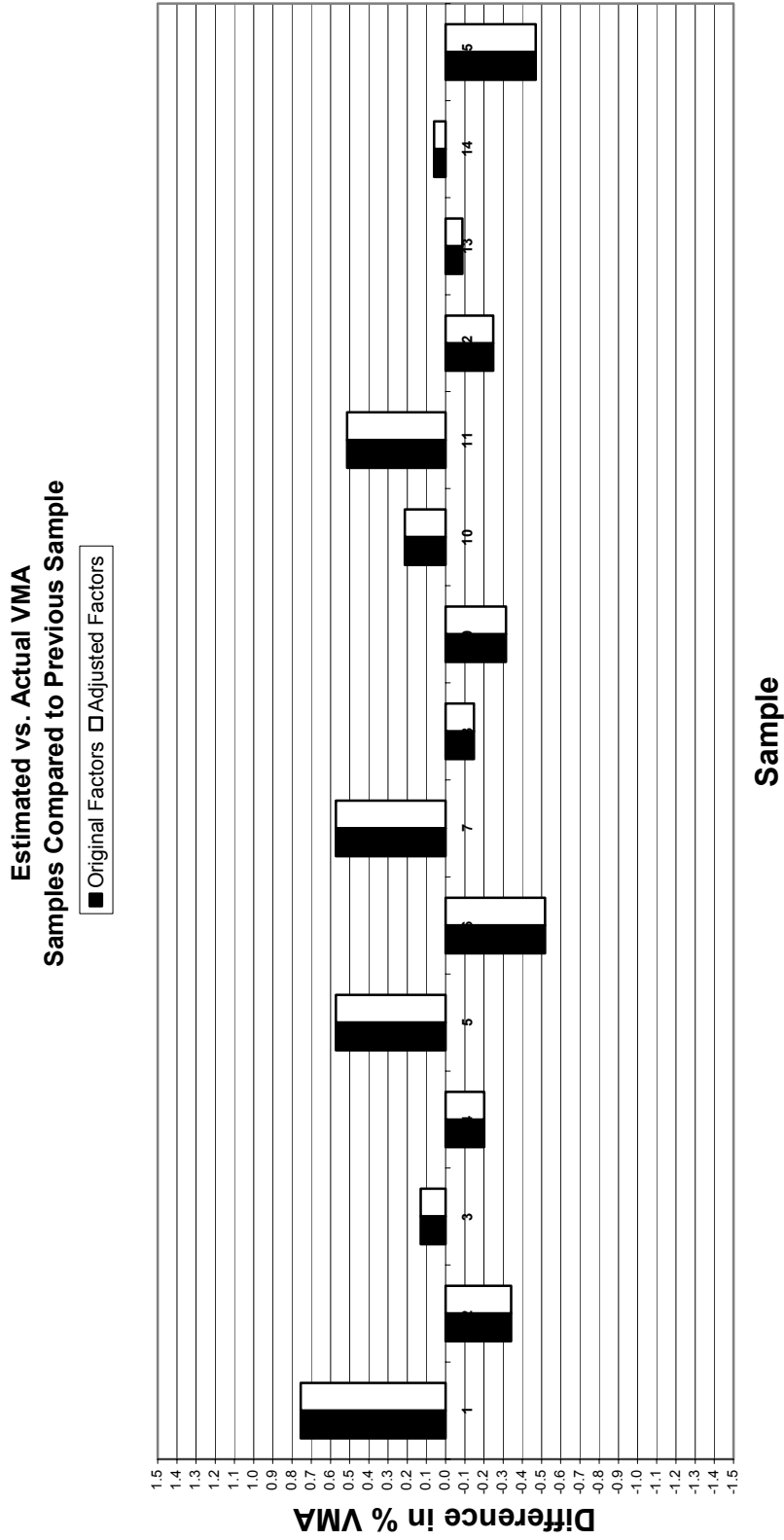


Figure 8. Directional Change in Estimated vs. Actual VMA



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Volume Blending - Coarse Graded

Version 03/22/2004

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The User hereby agrees not to reproduce or distribute this material without the expressed written consent of Heritage Research Group. Reasonable precautions have been taken to ensure the spreadsheets contain no errors; however, Heritage Research Group makes no claim that mixtures designed by this method will perform in a given application. The User must evaluate the results for reasonableness. It is the opinion of Heritage Research Group, that all Users be adequately instructed on the principles of *The Bailey Method of Gradation Selection* before attempting to utilize these Spreadsheets.

- Highlighted cells indicate areas that allow or require data input
- Cells with small red triangles in the upper right corner contain comment boxes to provide additional information
- The Spreadsheets are protected to prevent data entry into cells that contain formulas
- To determine the Individual Aggregate %'s and the Combined Blend, the following input information is required:
 1. Individual Aggregate Gradation in percent passing
 2. Individual Aggregate Unit Weight(s)
 3. % CA LOOSE Unit Weight for Coarse Aggregate(s) (Recommend 95-105%)
 4. Individual Aggregate Dry Bulk Specific Gravity (Gsb)
 5. Multiplication factor (e.g. 62.4 lbs./ft³ or 1000 kg/m³) corresponding to the Unit Weight values
 6. Desired blend by volume of Coarse Aggregate(s)
 7. Desired blend by volume of Fine Aggregate(s)
 8. Desired percent passing the 0.075mm sieve in the Combined Blend
- The step-by-step calculations are provided on each Spreadsheet directly below the normal working area

Figure 9. Bailey Method Excel™ Spreadsheet – First TAB



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Design Number: _____
 Design Date: _____
 Mix Producer Name: _____
 Mixture Name/Code: _____
 Aggregate: #1-CA #2-CA #3-CA #4-CA #1-FA #2-FA #3-FA #4-FA MF MF Hyd Lime AC
 Today: _____
 9.5mm Coarse-graded Virgin blend

Code	Coarse Aggregate	Chips	Natural Sand	Bag House	Black Magic
Source id					
Name					
Location					

Agg %'s (P)	#1-CA	#2-CA	#3-CA	#4-CA	#1-FA	#2-FA	#3-FA	#4-FA	MF	Hyd Lime	AC
19.0	64.2	0.0	0.0	0.0	32.7	0.0	0.0	0.0	3.1	0.0	100.0
12.5	100.0				100.0				100.0		100.0
9.5	100.0				100.0				100.0		100.0
4.75	30.8				99.6				100.0		55.4
2.36	7.7				85.8				100.0		36.1
1.18	4.9				79.2				100.0		29.2
0.600	4.1				51.2				100.0		22.5
0.300	3.7				15.7				100.0		10.6
0.150	3.5				1.7				99.0		5.9
0.075	3.0				0.9				88.0		4.9

% CA LUW	100.0	% FA RUW								100.0
LUW	1422.2									
CHOSEN LUW	1422.2	0.0	0.0	0.0	1722.8	0.0	0.0	0.0	0.0	
RUW	1580.9				1722.8					
Bulk Spec Gr	2.630				2.880				2.800	
Apparent Gr									2.800	
% Abspfn.										
Loose Voids	45.9									
Rodded Voids	39.9				33.2					

Enter the multiplication factor to be used with the Bulk Specific Gravity of the Aggregates according to the values entered for the Unit Weights (e.g. 62.4 lbs./ft³ or 1000 kg/m³)

Desired Blends by VOLUME	
Coarse Agg's	100.0 ← MUST TOTAL 100.0%
Fine Agg's	MUST TOTAL 100.0% → 100.0
Total Volume %'s	
	84.1
	45.9

Enter the percent passing the 0.075mm sieve desired in the Combined Blend:

Combined Bulk Specific Gravity of the Aggregates (Gsb):

CA	0.434	Percent Passing By Volume	100.0
			100.0
FA _c	0.623 <td></td> <td>98.0</td>		98.0
			55.6
			36.3
			29.3
			22.5
			10.5
FA _f	0.261 <td></td> <td>5.7</td>		5.7
			4.8

% AC	Gmb	VCAmix
4.5	2.332	45.8
5.0	2.351	45.7
5.5	2.363	45.7
6.0	2.374	45.7

Figure 10. Bailey Method Volume Blending Worksheet

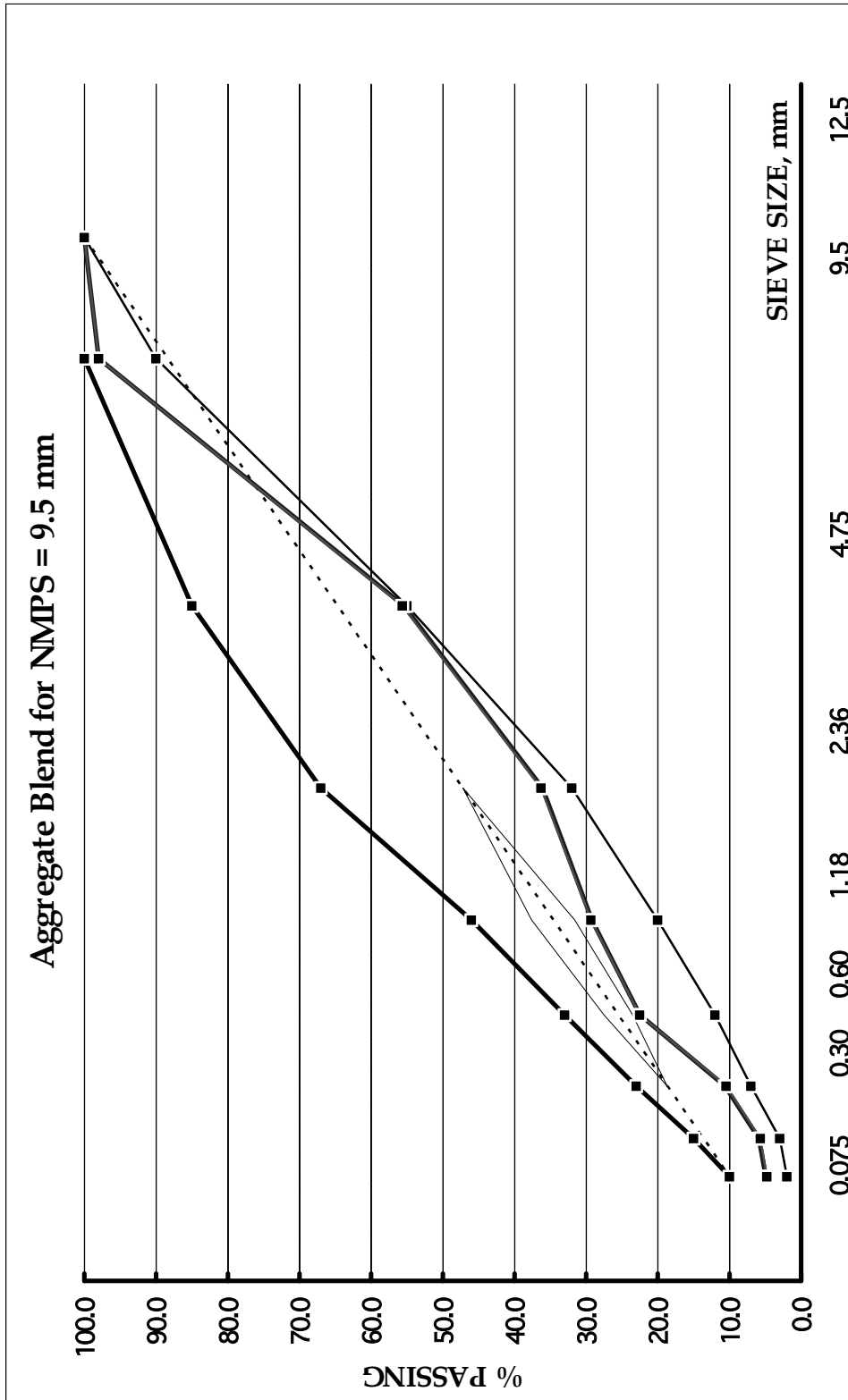


Figure 11. Gradation Plot

The following table is presented to summarize the ratios that are used in the various NMPS worksheets. Note that the sieve size designations used in the three ratios of the table represent the percent passing for that particular sieve.										Information for Coarse-Graded Mixes ONLY
NMPS	37.5mm	25.0mm	19.0mm	12.5mm	9.5mm	4.75mm	2.36mm	1.18mm	0.30mm	
PCS	9.5mm	4.75mm	4.75mm	2.36mm	2.36mm	2.36mm	1.18mm	1.18mm	0.30mm	NMPS = 37.5mm, 0.80 - 0.95 NMPS = 25.0mm, 0.70 - 0.85 NMPS = 19.0mm, 0.60 - 0.75 NMPS = 12.5mm, 0.50 - 0.65 NMPS = 9.5mm, 0.40 - 0.55 NMPS = 4.75mm, 0.30 - 0.45
Half sieve	19.0mm	12.5mm	9.5mm	6.25mm	4.75mm	2.36mm	2.36mm	2.36mm	0.30mm	
CA Ratio	19.0 - 9.5 100% - 19.0	12.5 - 4.75 100% - 12.5	9.5 - 4.75 100% - 9.5	6.25 - 2.36 100% - 6.25	4.75 - 2.36 100% - 4.75	2.36 - 1.18 100% - 2.36	2.36 - 1.18 100% - 2.36	2.36 - 1.18 100% - 2.36	0.30 - 0.15 100% - 0.30	
SCS	2.36mm	1.18mm	1.18mm	0.60mm	0.60mm	0.60mm	0.30mm	0.30mm	0.30mm	
FA _c Ratio	2.36 9.5	1.18 4.75	1.18 4.75	0.60 2.36	0.60 2.36	0.60 2.36	0.30 1.18	0.30 1.18	0.30 1.18	0.35 - 0.50 stay > 0.40 if possible
TCS	0.60mm	0.30mm	0.30mm	0.150mm	0.150mm	0.150mm	0.075mm	0.075mm	0.075mm	
FA _f Ratio	0.60 2.36	0.30 1.18	0.30 1.18	0.150 0.60	0.150 0.60	0.150 0.60	0.075 0.30	0.075 0.30	0.075 0.30	0.35 - 0.50

The CA Ratio relates to the **packing** achieved in the material above the PCS (the coarse fraction), which also influences the **packing** achieved in the fine fraction. As the CA Ratio increases, VMA and Voids increase.

The FA_c Ratio relates to the **packing** achieved in the overall fine fraction. The SCS is used as the break between the particles that create voids, and the particles that fill them. As the FA_c Ratio increases, VMA and Voids decrease.

The FA_f Ratio relates to the **packing** achieved in the material passing the SCS, considered the fine part of the fine fraction. The TCS is used as the break between the particles that create voids, and the particles that fill them. As the FA_f Ratio increases, VMA and Voids decrease.

Figure 12. Ratio Guidelines for Coarse Graded Mixes included in the Excel™ Spreadsheets

Rut testing was conducted on a number of mixes to determine if any correlation exists between the Bailey principles and rutting. The data was analyzed to compare the following factors. Figure 13 shows a typical regression plot for one of the mixes studied.

- PCS vs. Rutting.
- CA Ratio vs. Rutting.
- FA_c Ratio vs. Rutting.
- FA_f Ratio vs. Rutting.
- VMA vs. Rutting.
- Voids vs. Rutting.

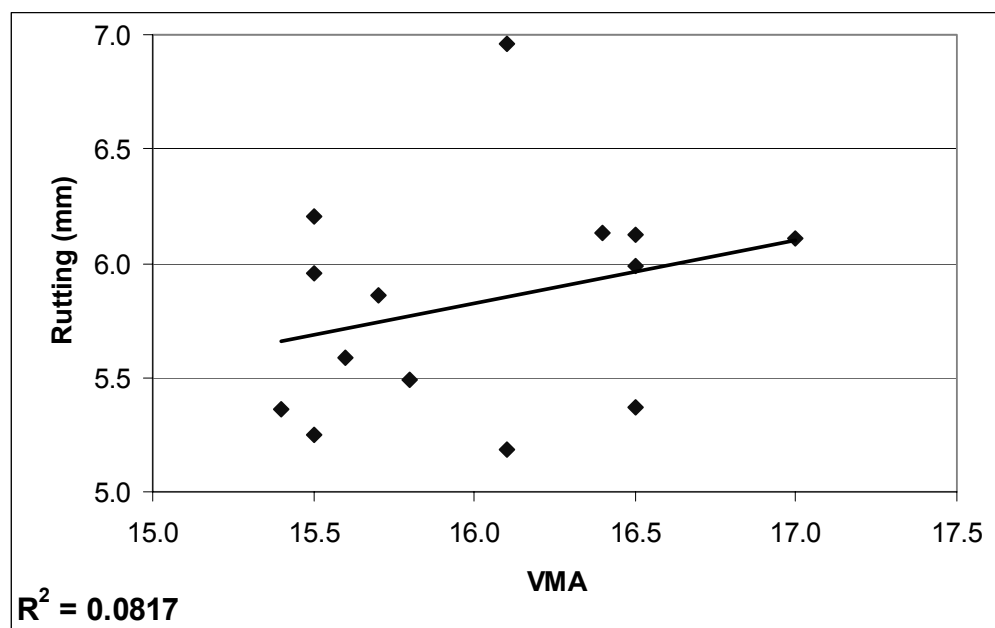


Figure 13. Correlation Graph, VMA versus Rutting

In general, the data does not show a good correlation between rutting and any one of the individual Bailey principles. This makes sense from the standpoint that each of the Bailey principles is a measure of aggregate packing for a particular fraction of the blend and not the overall blend. However, we know that the overall aggregate packing plays a role in rutting. Ideally, designer would like to relate a “total” factor for the combined Bailey principles to the degree of rutting (or whatever performance parameter we have) to the results achieved. This is potentially an area for further study in the future.

5.0 CLOSING REMARKS

The Bailey Method has been proven to be a useful and practical tool to help mix designers and quality control personnel better understand volumetrics and hot mix asphalt compactability. While there is still some trial and error involved, understanding the principles involved in the Bailey Method provides a good starting point for mix design and an invaluable aid when making adjustments at the plant or in the field to

improve mix volumetric properties and the workability of the mix during lay down and compaction. Based on the limited analysis of data from five projects it would appear that there is no correlation with any of the individual Bailey principles to rutting. This is not unexpected given that all four Bailey principles influence the packing characteristics of a mix. However, for each project the estimated VMA exhibited good trends when compared to the actual VMA calculated based on the field produced mix. In closing, it really must be emphasized that proper training is essential to understanding the Bailey principles and ultimately applying the method in practice.

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