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Bailey Method for Gradation Selection in Hot-Mix Asphalt Mixture Design

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Foreword

This Circular is a synopsis of current information on the Bailey Method, a systematic approach to selecting and adjusting aggregate gradation in hot-mix asphalt (HMA) design.

Originally developed by Robert Bailey (retired) of the Illinois Department of Transportation (IDOT), the method advocates a strong aggregate skeleton for rut resistance along with adequate voids in mineral aggregate for good durability. The method has been used by District 5 of the IDOT since the early 1980s, and in the 1990s IDOT promoted the use of the method throughout the state.

Two Transportation Research Board Committees—Committee on Characteristics of Bituminous–Aggregate Combinations to Meet Surface Requirements (A2D03) and Committee on Characteristics of Bituminous Paving Mixtures to Meet Structural Requirements (A2D04)—were asked to review the information presented by the authors. The committees agreed that it should be of interest to materials and pavement engineers and others responsible for designing HMA pavements.

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Asphalt mixtures are composed of pieces of broken rock glued together with an asphalt binder. In practice, hot-mix asphalt (HMA) is a very simple material. Actually, HMA as a construction material is much more complicated than it appears.

HMA is a composite material consisting of aggregate particles (hard pieces of rock) of different sizes, an asphalt binder that is much softer than the aggregate, and air voids. The response of HMA to traffic and environmental loads depends on the properties of the constituents and the proportion (by volume) of each. In turn, the performance of the HMA in rutting, cracking, and durability is directly related to the mixture response to loads.

Highway engineers often refer to a skeleton in the mixture when discussing the role of aggregate. Indeed, most of the compressive strength and resistance to movement under truck loads comes from the aggregate. Properties of the skeleton are related directly to the hardness, shape, texture, and gradation of the aggregate. Of these properties, gradation is the most unstructured.

The 0.45-power grading chart is the only tool available to designers for the evaluation of gradation. Except for some very general rules, such as "Stay away from the maximum density line to increase voids in the mineral aggregate," there was no guidance for the effect of gradation on mixture properties. Most designers just learn by experience how gradation changes mixture properties.

The Bailey Method for gradation selection considers the packing characteristics of aggregates. The parameters in the method are related directly to voids in the mineral aggregate (VMA), air voids, and compaction properties.

The Bailey Method is a means to design the aggregate interlock and aggregate structure in an asphalt mixture. The principles in the method can be used from the asphalt mix design through the quality control process, but are not a mix design method. The method does not address the appropriate aggregate properties or asphalt mix properties required to produce a quality asphalt mixture. This document describes the Bailey Method for Aggregate Selection in HMA Mixture Design.

What Is the Bailey Method?

Traditionally, asphalt mixtures have been designed using a trial-and-error procedure to select the aggregate gradation. Aggregates are combined in “typical” percentages that were developed from years of experience. A design method for all mixtures has not been available that provides a means to design the degree of coarse aggregate interlock desired in the asphalt mixture. Work done by National Center for Asphalt Technology for designing stone matrix asphalt (SMA) mixtures is very helpful to determine the degree of interlock achieved. This concept of comparing voids in the coarse aggregate (VCA) of the mix to the dry rodded condition (DRC) of the coarse aggregate can also be used for evaluating interlock in dense-graded mixtures.

The Bailey Method is a systematic approach to blending aggregates that provides aggregate interlock as the backbone of the structure and a balanced continuous gradation to complete the mixture. The method provides a set of tools that allows the evaluation of aggregate blends. These tools provide a better understanding in the relationship between aggregate gradation and mixture voids.

The Bailey Method gives the practitioner tools to develop and adjust aggregate blends. The new procedures help to ensure aggregate interlock (if desired) and good aggregate packing, giving resistance to permanent deformation, while maintaining volumetric properties that provide resistance to environmental distress.

DEVELOPMENT

The Bailey Method was originally developed by Mr. Robert Bailey (retired) of the Illinois Department of Transportation, District 5. This method is based on his experience in the design of asphalt mixtures. Mr. Bailey developed these methods as a means to combat the rutting of asphalt mixes while maintaining the proper durability characteristics.

The procedures originally developed by Mr. Bailey have been refined by Dr. Bill Vavrik, ERES Consultant Division of Applied Research Associates, Inc., and Mr. Bill Pine, Heritage Research, to present a systematic approach to aggregate blending that is applicable to all dense-graded asphalt mixtures, regardless of the maximum size aggregate in the mixture. It can be used with any method of mix design, including Superpave®, Marshall, or Hveem. The method can also be used with SMA, for which guidance is provided in the section on Bailey Method Principles and SMA Mixes, page 19.

In the Bailey Method aggregate interlock is selected as a design input. Aggregate interlock will provide a rut-resistant mixture. To ensure that the mixture contains adequate asphalt binder, VMA is changed by changing the packing of the coarse and fine aggregates. In this way asphalt mixtures developed with the Bailey Method can have a strong skeleton for high stability and adequate VMA for good durability.

These aggregate blending procedures have been validated with laboratory analysis and field trials (*1,2,3,4*). The laboratory work performed to date includes the many mix designs used in Illinois by Mr. Robert Bailey, who used the method to improve the performance of Illinois highways but did not publish his studies. Additionally, the relationships between aggregate gradation and the resulting mixture volumetric properties are well documented in the studies of Vavrik (*4*). Internationally, the Bailey Method has been used in a laboratory asphalt research program in Dubai, United Arab Emirates, to improve the rutting performance of their mixtures. Field trials have been placed in Dubai, France, Canada, and throughout the United States. The results of these laboratory and field trials will be published as the results are available.

BASIC PRINCIPLES

To develop a method for combining aggregates to optimize aggregate interlock and provide the proper volumetric properties, it is necessary to understand some of the controlling factors that affect the design and performance of these mixtures. The explanation of coarse and fine aggregates given in the following section provide a background for understanding the combination of aggregates. The Bailey Method builds on that understanding and provides more insight into the combination of aggregates for use in an asphalt mixture.

The Bailey Method uses two principles that are the basis of the relationship between aggregate gradation and mixture volumetrics:

- Aggregate packing, and
- Definition of coarse and fine aggregate.

With these principles, the primary steps in the Bailey Method are:

- Combine aggregates by volume, and
- Analyze the combined blend.

Aggregate Packing

Aggregate particles cannot be packed together to fill a volume completely. There will always be space between the aggregate particles. The degree of packing depends on:

- Type and amount of compactive energy. Several types of compactive force can be used, including static pressure, impact (e.g., Marshall hammer), or shearing (e.g., gyratory shear compactor or California kneading compactor). Higher density can be achieved by increasing the compactive effort (i.e., higher static pressure, more blows of the hammer, or more tamps or gyrations).
- Shape of the particles. Flat and elongated particles tend to resist packing in a dense configuration. Cubical particles tend to arrange in dense configurations.
- Surface texture of the particles. Particles with smooth textures will re-orient more easily into denser configurations. Particles with rough surfaces will resist sliding against one another.
- Size distribution (gradation) of the particles. Single-sized particles will not pack as densely as a mixture of particle sizes.
- Strength of the particles. Strength of the aggregate particles directly affects the amount of degradation that occurs in a compactor or under rollers. Softer aggregates typically degrade more than strong aggregates and allow denser aggregate packing to be achieved.

The properties listed above can be used to characterize both coarse and fine aggregates. The individual characteristics of a given aggregate, along with the amount used in the blend, has a direct impact on the resulting mix properties. When comparing different sources of comparably sized aggregates, the designer should consider these individual characteristics in addition to the Bailey Method principles presented. Even though an aggregate may have acceptable characteristics, it may not combine well with the other proposed aggregates for use in the design. The final combination of coarse and fine aggregates, and their corresponding individual properties, determines the packing characteristics of the overall blend for a given type and amount of compaction. Therefore, aggregate source selection is an important part of the asphalt mix design process.

Coarse and Fine Aggregate

The traditional definition of coarse aggregate is any particle that is retained by the 4.75-mm sieve. Fine aggregate is defined as any aggregate that passes the 4.75-mm sieve (sand, silt, and clay size material). The same sieve is used for 9.5-mm mixtures as 25.0-mm mixtures.

In the Bailey Method, the definition of coarse and fine is more specific in order to determine the packing and aggregate interlock provided by the combination of aggregates in various sized mixtures. The Bailey Method definitions are:

- Coarse Aggregate: Large aggregate particles that when placed in a unit volume create voids.
- Fine Aggregate: Aggregate particles that can fill the voids created by the coarse aggregate in the mixture.

From these definitions, more than a single aggregate size is needed to define coarse or fine. The definition of coarse and fine depends on the nominal maximum particle size (NMPS) of the mixture.

In a dense-graded blend of aggregate with a NMPS of 37.5 mm, the 37.5-mm particles come together to make voids. Those voids are large enough to be filled with 9.5-mm aggregate particles, making the 9.5-mm particles fine aggregate. Now consider a typical surface mix with a NMPS of 9.5 mm. In this blend of aggregates, the 9.5-mm particles are considered coarse aggregate.

In the Bailey Method, the sieve which defines coarse and fine aggregate is known as the primary control sieve (PCS), and the PCS is based on the NMPS of the aggregate blend.

The break between coarse and fine aggregate is shown in Figure 1. The PCS is defined as the closest sized sieve to the result of the PCS formula in Equation 1.

$$\text{PCS} = \text{NMPS} \times 0.22 \qquad (1)$$

where

PCS = PCS for the overall blend
NMPS = NMPS for the overall blend, which is one sieve larger than the first sieve that retains more than 10% (as defined by Superpave terminology)

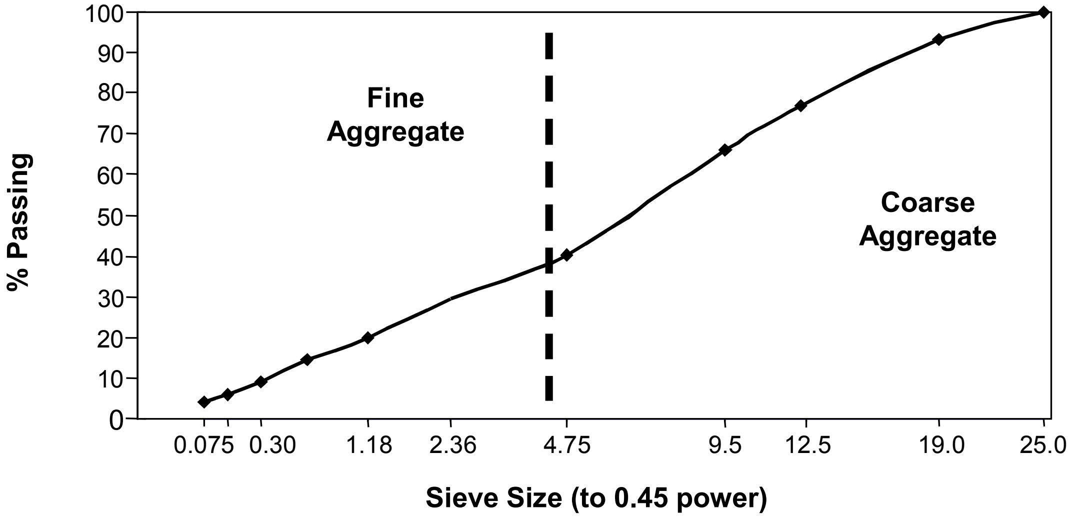

FIGURE 1 Example of break between coarse and fine aggregate for 19.0 NMPS mixture.

The value of 0.22 used in the control sieve equation was determined from a two- (2-D) and three-dimensional (3-D) analysis of the packing of different shaped particles. The 2-D analysis of the combination of particles shows that the particle diameter ratio ranges from 0.155 (all round) to 0.289 (all flat) with an average value of 0.22 (*1,2,3,4*). The 3-D analysis of the combination of particles gives a similar result with the particle diameter ratio ranging from 0.15 (hexagonal close-packed spheres) to 0.42 (cubical packing of spheres) (*5,6,7*). In addition, research on particle packing distinctly shows that the packing of particles follows different models when the characteristic diameter is above or below 0.22 ratio (*8,9,10,11*).

While 0.22 may not be exactly correct for every asphalt mixture, the analysis of gradation is not affected if the value ranges from 0.18 to 0.28. The 0.22 factor is the average condition of many different packing configurations.

Combining Aggregates by Volume

All aggregate blends contain an amount and size of voids, which are a function of the packing characteristics of the blend. In combining aggregates we must first determine the amount and size of the voids created by the coarse aggregates and fill those voids with the appropriate amount of fine aggregate.

Mix design methods generally are based on volumetric analysis, but for simplicity, aggregates are combined on a weight basis. Most mix design methods correct the percent passing by weight to percent passing by volume when significant differences exist among the aggregate stockpiles. To evaluate the degree of aggregate interlock in a mixture the designer needs to evaluate a mixture based on volume.

To evaluate the volumetric combination of aggregates, additional information must be gathered. For each of the coarse aggregate stockpiles, the loose and rodded unit weights must be determined, and for each fine aggregate stockpile, the rodded unit weight must be determined. These measurements provide the volumetric data at the specific void structure required to evaluate interlock properties.

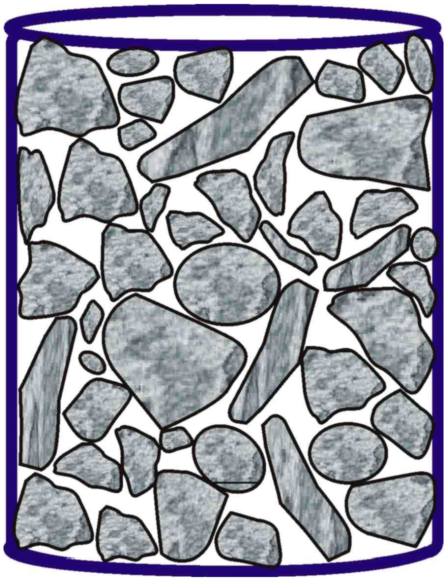

FIGURE 2 Loose unit weight of coarse aggregate.

Loose Unit Weight of Coarse Aggregate

The loose unit weight of an aggregate is the amount of aggregate that fills a unit volume without any compactive effort applied. This condition represents the beginning of coarse aggregate interlock (i.e., particle-to-particle contact) without any compactive effort applied. The loose unit weight is depicted in Figure 2.

The loose unit weight is determined on each coarse aggregate using the shoveling procedure outlined in AASHTO T-19: Unit Weight and Voids in Aggregate, which leaves the aggregate in a loose condition in the metal unit weight bucket. The loose unit weight (density in kg/m^3) is calculated by dividing the weight of aggregate by the volume of the metal bucket. Using the aggregate bulk specific gravity and the loose unit weight, the volume of voids for this condition is also determined. This condition represents the volume of voids present when the particles are just into contact without any outside compactive effort being applied.

Rodded Unit Weight of Coarse Aggregate

The rodded unit weight of aggregate is the amount of aggregate that fills a unit volume with compactive effort applied. The compactive effort increases the particle to particle contact and decreases the volume of voids in the aggregate. Rodded unit weight is depicted in Figure 3.

The rodded unit weight is determined on each coarse aggregate using the rodding procedure outlined in AASHTO T-19: Unit Weight and Voids in Aggregate, which leaves the aggregate in a compacted condition in the metal unit weight bucket. The rodded unit weight (density in kg/m^3) is calculated by dividing the weight of aggregate by the volume of the metal bucket. Using the aggregate bulk specific gravity and the rodded unit weight, the volume of voids for this condition is also determined. This condition represents the volume of voids present when the particles are further into contact due to the compactive effort applied.

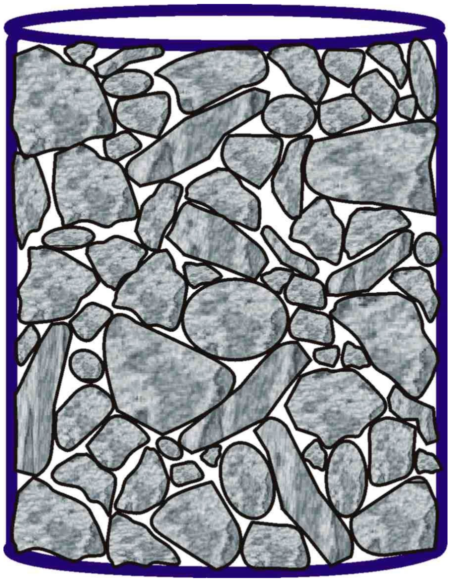

FIGURE 3 Rodded unit weight of coarse aggregate.

Chosen Unit Weight of Coarse Aggregate

The designer needs to select the interlock of coarse aggregate desired in their mix design. Therefore, they choose a unit weight of coarse aggregate, which establishes the volume of coarse aggregate in the aggregate blend and the degree of aggregate interlock.

In the Bailey Method, coarse-graded is defined as mixtures which have a coarse aggregate skeleton. Fine-graded mixtures do not have enough coarse aggregate particles (i.e., larger than the PCS) to form a skeleton, and therefore the load is carried predominantly by the fine aggregate. To select a chosen unit weight the designer needs to decide if the mixture is to be coarse-graded or fine-graded. Considerations for selecting a chosen unit weight are shown in Figure 4.

The loose unit weight is the lower limit of coarse aggregate interlock. Theoretically, it is the dividing line between fine-graded and coarse-graded mixtures. If the mix designer chooses a unit weight of coarse aggregate less than the loose unit weight, the coarse aggregate particles are spread apart and are not in a uniform particle-to-particle contact condition. Therefore, a fine aggregate skeleton is developed and properties for these blends are primarily related to the fine aggregate characteristics.

The rodded unit weight is generally considered to be the upper limit of coarse aggregate interlock for dense-graded mixtures. This value is typically near 110% of the loose unit weight. As the chosen unit weight approaches the rodded unit weight, the amount of compactive effort required for densification increases significantly, which can make a mixture difficult to construct in the field.

For dense-graded mixtures, the chosen unit weight is selected as a percentage of the loose unit weight of coarse aggregate. If the desire is to obtain some degree of coarse aggregate interlock (as with coarse-graded mixtures), the percentage used should range from 95% to 105% of the loose unit weight. For soft aggregates prone to degradation the chosen unit weight should be nearer to 105% of the loose unit weight (*2*). Values exceeding 105% of the loose unit weight should be

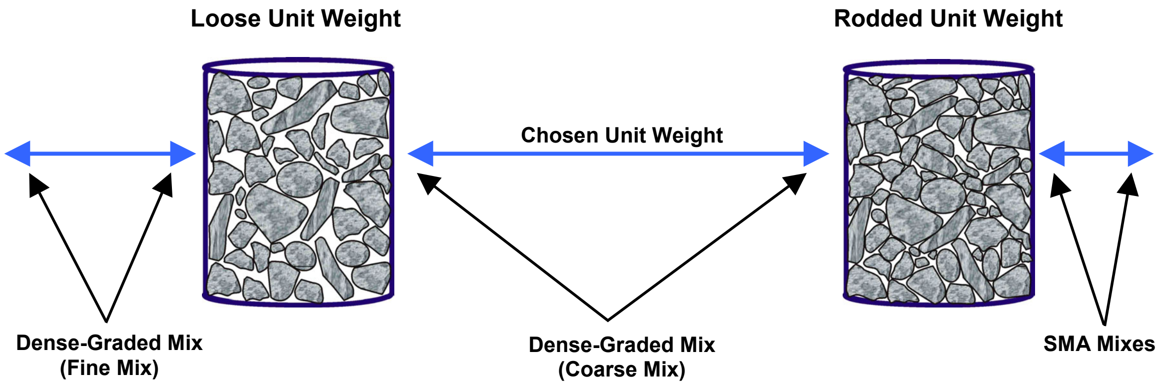

FIGURE 4 Selection of chosen unit weight of coarse aggregates.

avoided due to the increased probability of aggregate degradation and increased difficulty with field compaction.

With fine-graded mixtures, the chosen unit weight should be less than 90% of the loose unit weight, to ensure the predominant skeleton is controlled by the fine aggregate structure. Additional information for fine-graded mixtures is presented in the section on Bailey Method Principles and Fine-Graded Mixes, page 17.

For all dense-graded mixtures, it is recommended the designer should not use a chosen unit weight in the range of 90% to 95% of the loose unit weight. Mixtures designed in this range have a high probability of varying in and out of coarse aggregate interlock in the field with the tolerances generally allowed on the PCS.

It is normal for an aggregate blend to consolidate more than the selected chosen unit weight due to the lubricating effect of asphalt binder. Also, each coarse aggregate typically contains some amount of fine material when the unit weights are determined, which causes both unit weights (i.e., loose and rodded) to be slightly heavier than they would have been, had this material been removed by sieving prior to the test. Therefore, a chosen unit weight as low as 95% of the loose unit weight can often be used and still result in some degree of coarse aggregate interlock.

If the designer wants to determine the degree of interlock achieved with a given design in relation to the actual loose unit weight of the coarse aggregate, it is suggested they refer to the National Asphalt Pavement Association Quality Improvement Series 122: Designing and Constructing SMA Mixtures—State-of-the-Practice (*12*). This document discusses the calculations necessary for determining the VCA of the mixture and the VCA of the coarse aggregate in the DRC, which are used for evaluating interlock in SMA mixtures. In the case of a dense-graded mixture, the designer can determine the actual VCA in the dry loose condition (DLC) by performing a loose unit weight test on the combined material retained on the PCS for a given blend, along with determining the combined specific gravity for this material. By also determining the VCA_{MIX}, it can be compared to the VCA_{DLC} to determine the degree of aggregate interlock achieved in relation to the loose unit weight condition for a specific blend.

In summary, the amount of additional consolidation, if any, beyond the selected chosen unit weight depends on several factors:

- Aggregate strength, shape, and texture;

- The amount of fine aggregate that exists in each coarse aggregate when the loose and rodded unit weight tests are performed;
- Combined blend characteristics;
- Relation of the selected chosen unit weight to the rodded unit weight of coarse aggregate;
- Type of compactive effort applied (Marshall, Gyratory, etc.); and
- Amount of compactive effort applied (75 versus 125 gyrations, 50 versus 75 blows, etc.).

After selecting the desired chosen unit weight of the coarse aggregate, the amount of fine aggregate required to fill the corresponding VCA is determined.

Rodded Unit Weight of Fine Aggregate

For dense-graded mixtures, the voids created by the coarse aggregate at the chosen unit weight are filled with an equal volume of fine aggregate at the rodded unit weight condition. The rodded unit weight is used to ensure the fine aggregate structure is at or near its maximum strength. The rodded unit weight of fine aggregate is shown in Figure 5.

Rodded unit weight is determined on each fine aggregate stockpile as outlined in the rodding procedure in AASHTO T-19: Unit Weight and Voids in Aggregate, which leaves the aggregate in a compacted condition in the unit weight container. For most fine aggregates, which typically have a NMPS of 4.75 mm or less, a proctor mold, 100-mm diameter is used, which is a metal mold, approximately 0.9 liter in volume. The rodded unit weight (density in kg/m^3) is calculated by dividing the weight of the aggregate by the volume of the mold. In a dense-graded mixture, the rodded unit weight is always used to determine the appropriate amount of fine aggregate needed to fill the voids in the coarse aggregate at the chosen unit weight condition. A chosen unit weight is not selected. Note that the rodded unit weight is not determined for dust sized material, such as mineral filler (MF) or bag house fines.

Determining a Design Blend

The only additional information required other than that typically used in a dense-graded mix design is the corresponding unit weight for each coarse and fine aggregate [excluding MF, bag house fines, and recycled asphalt pavement (RAP)]. The following decisions are made by the designer and used to determine the individual aggregate percentages by weight and the resulting combined blend:

- Bulk specific gravity of each aggregate,
- Chosen unit weight of the coarse aggregates,
- Rodded unit weight of the fine aggregates,
- Blend by volume of the coarse aggregates totaling 100.0%,
- Blend by volume of fine aggregates totaling 100.0%, and
- Amount of –0.075-mm material desired in the combined blend, if MF or bag house fines are being used.

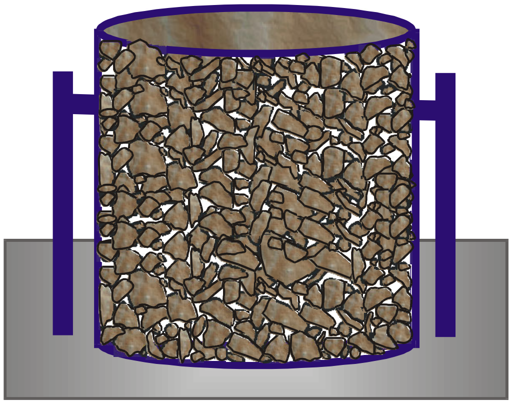

FIGURE 5 Rodded unit weight of fine aggregate.

An example design is presented in the section on page 24, which provides the step-by-step calculations required to blend a set of aggregates by volume and determine the resulting combined blend by weight. Developing a computer spreadsheet to perform these calculations is relatively simple. This allows the designer to vary the inputs for the above listed data so iterations can be made quickly to review multiple blends.

The following steps are presented to provide a general sense of blending aggregates by volume.

1. Pick a chosen unit weight for the coarse aggregates, kg/m^3.
2. Calculate the volume of voids in the coarse aggregates at the chosen unit weight.
3. Determine the amount of fine aggregate to fill this volume using the fine aggregates rodded unit weight, kg/m^3.
4. Using the weight (density) in kg/m^3 of each aggregate, determine the total weight and convert to individual aggregate blend percentages.
5. Correct the coarse aggregates for the amount of fine aggregate they contain and the fine aggregates for the amount of coarse aggregate they contain, in order to maintain the desired blend by volume of coarse and fine aggregate.
6. Determine the adjusted blend percentages of each aggregate by weight.
7. If MF or bag house fines are to be used, adjust the fine aggregate percentages by the desired amount of fines to maintain the desired blend by volume of coarse and fine aggregate.
8. Determine the revised individual aggregate percentages by weight for use in calculating the combined blend.

Analysis of the Design Blend

After the combined gradation by weight is determined, the aggregate packing is analyzed further. The combined blend is broken down into three distinct portions, and each portion is evaluated individually. The coarse portion of the combined blend is from the largest particle to the PCS. These particles are considered the coarse aggregates of the blend.

The fine aggregate is broken down and evaluated as two portions. To determine where to split the fine aggregate, the same 0.22 factor used on the entire gradation is applied to the PCS to determine a secondary control sieve (SCS). The SCS then becomes the break between coarse sand and fine sand. The fine sand is further evaluated by determining the tertiary control sieve (TCS), which is determined by multiplying the SCS by the 0.22 factor. A schematic of how the gradation is divided into the three portions is given in Figure 6.

An analysis is done using ratios that evaluate packing within each of the three portions of the combined aggregate gradation. Three ratios are defined: Coarse Aggregate Ratio (CA Ratio), Fine Aggregate Coarse Ratio (FA_c Ratio), and Fine Aggregate Fine Ratio (FA_f Ratio).

These ratios characterize packing of the aggregates. By changing gradation within each portion modifications can be made to the volumetric properties, construction characteristics, or performance characteristics of the asphalt mixture.

CA Ratio

The CA Ratio is used to evaluate packing of the coarse portion of the aggregate gradation and to analyze the resulting void structure. Understanding the packing of coarse aggregate requires the introduction of the half sieve. The half sieve is defined as one half the NMPS. Particles smaller than the half sieve are called "interceptors." Interceptors are too large to fit in the voids created by the larger coarse aggregate particles and hence spread them apart. The balance of these particles can be used to adjust the mixture's volumetric properties. By changing the quantity of interceptors it is possible to change the VMA in the mixture to produce a balanced coarse aggregate structure. With a balanced aggregate structure the mixture should be easy to compact in the field and should adequately perform under load.

The equation for the calculation of the coarse aggregate ratio is given in Equation 2.

$$\text{CA Ratio} = \frac{(\%\ \text{Passing Half Sieve} - \%\ \text{Passing PCS})}{(100\% - \%\ \text{Passing Half Sieve})} \tag{2}$$

The packing of the coarse aggregate fraction, observed through the CA Ratio, is a primary factor in the constructability of the mixture. As the CA Ratio decreases (below ~1.0), compaction of the fine aggregate fraction increases because there are fewer interceptors to limit compaction of the larger coarse aggregate particles (*2*). Therefore, a mixture with a low CA

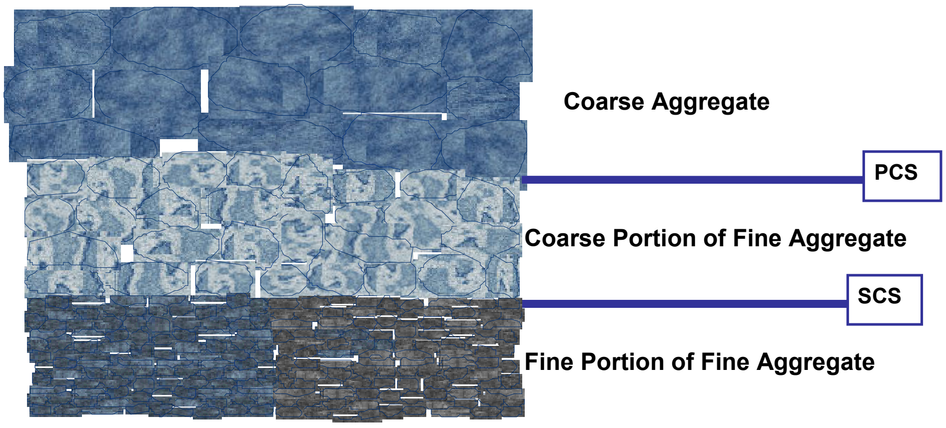

FIGURE 6 Overview of the divisions in a continuous gradation that allows an analysis of gradation.

TABLE 1 Recommended Ranges of Aggregate Ratios

	NMPS, mm					
	37.5	25.0	19.0	12.5	9.5	4.75
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	0.35–0.50	0.35–0.50	0.35–0.50	0.35–0.50	0.35–0.50
FA_f Ratio	0.35–0.50	0.35–0.50	0.35–0.50	0.35–0.50	0.35–0.50	0.35–0.50

NOTE: FA_c = fine aggregate coarse; FA_f = fine aggregate fine. These ranges provide a starting point where no prior experience exists for a given set of aggregates. If the designer has acceptable existing designs, they should be evaluated to determine a narrower range to target for future designs (see Evaluating Existing Mixture Designs with the Bailey Method).

Ratio typically requires a stronger fine aggregate structure to meet the required volumetric properties. Also, a CA Ratio below the corresponding range suggested in Table 1 could indicate a blend that may be prone to segregation. It is generally accepted that gap-graded mixes, which tend to have CA Ratios below these suggested ranges, have a greater tendency to segregate than mixes that contain a more continuous gradation.

As the CA Ratio increases towards 1.0, VMA will increase. However, as this value approaches 1.0, the coarse aggregate fraction becomes “unbalanced” because the interceptor size aggregates are attempting to control the coarse aggregate skeleton. Although this blend may not be as prone to segregation, it contains such a large quantity of interceptors that the coarse aggregate fraction causes the portion above the PCS to be less continuous. The resulting mixture can be difficult to compact in the field and have a tendency to move under the rollers because it does not want to “lock up.” Generally, mixes with high CA Ratios have a S-shaped gradation curve in this area of the 0.45-power grading chart. Superpave mixtures of this type have developed a reputation for being difficult to compact.

As the CA Ratio exceeds a value of 1.0, the interceptor-sized particles begin to dominate the formation of the coarse aggregate skeleton. The coarse portion of the coarse aggregate is then considered “pluggers,” as these aggregates do not control the aggregate skeleton, but rather float in a matrix of finer coarse aggregate particles.

Coarse Portion of Fine Aggregate

All of the fine aggregate (i.e., below the PCS) can be viewed as a blend by itself that contains a coarse and a fine portion and can be evaluated in a manner similar to the overall blend. The coarse portion of the fine aggregate creates voids that will be filled with the fine portion of the fine aggregate. As with the coarse aggregate, it is desired to fill these voids with the appropriate volume of the fine portion of the fine aggregate without overfilling the voids.

The equation that describes the fine aggregate coarse ratio (FA_c) is given in Equation 3. As this ratio increases, the fine aggregate (i.e., below the PCS) packs together tighter. This increase in packing is due to the increase in volume of the fine portion of fine aggregate. It is generally desirable to have this ratio less than 0.50, as higher values generally indicate an excessive amount of the fine portion of the fine aggregate is included in the mixture. A FA_c Ratio higher than 0.50, which is created by an excessive amount of natural sand and/or an excessively fine natural sand should be avoided. This type of a blend normally shows a “hump” in the sand portion of the gradation curve of a 0.45 gradation chart, which is generally accepted as an indication of a potentially tender mixture.

The equation for the calculation of the FA_c Ratio is given in Equation 3.

$$FA_c = \frac{\%\ \text{Passing SCS}}{\%\ \text{Passing PCS}} \tag{3}$$

If the FA_c Ratio becomes lower than the range of values in Table 1, the gradation is not uniform. These mixtures are generally gap-graded and have a "belly" in the 0.45-power grading chart, which can indicate instability and may lead to compaction problems. This ratio has a considerable impact on the VMA of a mixture due to the blending of sands and the creation of voids in the fine aggregate. The VMA in the mixture will increase with a decrease in this ratio.

Fine Portion of Fine Aggregate

The fine portion of the fine aggregate fills the voids created by the coarse portion of the fine aggregate. This ratio shows how the fine portion of the fine aggregate packs together. One more sieve is needed to calculate the FA_f, the TCS. The TCS is defined as the closest sieve to 0.22 times the SCS. The equation for the FA_f Ratio is given in Equation 4.

$$FA_f = \frac{\%\ \text{Passing TCS}}{\%\ \text{Passing SCS}} \tag{4}$$

The FA_f Ratio is used to evaluate the packing characteristics of the smallest portion of the aggregate blend. Similar to the FA_c Ratio, the value of the FA_f Ratio should be less than 0.50 for typical dense-graded mixtures. VMA in the mixture will increase with a decrease in this ratio.

Summary of Ratios

- CA Ratio—This ratio describes how the coarse aggregate particles pack together and, consequently, how these particles compact the fine aggregate portion of the aggregate blend that fills the voids created by the coarse aggregate.
- FA_c Ratio—This ratio describes how the coarse portion of the fine aggregate packs together and, consequently, how these particles compact the material that fills the voids it creates.
- FA_f Ratio—This ratio describes how the fine portion of the fine aggregate packs together. It also influences the voids that will remain in the overall fine aggregate portion of the blend because it represents the particles that fill the smallest voids created.

These ratios are valuable for evaluating and adjusting VMA. Once an initial trial gradation is evaluated in the laboratory, other gradations can be evaluated on paper to choose a second trial that will have an increased or decreased VMA as desired. When doing the paper analysis, the designer must remember that changes in particle shape, strength and texture must be considered as well. The ratios are calculated from the control sieves of an asphalt mixture, which are tied to the NMPS. Table 2 provides the listing of control sieves for various asphalt mixture sizes. The values in determining the aggregate ratios are the percent passing the control sieves for the final combined blend. The recommended range for the ratios is shown in Table 1.

TABLE 2 Control Sieves for Various Asphalt Mixes

	NMPS, mm					
	37.5	25.0	19.0	12.5	9.5	4.75
Half Sieve	19.0	12.5	9.5	**	4.75	2.36
PCS	9.5	4.75	4.75	2.36	2.36	1.18
SCS	2.36	1.18	1.18	0.60	0.60	0.30
TCS	0.60	0.30	0.30	0.150	0.150	0.075

** The nearest "typical" half sieve for a 12.5-mm NMPS mixture is the 4.75 mm. However, the 6.25 mm sieve actually serves as the breakpoint. Interpolating the percent passing value for the 6.25-mm sieve for use in the CA Ratio will provide a more representative ratio value.

Effect of Chosen Unit Weight Changes

Changing the chosen unit weight of the coarse aggregate will have a significant effect on the volumetric properties of the HMA mixture. Increasing the chosen unit weight above the loose unit weight will cause an increase in the air voids and VMA of the resulting mixture. The air voids increase because of additional volume of coarse aggregate in the mixture, which increases aggregate interlock and resists compaction.

The actual amount of increase in VMA with changes in chosen unit weight will depend on aggregate shape and texture. In a mixture with a coarse aggregate skeleton an increase of 5% in the chosen unit weight will increase VMA by 0.5 to 1.0%. In a fine-graded mixture (chosen weight less than 90% of loose unit weight) changes in the chosen unit weight will not have a significant effect on VMA because there is no coarse aggregate skeleton.

Chosen Unit Weight	VMA
increases	increases

Increases in the chosen unit weight will also affect the compactability of the mixture, both in the lab and in the field. As the chosen unit weight is increased, additional coarse aggregate is designed in the blend. This additional volume of coarse aggregate locks together under compactive effort and resists compaction. High chosen unit weight values may lead to strong mixes in the lab and field, but will be difficult to construct if taken too far.

Changing the chosen unit weight changes the percent passing the PCS in the final combined blend. During production extreme care should be taken to maintain consistency in the percent passing the PCS, especially for coarse-graded mixtures. Swings in the percent passing the PCS will cause changes in the degree of coarse aggregate interlock, the amount of voids, and constructability of the mixture. Changes to the percent passing the PCS are effectively changing the chosen unit weight. Deliberate change to the chosen unit weight during construction is an appropriate method to change the constructability of the mixture.

Effect of CA Ratio Changes

The CA Ratio has a significant effect on the volumetric properties of the HMA mixture. This ratio describes the balance between the larger particles and the interceptor particles in the coarse portion of the aggregate structure. Changes in this balance change the compactability of the mixture in both the lab and field conditions.

An increase in the CA Ratio will cause a corresponding increase in the air voids and VMA. This increase happens because more interceptor-sized aggregate particles are in the coarse portion of the aggregate structure, helping it to resist densification.

The actual amount of increase in VMA with changes in coarse aggregate ratio will depend on aggregate shape and texture. In coarse-graded mixtures an increase of 0.2 in the CA Ratio will create an increase of 0.5 to 1.0% VMA.

CA Ratio	**VMA**
increases	increases

In addition to the effect on the volumetrics, the CA Ratio can indicate possible construction problems. If the CA Ratio is too low, the mixture will be prone to segregation. Segregation causes the road to have areas of excess coarse aggregate, which will decrease the service life of the asphalt pavement. If the CA Ratio nears or goes above 1.0, the coarse aggregate region of the blend becomes unbalanced and neither size (large particles or interceptors) is controlling the coarse aggregate structure. This may cause the mixture to move during compaction, allowing the mat to widen.

CA Ratio	**Segregation Potential**
decreases	increases

Effect of FA_c and FA_f Ratio Changes

The FA Ratios have an effect on the volumetric properties of the HMA mixture. Increases in these ratios cause a decrease in the air voids and VMA in the mixture. As these ratios increase, the packing of the fine aggregates becomes more dense and the voids in the mixture decrease. The actual amount of increase in VMA with changes in FA_c Ratio will depend on aggregate shape and texture. An decrease of 0.05 in the FA_c of FA_f Ratio will create an increase of 0.5 to 1.0% VMA.

FA Ratios	**VMA**
increases	decreases

Four Bailey Method Parameters

The design and analysis of an aggregate blend using the Bailey Method of gradation selection is built on four parameters:

- Chosen unit weight describes interlock of the coarse aggregate.
- CA Ratio describes gradation of the coarse aggregate.
- FA_c Ratio describes the gradation of the coarse portion of the fine aggregate.
- FA_f Ratio describes the gradation of the fine portion of the fine aggregate.

Changes to any of these parameters will affect the air voids, VMA, constructability, and performance of the resulting asphalt mixture. These changes are the same whether the change is made in the laboratory during design or the field during construction.

When making changes to stockpile blends, the designer must be aware that often there is more than one effect on the Bailey parameters. Each of the parameters will tend to act independently to change the VMA. If different parameters cause changes in opposite directions the result will be the net effect. An example is shown in Table 3.

When making changes to gradation, the designer must be aware of the effect of changing other aggregate properties such as shape, texture, or hardness, i.e. decreasing the amount of natural sand, increasing the amount of manufactured sand, or increasing the amount of soft aggregate in the blend.

TABLE 3 Combined Effect of Changes in Bailey Parameters

	Before	**After**	**Result**
PCS value	38%	38%	No change
CA Ratio	0.76	0.56	Lower VMA
FA_c Ratio	0.55	0.50	Increased VMA
FA_f Ratio	0.47	0.46	Little to no change
Net Result			Little, if any, change in VMA

Bailey Method Principles and Fine-Graded Mixes

In a coarse-graded HMA, coarse aggregate interlock plays a significant role in resisting permanent deformation. However, in fine-graded mixes, the fine aggregate plays the predominant role in resisting permanent deformation.

The Bailey Method evaluates the aggregate packing characteristics of the entire blend. Fine-graded mixes generally are defined as combined aggregate blends that plot above the maximum density line on a 0.45 gradation curve. As defined by the Bailey Method, the primary difference between coarse-graded and fine-graded mixes is the portion of the aggregate structure that carries the load and controls VMA. From the Bailey Method perspective, fine-graded mixes contain a volume of fine aggregate that exceeds the volume of voids in the coarse aggregate loose unit weight condition.

VOLUME OF FINE AGGREGATE

With a coarse-graded mixture, the coarse aggregate plays a significant role in the compaction of the fine aggregate. However, with a fine-graded mixture, the coarse aggregate particles are floating in the fine aggregate structure. Since the coarse aggregate particles are not touching, VMA is primarily controlled by the fine aggregate.

Within the Bailey Method, raising or lowering the chosen unit weight of the coarse aggregates in the mixture changes both the relative volume of coarse aggregate and fine aggregate. As the chosen unit weight of the coarse aggregates decreases, the volume of fine aggregate increases. With fine-graded mixtures, as the volume of fine aggregate increases, VMA will increase.

THE TWO-PART PROCESS

Developing the combined blend of a fine-graded mixture using the Bailey Method principles is a two-part process. The initial process involves utilizing a chosen unit weight for the coarse aggregate(s) that is below the loose unit weight (90% or less). With this type of mixture the coarse aggregates (i.e., particles larger than the PCS) do not form a skeleton because they are not touching consistently and therefore are floating in a matrix of fine aggregate.

The second part of the process evaluates the combined blend gradation below the original PCS as an entire blend by itself. The portion below the original PCS is converted to 100% passing this sieve and is then evaluated as a blend of coarse and fine aggregate with a NMPS equal to the original PCS. A new PCS is then determined, along with a corresponding half sieve, SCS and TCS.

DETERMINING THE NEW RATIOS

Table 4 shows the new control sieves corresponding to the mixture NMPS and original PCS.

The new ratios can be calculated for the fine aggregate portion (100% passing the original PCS) using the formulas provided in the previous section and Equation 1 through Equation 3. Table 5 provides the ratios in relation to the NMPS for a fine-graded mixture and the sieves listed in the equations represent the percent passing for the newly calculated blend of the fine aggregate portion.

TABLE 4 Fine-Graded Mixture Control Sieves

	NMPS, mm					
	37.5	25.0	19.0	12.5	9.5	4.75
Original PCS	9.5	4.75	4.75	2.36	2.36	1.18
New Half Sieve	4.75	2.36	2.36	1.18	1.18	0.60
New PCS	2.36	1.18	1.18	0.60	0.60	0.30
New SCS	0.60	0.30	0.30	0.150	0.150	0.075
New TCS	0.150	0.075	0.075	—	—	—

TABLE 5 Aggregate Ratios for the Adjusted Blend for Fine-Graded Mixtures

NMPS, mm	Ratio		
	CA	FA_c	FA_f
37.5	$\frac{4.75-2.36}{100\%-4.75}$	$\frac{0.60}{2.36}$	$\frac{0.150}{0.60}$
25.0	$\frac{2.36-1.18}{100\%-2.36}$	$\frac{0.30}{1.18}$	$\frac{0.075}{0.30}$
19.0	$\frac{2.36-1.18}{100\%-2.36}$	$\frac{0.30}{1.18}$	$\frac{0.075}{0.30}$
12.5	$\frac{1.18-0.60}{100\%-1.18}$	$\frac{0.150}{0.60}$	**
9.5	$\frac{1.18-0.60}{100\%-1.18}$	$\frac{0.150}{0.60}$	**
4.75	$\frac{0.60-0.30}{100\%-0.60}$	$\frac{0.075}{0.30}$	**

** For these mixes, only the new CA and FA_c Ratios can be determined.

As for coarse-graded mixtures, changes in the new ratios for fine-graded mixtures create similar results in regards to the VMA. See the previous section for further discussion. Of these three new ratios, changes in the FA_c Ratio will have the most influence in altering the VMA. The following guidance is provided when the percent volume of fine aggregate remains constant in the entire blend.

- As the new CA Ratio increases, VMA will increase. The range should be 0.6–1.0. In fine-graded mixtures the CA Ratio tends to be more variable than in coarse-graded mixtures; therefore, the recommended range is wider.
- As the new FA_c Ratio decreases, VMA will increase. The range should be 0.35–0.50.
- As the new FA_f Ratio decreases, VMA will increase. The range should be 0.35–0.50.

The ranges provide a starting point where no prior experience exists for a given set of aggregates. If the designer has acceptable existing designs, they should be evaluated to determine a narrower range to target for future designs (see Evaluating Existing Mixture Designs with the Bailey Method, page 22).

Bailey Method Principles and SMA Mixes

The Bailey Method principle of deriving resistance to permanent deformation from coarse aggregate interlock is further enhanced with SMA mixes. To achieve the degree of coarse aggregate interlock desired with SMA, the rodded unit weight, which is performed for each individual coarse aggregate as described in What Is the Bailey Method?, is used as the reference for the chosen unit weight. With multiple coarse aggregates, the Bailey Method combines them by volume mathematically using the corresponding chosen unit weights and the desired overall blend by volume of the coarse aggregates.

However, to ensure compliance with specifications that require the VCA of the mixture to be equal to or less than the VCA in the DRC, the designer must determine the actual VCA of the dry rodded coarse aggregate for a given blend. In general, this consists of physically blending the coarse fraction (i.e., retained on the PCS) in the lab, performing a test in accordance with AASHTO T-19: Unit Weight and Voids in Aggregate, using the rodding procedure and determining a combined bulk specific gravity of the coarse aggregate for use in calculating the VCA_{DRC}.

The volume of coarse aggregate has the most influence on the VCA of the mixture and the VMA achieved. Strength of the coarse aggregate particles is very important in maintaining the degree of coarse aggregate interlock desired without degradation occurring under compaction. Weak coarse aggregate will break in the compaction mold or under rollers. Table 6 provides the listing of control sieves for various SMA sizes.

The 12.5-mm NMPS SMA appears to be the most common size in the United States. Research to date has shown the importance of using the 6.25-mm sieve as the half sieve to accurately indicate changes in the coarse aggregate fraction of the mixture. It is also recommended that the 2.36-mm sieve be used as the PCS or breakpoint between the coarse and fine aggregate for this mixture size as well (*12*). The predominant influence of the 4.75- to 2.36-mm sized material appears to be more related to the amount of degradation that does or does not occur.

The chosen unit weight for the coarse aggregates should be 110% to 125% of their corresponding rodded unit weight and the chosen unit weight of the fine aggregate(s) should be the corresponding loose unit weight. In reference to What Is the Bailey Method?, the only difference in determining the loose unit weight of fine aggregate is that the shoveling procedure is used as described in AASHTO T-19: Unit Weight and Voids in Aggregate, in lieu of the

TABLE 6 Control Sieves for SMA Mixtures

	NMPS, mm			
	19.0	12.5	9.5	4.75
Half Sieve	9.5	**	4.75	2.36
PCS	4.75	2.36	2.36	1.18
SCS	1.18	0.60	0.60	0.30
TCS	0.30	0.150	0.150	0.075

** The nearest “typical” half sieve for 12.5-mm NMPS mixture is 4.75 mm. However, the 6.25-mm sieve actually serves as the breakpoint. Interpolating the percent passing value for the 6.25-mm sieve for us in the CA Ratio will provide a more representative ratio value.

rodding procedure. The fine aggregate fraction should not interfere with the compaction of the coarse aggregate structure.

As previously described in What Is the Bailey Method, ratios are used to evaluate the blend gradation for increased understanding of the overall aggregate packing characteristics. The effects of the three ratios (CA, FA_c, and FA_f) create similar effects in the aggregate packing of a SMA as with coarse-graded mixes.

Of the three ratios, changes in the FA_c Ratio shows the most influence in altering the VMA. The following guidance is provided considering the volume of fine aggregate remains constant in the entire blend.

- As the CA Ratio increases, VMA will increase.
- As the FA_c Ratio decreases, VMA will increase.
- As the FA_f Ratio decreases, VMA will increase.

The designer should determine these ratio values for any existing SMA designs and compare them with the suggested ranges shown in Table 7 (see Evaluating the Existing Mixture Designs with the Bailey Method, page 22).

The FA_f Ratio is predominantly a function of the amount of MF used and its corresponding gradation. Although most SMA specifications provide an allowable range for the –0.075-mm material in the blend, there appears to be an optimum amount of this material. If too little is used, although within the specification limits, the filler effect in reducing voids and mortar stiffness will be insufficient. However, if too much is used, although within specifications, the material serves to create unnecessarily high stiffness in the mortar. Although this is a very general view concerning the influence of filler material in a SMA mixture, the designer should be cautious when making significant alterations in the FA_f Ratio to increase or decrease VMA since it can also have a significant impact on the stiffness of the mortar.

TABLE 7 Recommended Ranges for Aggregate Ratios in SMA Mixtures

	NMPS		
	19.0 mm	**12.5 mm**	**9.5 mm**
CA Ratio	0.35–0.50	0.25–0.40	0.15–0.30
FA_c Ratio	0.60–0.85	0.60–0.85	0.60–0.85
FA_f Ratio	0.65–0.90	0.60–0.85	0.60–0.85

Use of Recycled Asphalt Pavement

A mixture containing RAP can be designed with the Bailey Method using the same principles as a mixture design with new aggregates. The approach as outlined may not work for mixtures with a high percentage of RAP (about 40% or more). The Bailey Method may be used for mixtures with a high percentage of RAP, but the mixture VMA may not move with the chosen unit weight and the aggregate ratios because the RAP is overpowering the new aggregates. In such a case, the designer will need evaluate the mixture based on experience, the method most likely in current use.

The Bailey Method evaluation is done with the new aggregates only, and the designer selects a chosen unit weight to establishes the volume of coarse aggregate in the mixture, the degree of coarse aggregate interlock, and the corresponding volume of fine aggregate. The ratios are calculated to ensure that they are within the acceptable ranges for the corresponding mixture size and type (see Table 1, page 12, and the corresponding discussion in Bailey Method Principles and Fine-Graded Mixes).

After calculating the Bailey properties with the new aggregates, the desired percentage of RAP is added and the new aggregate percentages are altered such that the new combined blend containing RAP has the same percent passing the PCS as the original blend with the new aggregates. The percent passing the PCS should stay approximately the same with the inclusion of RAP in order to maintain the desired split of coarse and fine aggregate. The gradation used for the RAP is typically determined by solvent extraction.

When evaluating a trial blend with RAP (prior to lab work), the three aggregate ratios of the new RAP blend are compared to those of the new aggregate blend. As previously mentioned, it is important to maintain approximately the same PCS value. Also, RAP generally contains both coarse and fine aggregate. This will generally change all three ratio values, even when the PCS is approximately the same as the new aggregate blend. Compare the changes created to the ratios from the addition of the RAP and consider how this may alter the volumetric properties of the proposed RAP blend. Additional changes may be necessary to the RAP blend to meet the volumetric specifications required for a given mixture design.

Other things to consider when using RAP include:

- What are the individual characteristics of the RAP aggregates?
- Has the RAP been processed in a way that may have changed any of the aggregate characteristics?

The basic premise when using a RAP mixture is to consider the volume of coarse and fine aggregate and how that relates to compactability characteristics. To estimate this accurately, a blend with new aggregates must first be considered. The volume of coarse aggregate in the RAP blend determines whether the blend is coarse-graded or fine-graded and the degree of coarse aggregate interlock expected. The three ratios play the same role in volumetrics and compactability.

Evaluating Existing Mixture Designs with the Bailey Method

This section addresses the evaluation of existing dense-graded asphalt mixes using the Bailey Method. Experience is extremely valuable when selecting an aggregate blend that meets volumetric requirements, that will also be reproducible in production, easy to place and compact, and provide acceptable long-term in-place performance. History, both good and bad, provides seasoned designers with a safety factor of what to expect after choosing an aggregate blend gradation.

When starting with the Bailey Method, it is suggested the designer closely review existing mixture designs with the following evaluation procedures to better define acceptable ranges to work within for their specific aggregates. Generally, experienced designers have a few mixes that have worked extremely well during production and placement, and a few others that proved to be much harder to reproduce and/or place in the field. These mixes in particular should be reviewed from the Bailey Method perspective to provide guidance on acceptable chosen unit weight values and ratio ranges and to also help determine why they did or did not work well during production and/or placement.

The calculations to evaluate a blend are shown in Example Bailey Method Design Calculations. Although these calculations can be done manually using a calculator, it is recommended that the user construct a spreadsheet to do the calculations. To evaluate an existing design, the user must estimate some of the input variables and compare the calculated gradation with the actual gradation. Adjustments are made to the input variables until the calculated and actual gradations are as close as possible. This process would be time consuming without a spreadsheet.

The three input variables to be estimated are:

- Chosen unit weight of each coarse aggregate in relation to its corresponding loose unit weight;
- Volume of coarse aggregate;
- Volume of fine aggregate; and
- After the user has adjusted the input variables to obtain a calculated gradation that matches the design gradation, the three Bailey ratios (CA, FA_c, and FA_f), which have been calculated for the mix, are available. By evaluating several mixtures the designer can see the Bailey parameters for the mixtures currently in use.

EVALUATING CONVENTIONAL DENSE-GRADED HMA DESIGNS WITH NO RECYCLED ASPHALT PAVEMENT

This method of evaluation can be used for either coarse-graded or fine-graded mixtures without differentiation. One of the input variables the designer will estimate is the chosen weight. At the end of the evaluation, if the chosen weight is less than 95% of loose unit weight, the mix will have been determined to be fine-graded. The mixture is to be evaluated as follows:

1. Obtain representative samples of each aggregate used in the original design. Particle shape, surface texture, gradation, and bulk specific gravity of each aggregate should be as close as possible to what was used originally. If the designer feels there is a significant difference in an

aggregate in regards to one or more of these properties, appropriate steps should be taken to obtain more representative material. If that is not possible, it must be understood that this can significantly affect the final evaluation.

2. Determine the loose and rodded unit weights for each coarse aggregate and the rodded unit weight for each fine aggregate by performing the appropriate lab tests presented earlier.
3. Enter the corresponding unit weights (loose and rodded for coarse and rodded for fine) in the user spreadsheet.
4. Enter the original design gradation and bulk specific gravity for each individual aggregate in the user spreadsheet. These properties must be very similar to the current aggregate samples used for the loose and rodded unit weight tests mentioned in Step 2.
5. Enter the corresponding rodded unit weight for each fine aggregate as the chosen unit weight in the user spreadsheet
6. As a starting point, select the loose unit weight for each coarse aggregate as the chosen unit weight.
7. Estimate the blend by volume for the coarse aggregates and enter the percentage of each. Normally, the blend by weight (as 100% coarse aggregate) can be used as a starting point, unless there are significant differences in bulk specific gravity of the coarse aggregates involved.
8. Estimate the blend by volume for the fine aggregates and enter the percentage of each. Normally, the blend by weight (as 100% fine aggregate) can be used as a starting point, unless there are significant differences in bulk specific gravity of the fine aggregates involved.
9. Enter the amount of –0.075 mm corresponding to the original design blend. This value may need to be altered by a few tenths of a percent later to match the design. At this point, the spreadsheet should have calculated the combined blend.
10. Adjust the blend by volume of the coarse aggregates and/or fine aggregates to get the individual aggregate percentages by weight closer to the original design values.
11. Increase or decrease the percentage of the loose unit weight (i.e., chosen unit weight) for the coarse aggregates to get the percent passing the PCS closer to the original design value.
12. Always leave the chosen unit weight of the fine aggregates at their respective rodded unit weight, even if this means selecting a chosen unit weight of the coarse aggregates below the loose unit weight.
13. Most designs will take several iterations to the variables that can be changed but the designer should be able to get the individual aggregate percentages to within a few tenths of a percent of the original design.

EVALUATING DENSE-GRADED DESIGNS CONTAINING RAP

For reviewing an existing design containing RAP, the steps outlined earlier for virgin blends should be followed using only the virgin aggregates, to determine a combined blend gradation that closely matches the RAP blend, especially in percent passing the PCS. Although the designer should get the entire combined blend of the virgin aggregates as close as possible, there will be some sieve values that are different since the RAP gradation is not included. The desired result for the RAP design evaluation is to accurately establish the volumes of coarse aggregate, fine aggregate, and the relationship between the coarse aggregate chosen unit weights to the coarse aggregate loose unit weights, to relate to compactability of the mixture, along with reviewing the three ratio values.

Example Bailey Method Design Calculations

BAILEY METHOD BLENDING EXAMPLE CALCULATIONS

The calculations in Figure 7 provide an example of a design using two coarse aggregates, one fine aggregate, and MF. This design uses aggregates of different specific gravity to show how aggregates are blended together by volume.

The designer will need to collect information including:

- Stockpile gradation, and bulk specific gravity, and
- Loose and rodded unit weights (AASHTO T-19).

In addition the designer will make several decisions that will determine the stockpile splits. These items include:

- Chosen unit weight as a percentage of the loose unit weight;
- Desired percent passing 0.075-mm sieve;
- Blend by volume of coarse aggregates; and
- Blend by volume of fine aggregates.

Step 1

Determine the chosen unit of weight for each aggregate according to the loose unit weight for each coarse aggregate and the overall coarse aggregate chosen unit weight for the mixture. The chosen unit weight for the fine aggregates is simply the rodded weight of that aggregate.

Calculation

Multiply the loose unit weight percent for each coarse aggregate by the coarse aggregate chosen unit weight for the mixture.

Equation

Coarse aggregate chosen unit weight = loose unit weight $*$ desired percent of loose unit weight

CA # 1: $$\text{Chosen unit weight} = 1425\ \text{kg/m}^3 * 103\% = 1469\ \text{kg/m}^3 \quad (1a)$$

CA # 2: $$\text{Chosen unit weight} = 1400\ \text{kg/m}^3 * 103\% = 1441\ \text{kg/m}^3 \quad (1b)$$

Step 2

Determine the unit weight contributed by each coarse aggregate according to the desired proportions (by volume) of coarse aggregate.

Calculation

Multiply the blend percent of coarse aggregate by the chosen unit weight of each aggregate.

	Coarse Aggregate Number			Fine Aggregate Number			Mineral Filler
	CA-1	CA-2	CA-3	FA-1	FA-2	FA-3	
Material Grade	Coarse	Intermediate		Slag Sand			MF

	Design Value	Specification
CA Chosen Weight as % of Loose Weight	**103**	95 – 105
Desired % Pass 0.075 mm	**4.5**	3.5 – 6.0

Coarse Aggregate Blend by Volume		
25.0	75.0	
Above blending % must sum to 100		100.0

Fine Aggregate Blend by Volume		
100.0		
Above blending % must sum to 100		100.0

Combined Bulk Specific Gravity of All Aggregates	2.888

Total Volume of Coarse Aggregate	53.7
Total Volume of Fine Aggregate	46.3

Aggregate Properties							
19.0	100.0	100.0		100.0			100.0
12.5	94.0	100.0		100.0			100.0
9.5	38.0	99.0		100.0			100.0
4.75	3.0	30.0		99.0			100.0
2.36	1.9	5.0		79.9			100.0
1.18	1.8	2.5		48.8			100.0
0.60	1.8	1.9		29.0			100.0
0.30	1.8	1.4		14.2			100.0
0.15	1.8	1.3		8.8			98.0
0.075	1.7	1.2		3.0			90.0

Bulk Spec. Gr.	2.702	2.698		3.162	3.162		2.806
Apparent Gr.	2.812	2.812		3.600	3.600		2.806
% Absorp.	1.452	1.502		3.844	3.844		

Loose Weight kg/m^3	1426	1400				
Rodded Weight kg/m^3	1608	1592		2167	2167	

FIGURE 7 An example of a design using two coarse aggregates, one fine aggregate, and MF.

Equation

Contribution = percent coarse aggregate $*$ chosen unit weight

CA # 1: Contribution = 25% $*$ 1469 kg/m^3 = 367 kg/m^3 (2a)

CA # 2: Contribution = 75% $*$ 1441 kg/m^3 = 1081 kg/m^3 (2b)

Step 3

Determine the voids in each coarse aggregate according to its corresponding chosen unit weight and contribution by volume. Then sum the voids contributed by each coarse aggregate.

Calculation

First calculate one minus the chosen unit weight divided by the bulk specific gravity and density of water. Multiply the result by the percent of coarse aggregate blend. Then, sum the contribution of each coarse aggregate.

Equation

$$\text{Voids in coarse aggregate} = \left(1 - \frac{\text{chosen unit weight}}{G_{sb} * 1000}\right) * \text{Blend}\,\%$$

Where G_{sb} = bulk specific gravity.

CA #1: $$\text{Voids in CA \#1} = \left(1 - \frac{1468}{2.702 * 1000}\right) * 25.0 = 11.4 \qquad (3a)$$

CA #2: $$\text{Voids in CA \#2} = \left(1 - \frac{1441}{2.698 * 1000}\right) * 75.0 = 34.9 \qquad (3b)$$

Total: Voids in CA #1 + Voids in CA #2 = 11.4 + 34.9 = 46.3 (3c)

Step 4

Determine the unit weight contributed by each fine aggregate according to the desired volume blend of fine aggregate. This is the unit weight that fills the voids in the coarse aggregate.

Calculation

Multiply the fine aggregate chosen unit weight by the volume percentage of this aggregate in the fine aggregate blend and multiply this by the total percentage of coarse aggregate voids from (3c).

Equation

Contribution of each fine aggregate = fine aggregate chosen unit weight $*$ % fine aggregate blend $*$ % voids in coarse aggregate.

FA #1: Contribution = 2167 kg/m^3 $*$ 100% $*$ 46.3% = 1002 kg/m^3 (4)

Note: If there is more than one fine aggregate the calculation is repeated for each fine aggregate.

Step 5

Determine the unit weight for the total aggregate blend.

Calculation

Sum the unit weight of each aggregate.

Equation

Unit weight of blend = (2a) + (2b) + (4)

Unit weight of blend = 367 kg/m^3 + 1081 kg/m^3 + 1002 kg/m^3 = 2450 kg/m^3 (5)

Step 6

Determine the initial blend percentage by weight of each aggregate.

Calculation

Divide the unit weight of each aggregate by the unit weight of the total aggregate blend.

Equation

Percent by weight = unit weight of aggregate/unit weight of blend

CA #1: % by weight = 367 kg/m^3 / 2450 kg/m^3 = 0.150 = 15.0 % (6a)

CA #2: % by weight = 1081 kg/m^3 / 2450 kg/m^3 = 0.441 = 44.1 % (6b)

FA #1: % by weight = 1002 kg/m^3 / 2450 kg/m^3 = 0.409 = 40.9 % (6c)

These initial estimates of stockpile splits are based on the choice of how much coarse aggregate to have in the mixture. The initial estimates of stockpile splits will be adjusted to account for fine aggregate particles in the coarse aggregate stockpiles and coarse aggregate particles in the fine aggregate stockpiles.

Step 7

In a 12.5-mm NMPS mixture, the CA/FA break (PCS) is the 2.36-mm sieve.

Calculation

For the coarse aggregate stockpiles, determine the percent passing the 2.36-mm sieve. For the fine aggregate stockpiles, determine the percent retained on the 2.36-mm sieve.

CA #1: % fine aggregate = 1.9% (7a)

CA #2: % fine aggregate = 5.0% (7b)

FA #1: % coarse aggregate = 100.0% – 79.9% = 20.1% (7c)

Step 8

Determine the fine aggregate in each coarse stockpile according to its percentage in the blend.

Calculation

For each coarse aggregate stockpile determine the percent passing the 2.36-mm sieve as a percentage of the total aggregate blend.

Equation

Percent fine aggregate in blend = Coarse stockpile percent of blend ∗ percent fine aggregate in coarse stockpile.

CA #1: Percent fine aggregate in blend = 15.0% ∗ 1.9% = 0.3% (8a)

CA #2: Percent fine aggregate in blend = 44.1% ∗ 5.0% = 2.2% (8b)

Step 9

Sum the percent of fine aggregate particles in all the coarse aggregate stockpiles.

All CAs: Percent fine aggregate in blend = 0.3% + 2.2% = 2.5% (9)

Step 10

Determine the coarse aggregate in each fine stockpile according to its percentage in the blend.

Calculation

For each fine aggregate stockpile determine the percent retained on the 2.36-mm sieve as a percentage of the total aggregate blend.

Equation

Percent coarse aggregate in blend = Stockpile percent of blend ∗ percent coarse aggregate in fine stockpile.

FA #1: Percent coarse aggregate in blend = 40.9% ∗ 20.1% = 8.2% (10)

Step 11

Sum the percent of fine aggregate particles in all the coarse aggregate stockpiles.

All FAs: Percent fine aggregate in blend = 8.2% (11)

Step 12

Correct the initial blend percentage of each coarse aggregate to account for the amount of fine aggregate it contains and coarse aggregate contributed by the fine aggregate stockpiles.

Equation

$$\text{Adjusted stockpile percent in blend} = (\text{initial } \%) + (\text{FA in CA}) - \left(\frac{\text{initial } \% * \text{Sum CA in FA}}{\text{Total } \% \text{ of CA}}\right)$$

CA #1:

$$\text{Adjusted stockpile percent in blend} = (15.0\%) + (0.3\%) - \left(\frac{15.0\,\% * 8.2\,\%}{15.0\,\% + 44.1\,\%}\right) = 13.2\% \qquad (12a)$$

CA #2:

$$\text{Adjusted stockpile percent in blend} = (44.1\%) + (2.2\%) - \left(\frac{44.1\,\% * 8.2\,\%}{15.0\,\% + 44.1\,\%}\right) = 40.2\% \qquad (12b)$$

Step 13

Correct the initial blend percentage of each fine aggregate to account for the amount of coarse aggregate it contains and fine aggregate contributed by the coarse aggregate stockpiles.

Equation

Adjusted stockpile percent in blend

$$= (\text{initial } \%) + (\text{CA in FA}) - \left(\frac{\text{initial } \% * \text{Sum FA in CA}}{\text{Total } \% \text{ of FA}}\right)$$

FA #1: Adjusted stockpile percent in blend

$$= (40.9\%) + (8.2\%) - \left(\frac{40.9\% * 2.5\%}{40.9\%}\right) = 46.7\% \qquad (13)$$

The next steps will determine whether MF will be needed to bring the percent passing the 0.075-mm sieve to the desired level.

Step 14

Determine the amount of –0.075-mm material contributed by each aggregate using the adjusted stockpile percentages.

Calculation

Multiply the percent passing the 0.075-mm sieve for each aggregate by the adjusted blend percentage for each aggregate.

Equation

Percent contribution of 0.075-mm sieve for each stockpile = adjusted stockpile percent $*$ percent passing 0.075-mm sieve for that stockpile.

CA #1: Percent contribution 0.075 mm = 13.2% $*$ 1.7% = 0.2% (14a)

CA #2: Percent contribution 0.075 mm = 40.2% $*$ 1.2% = 0.5% (14b)

FA #1: $$\text{Percent contribution } 0.075\text{ mm} = 46.7\% * 3.0\% = 1.4\% \tag{14c}$$

Step 15

Determine the amount of mineral filler required, if any, to bring the percent passing the 0.075-mm sieve to the desired level. For this mixture the desired amount of –0.075-mm material is 4.5%.

Equation

$$\text{Percent of MF} = \left(\frac{\%\ 0.075\ \text{mm desired} - \%\ 0.075\ \text{mm in blend}}{\%\ 0.075\ \text{mm in filler}}\right)$$

MF: $$\text{Percent MF} = \left(\frac{4.5 - 2.1}{90\%}\right) = 2.7\% \tag{15}$$

Step 16

Determine the final blend percentages of fine aggregate stockpiles by adding the percent MF to the fine aggregate. In this step the blend percentage of CA is not changed. The blend percentage of FA is adjusted to account for the MF.

Equation

$$\text{Final blend percent for fine aggregate} = \text{Adjusted blend percent} - \left(\frac{\%\,\text{FA} * \%\,\text{MF}}{\text{Total}\ \%\,\text{FA}}\right)$$

FA #1: $$\text{Final blend percent} = 46.7\% - \left(\frac{46.7\% * 2.7\%}{46.7\%}\right) = 44.0 \tag{16}$$

Results

The final blending percentages are taken from the following equation results:

	Equation	Result (%)
CA #1	12a	13.2
CA #2	12b	40.2
FA #1	16	44.0
MF	15	2.7

Using these blending percentages, the job mix formula and resulting aggregate ratios are determined, which are shown in Figure 8.

EXAMPLE CALCULATIONS FOR FINE-GRADED MIXES

The calculations below provide an example of the application of the aggregate ratios to fine-graded mixes. The calculations required for this are shown as follows:

Starting with the gradation shown in the Table 8, which is a 12.5-mm NMPS mixture, the determination of the original ratios is first performed using the equations given in What Is the Bailey Method?

Step 1: Determination of the Half-Sieve

The half sieve for a 12.5-mm NMPS mixture is the 6.25-mm sieve. The calculation of the percent passing the 6.25-mm sieve is:

$$\begin{aligned}\text{\% Passing Half Sieve} &= \text{\% Passing 9.5 mm} - [0.6842 \times (\text{\% Passing 9.5 mm} - \\ &\quad \text{\% Passing 4.75 mm})] \\ &= 90.0 - [0.6842 \times (90.0 - 65.5)] \\ &= 73.2\end{aligned}$$

Step 2: Determination of the CA Ratio

$$\text{CA Ratio} = \frac{(\text{\% Passing Half Sieve} - \text{\% Passing PCS})}{(100\% - \text{\% Passing Half Sieve})}$$

$$\text{CA Ratio} = \frac{(73.2 - 49.1)}{(100 - 73.2)}$$

$$\text{CA Ratio} = 0.899$$

Step 3: Determination of the FA_c Ratio

$$FA_c = \frac{\text{\% Passing SCS}}{\text{\% Passing PCS}}$$

$$FA_c = \frac{26.5}{49.1}$$

$$FA_c = 0.540$$

	Material Grade	Aggregate %
CA #1	Coarse	**13.2**
CA #2	Intermediate	**40.2**
FA #1	Slag Sand	**44.0**
Filler	MF	**2.7**

Sieve Size	Design Blend
19.0	100.0
12.5	99.2
9.5	91.4
4.75	58.7
2.36	40.1
1.18	25.4
0.60	16.4
0.30	9.7
0.15	7.2
0.75	4.4

CA Ratio	**0.45**
FA_c Ratio	**0.41**
FA_f Ratio	**0.44**

FIGURE 8 Job-mix formula and resulting aggregate ratios.

TABLE 8 Gradation for a 12.5-mm NMPS Mixture

Sieve Size (mm)	Percent Passing
19	100.0
12.5	99.0
9.5	90.0
4.75	65.5
2.36	49.1
1.18	36.8
0.600	26.5
0.300	16.7
0.150	10.1
0.075	6.5

Step 4: Determination of the FA_f Ratio

$$FA_f = \frac{\%\ \text{Passing TCS}}{\%\ \text{Passing SCS}}$$

$$FA_f = \frac{10.1}{26.5}$$

$$FA_f = 0.381$$

Step 5: Normalize the Gradation to 100% Passing the PCS

For this 12.5-mm NMPS mixture, the PCS is the 2.36-mm sieve, which has 49.1% passing. To determine the normalized gradation, the percent passing each sieve size below the PCS is divided by the percent passing the primary control sieve (Table 9).

Step 6: Determination of the Fine-Graded CA Ratio

$$FG-CA\ \text{Ratio} = \frac{(\%\ \text{Passing Half Sieve} - \%\ \text{Passing PCS})}{(100\% - \%\ \text{Passing Half Sieve})}$$

$$FG-CA\ \text{Ratio} = \frac{(74.9-54.0)}{(100-74.9)}$$

$$FG-CA\ \text{Ratio} = 0.832$$

Step 7: Determination of the Fine-Graded FA_c Ratio

$$FG-FA = \frac{\%\ \text{Passing SCS}}{\%\ \text{Passing PCS}}$$

$$\text{FG} - \text{FA} = \frac{20.5}{54.0}$$

$$\text{FG} - \text{FA} = 0.380$$

The final fine-graded aggregate ratios for evaluation are:

CA Ratio	0.899
FA_c Ratio	0.540
FA_f Ratio	0.381
FG–CA Ratio	0.832
FG–FA Ratio	0.380

TABLE 9 Normalizing a 12.5-mm NMPS Mixture Gradation to 100% Passing the PCS

Sieve Size (mm)	Original Percent Passing	Normalization Equation	Normalized Gradation
19	100.0		
12.5	99.0		
9.5	90.0		
4.75	65.5		
2.36	49.1	$\frac{49.1}{49.1}$	100%
1.18	36.8	$\frac{36.8}{49.1}$	74.9%
0.600	26.5	$\frac{26.5}{49.1}$	54.0%
0.300	16.7	$\frac{16.7}{49.1}$	34.0%
0.150	10.1	$\frac{10.1}{49.1}$	20.5%
0.075	6.5	$\frac{6.5}{49.1}$	13.2%

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