Statistical Analysis and Optimization of Bailey Method Gradation Control Parameters Based on Field Engineering Data

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Abstract. The design of the gradation of asphalt mixtures is an important aspect that determines the performance of pavements. The traditional design techniques remain inadequate in balancing the interlocking of coarse and fine aggregates and also in guaranteeing the stability of construction. This paper concentrates on the gradation control parameters of the Bailey Method, which are the CA ratio, FAc ratio, and FAf ratio, and statistically examines the statistical distributions of these parameters with the use of mix-proportion data obtained through recent AC asphalt mixture projects. The findings indicate that the CA ratio varies significantly between mixtures of various nominal maximum aggregate sizes (NMAS) and that the traditionally recommended ranges should be adjusted to represent domestic aggregate quality and construction conditions. The ratios of FAc and FAf are relatively concentrated due to the nature of fine aggregate (manufactured sand). According to the statistical results, there are suggested optimized ranges of parameters of multi-level interlocking skeleton dense mixtures. The suggested ranges can successfully increase skeleton stability, minimize construction segregation, and optimize voids in mineral aggregate (VMA). The research gives more engineering-based control standards in the asphalt pavement mix design and has practical applications in the field.

Keywords: asphalt mixture; Bailey Method; gradation control parameters; optimized design

1 Introduction

As the volume of traffic on highways increases rapidly and the proportion of heavy vehicles in China continues to rise, asphalt pavements are being subjected to extreme conditions, including high-temperature rutting, fatigue cracking, and moisture damage Mixture gradation design is one of the fundamental technologies to enhance pavement durability among the factors affecting these distresses, since it directly defines the structure of the aggregate skeleton and volumetric parameters (Guan et al., 2022; Wu et al., 2023). The traditional Marshall mix design approach and the Superpave approach are based primarily on empirical trial blending and volumetric checks and have

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H. Wu et al. (eds.), *Proceedings of the 2026 3rd International Conference on Civil Engineering Structures and Concrete Materials (CESCM 2026)*, Advances in Engineering Research 312,
https://doi.org/10.2991/978-94-6239-865-8_8

issues of arbitrary gradation choice, imbalance in interlocking between coarse and fine aggregates, and high potential for construction segregation (Hassan et al., 2025).

The Bailey Method presents control parameters like the coarse aggregate ratio (CA ratio), fine aggregate coarse ratio (FAc ratio), and fine aggregate fine ratio (FAf ratio) that can be used to quantitatively assess the aggregate packing properties. Based on the principle that coarse aggregates are supposed to create a stable skeleton and fine aggregates are supposed to fill the voids, the method can successfully predict the voids in mineral aggregate (VMA) and the workability of the mixture and has been used in many projects both within China and outside the country (Vavrik et al., 2002; Alsheyab 2024).

Nevertheless, the majority of the available literature is based on the aggregate properties and specifications applied abroad. The direct application of Bailey Method parameters is less effective in domestic engineering practice due to variations in stone quality, percentage of manufactured sand, and construction equipment capabilities. As an illustration, whether the traditionally suggested range of CA ratio (0.41.0) can be applied to mixtures of various nominal maximum aggregate sizes remains to be confirmed (Lü et al., 2005).

To fill these gaps, this paper gathers mixed-proportion data of real projects in southeastern China and Shandong Province, conducts a statistical analysis of the Bailey Method parameters of AC asphalt mixtures (Kongkitkul, 2024), analyzes their distribution patterns and factors that affect them, and suggests optimized recommendations. The objective is to offer a parameter control model of asphalt mixture gradation design that more closely reflects domestic engineering practice to improve pavement structural stability and quality of construction.

2 Optimization of Gradation Control Parameters for Asphalt Mixtures

The Bailey Method is a gradation design framework originally developed by Robert D. Bailey within the Illinois Department of Transportation, aiming to evaluate whether asphalt mixtures can form a stable interlocking aggregate skeleton with adequate durability and rutting resistance. Unlike traditional empirical gradation approaches, the Bailey Method is based on a structural packing concept in which mixture performance is governed by aggregate interlock and controlled void filling.

The fundamental assumption of the method is that asphalt mixture strength originates from a hierarchical aggregate structure. Coarse aggregates form the primary load-bearing skeleton by creating an interconnected void structure, while fine aggregates function as filling materials that progressively occupy the void space within the coarse skeleton. The overall performance of the mixture is therefore determined by the balance between skeleton formation and void filling rather than by a single gradation curve.

To implement this structural concept, the Bailey Method introduces a systematic division of aggregate fractions based on nominal maximum aggregate size (NMAS), rather than a fixed sieve size. In this framework, aggregates are classified into coarse

and fine components according to their functional role in forming or filling voids. The boundary between these fractions is defined using a series of control sieves, enabling a hierarchical description of mixture structure.

Based on this partitioning concept, three key gradation control parameters are defined:

The CA ratio represents the packing condition of the coarse aggregate skeleton and reflects the degree of interlocking among coarse particles.

The FAc ratio characterizes the intermediate filling behavior within the fine aggregate fraction, controlling the transition between skeleton formation and void filling.

The FAf ratio describes the fine-scale packing density of the smallest aggregate fraction and governs the micro-void structure of the mixture.

Through the introduction of PCS (Primary Control Sieve) and related control sieves, the Bailey Method converts traditional gradation curves into a structural parameter system. This transformation enables gradation design to move from curve-fitting approaches toward structure-oriented design, where each parameter corresponds to a specific physical function within the aggregate skeleton.

Overall, the Bailey method provides a physically interpretable framework that links aggregate gradation to the volumetric properties of asphalt mixtures, such as voids in the mineral aggregate (VMA) and air voids. However, the original parameter ranges were established based on aggregate characteristics and construction practices in the United States. Bailey also provided recommended reference values for these parameters, as shown in Table 1.

In recent years, with the observed deterioration in aggregate quality and the increasing demand for rutting resistance, gradation designs have tended to become coarser. Meanwhile, advances in paving and compaction equipment have significantly improved the mixture's resistance to segregation. Field practice indicates that the parameter values of actual gradations often fall outside the originally recommended ranges; however, mixtures with CA ratios exceeding the recommended upper limits may still exhibit satisfactory performance.

Therefore, direct application of the Bailey method in China requires recalibration based on local aggregate properties and construction conditions, so that its intended structural control function can be properly maintained.

Table 1. Recommended values of gradation control parameters (continuous gradation)

Parameter	Nominal Maximum Aggregate Size (mm)					
	37.5	26.5	19.0	13.2	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
FAc 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
FAf 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

To investigate the statistical characteristics of Bailey gradation control parameters under realistic engineering conditions, a large dataset of asphalt mixture design results

was collected from highway engineering projects completed in China over the past five years (2021–2026). These projects are mainly distributed in southeastern China and Shandong Province, covering expressways and arterial highways under medium-to-high traffic loading conditions.

The dataset includes commonly used dense-graded asphalt mixtures in China, namely AC-25, AC-20, AC-13, and AC-10. The mixtures were designed for different pavement structural layers, including surface, intermediate, and base courses. The coarse aggregates used in these projects are primarily crushed stone materials such as limestone and basalt, while the fine aggregate fraction mainly consists of manufactured sand, with limited use of natural river sand depending on local material availability. This reflects the typical aggregate composition characteristics of current asphalt pavement engineering practice in China.

For each mixture type, full gradation curves and corresponding volumetric design data were obtained from production-level mix design reports and construction quality control records. All datasets were derived from verified engineering documents, ensuring that the collected results represent stable and implementable mixture designs rather than preliminary laboratory trial blends. The Bailey Method parameters, including the coarse aggregate ratio (CA ratio), fine aggregate coarse ratio (FAc), and fine aggregate fine ratio (FAf), were calculated based on standard sieve analysis following the original Bailey framework.

A total of 100 representative mix design records were included in the final dataset, comprising 20 AC-25, 40 AC-20, 30 AC-13, and 10 AC-10 cases. These records reflect real engineering gradation adjustment behavior under different structural layers, traffic conditions, aggregate sources, and construction practices. Based on this dataset, statistical distributions of Bailey parameters were established to evaluate their variation characteristics and applicability in domestic asphalt pavement engineering.

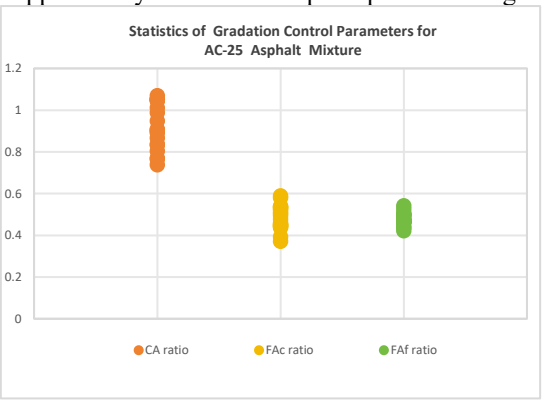


Fig. 1. Gradation control parameters of AC-25

The results of the CA ratio indicate that AC-25 mixtures are located at a rather high level in general, with certain gradations already surpassing the traditional upper limit. Figure 1 also indicates that the CA ratio of AC-25 is significantly larger than its FAc and FAf ratios, which means that the relative change between various particle-size

fractions of the coarse aggregate is more significant in coarse-graded mixtures. The reason is that AC-25 has a large nominal maximum aggregate size and a broad range of coarse-aggregate particle sizes; in engineering design, the percentage of intermediate-size aggregate is usually enhanced to enhance gradation continuity and compactability, which increases the CA ratio. When the traditional recommended range was strictly applied, there would be gradations that have been extensively used in practice and pass construction requirements, but would be wrongly considered unreasonable. Based on this, in the case of AC-25 mixtures, the CA ratio control range must be duly expanded based on domestic aggregate specifications, gradation conventions, and field compaction conditions.

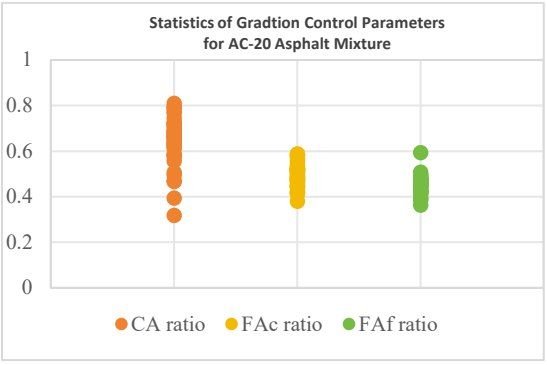


Fig. 2. Gradation control parameters of AC-20

As Figure 2 indicates, the dispersion of the CA ratio of AC-20 is significantly higher than that of AC-13 and AC-10, which is indicative of the increased design flexibility and adaptability of AC-20. Intermediate or lower courses normally use AC-20, which has to be sufficiently rutting resistant and at the same time, dense, moisture stable, and workable. Consequently, various projects use either coarser or finer gradation schemes based on traffic load class, available aggregate gradations, layer functionality, and local construction practices. In cases where the design goal is more focused on resistance to rutting and skeleton stability, the CA ratio will be lower; in cases where the design goal is more focused on continuous density and compactability, the CA ratio will be higher. This means that the CA ratio of AC-20 cannot be restricted to a small range but can be left to vary within a relatively wide one.

As Figure 3 indicates, the AC-13 mixtures are relatively concentrated and distinctly less distributed than the AC-25 and AC-20. This means that the possibility of varying the coarse-aggregate skeleton in fine-graded dense mixtures is not very large, and the CA ratio is more sensitive to gradation changes. Since AC-13 has a small nominal maximum aggregate size, the scale of the coarse-aggregate skeleton is restricted, and even slight variations in the passing percentage of some key sieves can significantly influence the CA ratio. In the design of AC-13, therefore, more emphasis must be placed on ensuring that the CA ratio remains constant to prevent local segregation, poor skeleton, or compaction problems due to an imbalanced coarse-to-fine aggregate ratio.

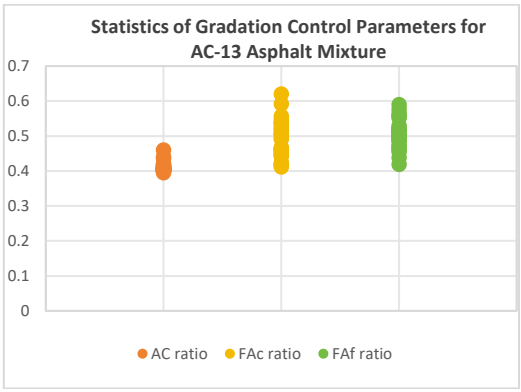


Fig. 3. Gradation control parameters of AC-13

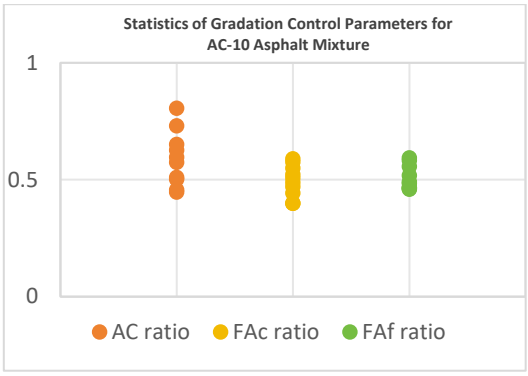


Fig. 4. Gradation control parameters of AC-10

As Figure 4 indicates, AC-10 mixtures have higher CA ratios on average than AC-13 and are more variable. This implies that, despite its small particle size, AC-10 is frequently used in thin overlays, levelling courses and special-function layers, where design is likely to focus on density, surface uniformity and workability. This can result in a greater percentage of intermediate-sized aggregate in some gradations, increasing the CA ratio. Therefore, the CA ratio of AC-10 should not be simply managed like that of AC-13, but rather it should be established separately based on the position and functional requirements of the layer.

3 Analysis of Gradation Control Parameters for Asphalt Mixtures

Recent years' statistics on mix designs indicate that the CA ratio of dense-graded asphalt mixtures usually lies between 0.4 and 1.0. Out of the gradations obtained, seven AC-25 curves are above the upper limit of 1.0. It is analyzed that more than half of these blends are due to the fine portion of the coarse aggregate, which interferes with

skeleton formation and, in effect, degrades the primary control sieve (PCS). Even though verification testing indicated that all performance indicators were met, the aggregate skeleton itself had been demoted. Two gradation curves are below 0.4; analysis shows that over a third of these blends are due to the coarse part of the coarse aggregate, and coarse-aggregate clustering is inevitable. This kind of structure requires a more stable fine-aggregate structure to ensure a reasonable volume of mixture and is very susceptible to segregation during construction.

The analysis shows that the CA ratio needed varies significantly between gradation types, and that it is too broad to control the CA ratio in a single range of 0.41. 0. The CA ratios of various mixture types in the database were then tabulated separately (Table 2), and new CA ratio ranges were established based on this (Table 3).

Table 2. Statistics of CA ratio in recent years

Mixture type	AC-25	AC-20	AC-13	AC-10
Maximum CA ratio	1.07	0.81	0.46	0.81
Minimum CA ratio	0.74	0.32	0.39	0.45
Mean CA ratio	0.92	0.65	0.41	0.59

Table 3. CA ratio specifications for multi-level interlocking skeleton dense asphalt mixtures

Mixture type	AC-25	AC-20	AC-13	AC-10
CA ratio	0.70–1.0	0.50–0.80	0.35–0.55	0.40–0.70

The FAc and FAf ratios are determined by considering the fine aggregate as a mixture in its own right, which contains both coarse and fine fractions, with the voids of the coarse fraction being filled by the fine fraction. They therefore indicate the interlocking and filling of the coarse and fine parts of the fine aggregate. Practically, the gradation of the fine aggregate is the primary determinant of the FAc and FAf ratios, which are normally supplied in 05 mm or 03 mm fractions and have little practical adjustment potential. The original Bailey Method control parameters give recommended FAc and FAf values of continuously graded asphalt mixtures based on nominal maximum aggregate size, and the ranges of observed FAc and FAf are not very different from these recommended values. Manufactured sand is currently the most common fine aggregate; natural sand is seldom used, and existing specifications have rather stringent requirements on fine-aggregate gradation. Table 4 summarizes statistics of the FAc and FAf ratios of target mix designs of dense-graded asphalt mixtures over the past few years. The values lie predominantly between 0.35 and 0.65, based on which the requirements of the FAc and FAf parameters were re-optimized.

Table 4. Statistics of FAc and FAf ratios in recent years

Mixture type		AC-25	AC-20	AC-13	AC-10
FAc ratio	Maximum	0.59	0.59	0.62	0.59
	Minimum	0.37	0.38	0.41	0.40
	Mean	0.49	0.49	0.49	0.49
FAf ratio	Maximum	0.54	0.59	0.59	0.59
	Minimum	0.42	0.36	0.42	0.46
	Mean	0.48	0.45	0.51	0.51

Table 5. FAc and FAf specifications for multi-level interlocking skeleton dense asphalt mixtures

Mixture type	AC-25	AC-20	AC-13	AC-10
FAc ratio	0.35–0.65	0.35–0.65	0.35–0.65	0.35–0.65
FAf ratio	0.40–0.60	0.40–0.60	0.40–0.60	0.40–0.60

The suggested ranges of the CA, FAc and FAf ratios suggested in this paper are not determined based on the original values of Bailey Method; instead they are calculated based on the statistical analysis of target mix-design data of real projects considering the initial recommendations of the Bailey Method, gradation range normally used to prepare AC dense-graded asphalt mixtures in China, the properties of manufactured sand, and necessity to manage the risk of construction segregation. Since the ratio of CA depends on the type of mixture and nominal maximum size of the aggregate, as shown in Table 5, separate ranges are provided in AC-25, AC-20, AC-13, and AC-10. The specifications of fine-aggregate and gradation of manufactured sand have a strong influence on the FAc and FAf ratios, and their changes over the mixture types are rather concentrated; a single control range is thus taken. The proposed ranges in this paper are aimed mainly at preliminary gradation design, parameter checking, and construction quality control and can be used as a reference in the engineering application of AC dense-graded asphalt mixtures.

4 Conclusion

This paper presents a solution to the issue of uneven interlocking and filling of voids between coarse and fine aggregates in the existing asphalt mixture gradation design. Using the Bailey Method gradation control parameters (CA ratio, FAc ratio, and FAf ratio) as the starting point, a large set of target mix-design data of recent projects was

gathered, the gradation control parameters of AC asphalt mixtures were systematically analyzed, and optimal technical recommendations were made.

The overall findings are as follows. First, the most important parameter to regulate the coarse-aggregate skeleton is the CA ratio, and it varies with different nominal maximum aggregate sizes in mixtures. The optimized ranges are: AC-25, 0.701. 0; AC-20, 0.500. 80; AC-13, 0.350. 55; AC-10, 0.400. 70. These ranges strike a balance between skeleton stability and construction compactability. Second, FAc and FAf ratios are highly dependent on the properties of the fine aggregate, and their variation intervals are concentrated. The suggested ranges are 0.35-0.65 of the FAc ratio and 0.40-0.60 of the FAf ratio that assist in making sure that there is an acceptable air-void content in the mixture. Third, the principle of optimization is primarily controlled by the coarse aggregate and secondary verification by the fine aggregate. The skeleton structure is corrected by the CA ratio, and the fine-aggregate filling and gradation stability are checked by the FAc and FAf ratios, thus providing both workability and durability of the mixture.

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