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# Improving quality control through chance constrained programming: A case study using Bailey method

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**Abstract**

Worldwide it is an accepted practice that guidelines regarding aggregate gradation to be adopted for any asphalt concrete mixture are recommended by transportation agencies. In general, these specifications are based on past experience and knowledge about local conditions. Alternatively, Bailey method of mixture design considers actual aggregate properties (like shape, density, packing characteristics) while deciding aggregate gradation. Such a mechanistic approach guarantees better mixture performance. As a single source of aggregate cannot meet requirements at all sieve sizes, aggregates from different sources have to be combined to achieve target gradation. Currently used deterministic optimization approaches for aggregate blending use mean values. This leads to a situation where resultant gradation is beyond specification limits occasionally. Alternatively, stochastic optimization approaches consider inherent gradation variability while arriving at final blending proportions. The present work describes a novel chance constrained programming approach that minimizes overall cost of mixture while considering quality control issues. The proposed chance constrained programming approach offers flexibility of introducing various gradation limits as well as Bailey ratio constraints simultaneously. The proposed methodology is validated using Monte Carlo's simulation approach. The simulation results indicated that mixtures blended using chance constrained approach produce less number of failures when compared to deterministic approach. This is due to the fact that inherent material variability is considered during blend optimization. The proposed work offers advantages of producing asphalt concrete mixtures at lower cost while having better quality control.


*Keywords:* Aggregate blending; Optimization; Bailey method; Chance constrained programming; Quality control

## 1. Introduction

The main goal of asphalt mixture design is to determine the optimum combination of constituent materials that satisfies volumetric, and pavement performance requirements at minimum cost. In general, mixture design process involves preparation of asphalt concrete specimens with varying individual constituent proportions and testing the prepared specimens for specified engineering and volumetric properties. Further, mixture is expected to meet the requirements specified by concerned transportation agency. Aggregate gradation is an example of agency specification. Most of the current specifications for asphalt mixture design methods including aggregate gradation are empirical in nature [1–3]. Due to underlying empiricism, satisfactory performance of the asphalt mixture in future is not assured.

Robert Bailey from Illinois Department of Transportation proposed a method for choosing aggregate gradation and subsequent asphalt concrete mixture design. Hereafter,

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this method is referred to as Bailey method. A mechanistic approach like Bailey method accounts for aggregate characteristics in mixture design. Bailey method assumes that primary aggregate skeleton in asphalt concrete mixture is provided by bigger particles i.e. coarse aggregate. The voids left by these coarse aggregate are filled by aggregate particles of smaller size i.e. fine aggregate. This process of using smaller aggregate is continued until voids within aggregate skeleton are just sufficient for asphalt binder and air. The relative proportion of coarse aggregate and fine aggregate are quantified through Bailey ratios. With coarse aggregate interlock and proper aggregate packing, strength and rut resistance, and durability can be enhanced [4–7]. Several research works have indicated that Bailey method approach guarantees satisfactory performance when compared with traditional approach [8,9].

As such one source of aggregate cannot satisfy aggregate gradation requirements recommended by specifying agency. This necessitates combining aggregates of different particle sizes from different sources. This process is commonly referred to as aggregate blending. Aggregate blending can be achieved by experience or mathematical approaches. In either case, the averaged values of aggregate gradation from several samples are used. Usually, first set of proportion that gives satisfactory values is chosen as final blending proportion. However, this approach does not account for inherent aggregate variability. This aggregate variability can be attributed to spatial variation in aggregate source, temporal variation during crushing process, and stockpiling operations. Due to these variabilities, chances of having resultant aggregate gradation outside specification limits of mixture cannot be ruled out [10,11]. To avoid such a scenario, calibration and adjustments of machinery are carried out routinely. Such calibration/adjustments often cause frequent disruption to hot mix asphalt plant operations. Most of the clients/transportation agencies penalize the contractor when the resultant gradation is outside specification limits. Thus, the contractor might end up losing some of their profit.

This article attempts to solve the aggregate blending problem considering (i) specification limits given by transportation agency, and (ii) additional gradation restrictions based on Bailey ratios, (iii) variability in aggregate gradation, and (iv) aggregate cost. Aggregate variability issues and obtaining feasible solution for a given probability level is taken care through constrained programming approach. The proposed aggregate blending formulation is validated through a case study and Monte Carlo simulation approach.

## 2. Background

As mentioned previously, asphalt concrete mixture production involves blending of aggregates from different sources/batches to satisfy specified gradation limit. Over past few decades, various researchers have developed a number of aggregate blending approaches. These methods can be broadly classified into three major categories (i) trial-and-error method, (ii) graphical method, and (iii) analytical methods. Due to simplicity and ease of calculation, trial-and-error methods, and graphical methods were widely used previously. However, with availability of computers and optimization tools, analytical methods have gained prominence these days.

In trial-and-error methods, relative proportion of aggregates is selected based on educated guess. This educated guess by designer will primarily depend on experience of designer/engineer, prior information regarding aggregate from particular quarry as well as resultant gradation requirements. Using these trial guess on relative proportion, resultant gradation is calculated and checked against the specification. If the specifications are not met, then relative proportion of individual aggregate sources is varied and resultant aggregate gradation is rechecked against the specification. This process is repeated until satisfactory results are obtained. Thus, experience and logical conclusion at each stage play important role in these trial-and-error methods. Hence these iterative methods are time consuming in nature. However, with more than two aggregate sources, obtaining an optimum blend would be a laborious, time consuming process and a challenge for designer.

In case of graphical methods, aggregate gradation from different sources and final gradation requirements are plotted on a graph. These superimposed particle size distribution curves are visually interpreted to obtain the feasible solution. Some examples for graphical approach are balanced area method [12], triangular-chart method [13], and rectangular chart method [14]. For simplicity mean values of aggregate gradation at individual sieve sizes are used while arriving at final proportions. These graphical methods are effective for combining aggregates from three or less aggregate sources and few sieve sizes are used in analysis. These graphical methods neglect the cost of individual aggregate sources while arriving at final proportions. Any analysis considering cost component has to be taken up subsequently.

In case of analytical methods, a system of equations is developed using aggregate gradation information, and gradation specification. This system of equation is solved through numerical approach. General expression to calculate percentage of resultant mixture passing sieve size ($R_i^{det}$) in a deterministic case is given by Eq. (1). Ritter and Shaffer [15] developed a linear optimization model with objective to minimize the cost of the final blend under the constraints on aggregate gradation. Neumann [16] used optimization technique to minimize the mean deviation from the midpoint of the gradation specification limits. Quadratic optimization model was developed by Easa and Can [17] with objective to minimize the squared deviations from the midpoints of the specification limits, with constraints on the gradation specification limits, cost, plasticity index, and fineness modulus. Various researchers [18,19] have used

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