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Improving the Gradation of Aggregate used in Asphalt Mixtures Using Bailey Method

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A B S T R A C T

The Bailey method of gradation analysis it is one of the techniques used in pavement engineering for evaluating and designing asphalt mixtures based on the particle size distribution. This paper presents a comprehensive review of research conducted on the Bailey technique, focusing on its application and impact in the field of pavement engineering. The review encompasses studies that have investigated the effectiveness of the Bailey technique as a mix design tool, a quality control tool, and a performance assessment tool. Researchers have explored its ability to optimize asphalt mixtures for desired performance characteristics, such as rutting resistance, stability, and durability. They have also examined its effectiveness in ensuring consistency and conformity to specified requirements during asphalt production. Furthermore, the review highlights the correlation between the Bailey technique's gradation data and various performance properties of asphalt mixtures. Researchers have investigated the relationship between particle size distribution and properties like rutting resistance, moisture susceptibility, drainage, and particle packing. These studies have provided valuable insights into the influence of gradation on the performance of asphalt pavements.

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Introduction

Background of Asphalt Mixture Gradation

The composition of asphalt mixture primarily comprises aggregates and asphalt binder. In the realm of civil engineering, the process of designing asphalt mixtures encompasses the meticulous consideration of various factors. These factors primarily revolve around the careful selection of mineral aggregate gradation and the crucial determination of the appropriate asphalt content. Nevertheless, these two intricately interconnected facets have been progressing along divergent trajectories over an extended period. The former branch of study progresses in the realm of theoretical analysis, while the latter branch advances through practical experimentation conducted in laboratory settings. The initial gradation design techniqueologies prioritized achieving optimal aggregate compactness, exemplified by approaches like the Fuller-Talbol's design technique [1], the K technique, and the particle interference theory. The endeavors were driven by the intention to develop an asphalt mixture featuring a robust aggregate framework, thereby enhancing the resistance to rutting distress in asphalt pavement caused by substantial loads and overloads. The initial development of Stone Mastic Asphalt (SMA) can be attributed to its inception in Germany. It has been demonstrated that SMA exhibits commendable rutting resistance when employed in practical civil engineering projects. The technique of coarse aggregate void filling (CAVF) was pioneered by Zhang et al. [2], wherein they presented design formulas to facilitate the formation of a robust aggregate skeleton. The Bailey technique, as introduced by the esteemed civil engineer Robert D. Bailey [3], was brought forth for consideration. In this particular approach, the notion of the aggregate skeleton was introduced. The formation of the aggregate skeleton during the process of gradation design holds significant importance in the overall design of asphalt mixture. Nevertheless, the existing techniques utilized for the gradation design predominantly rely on the empirical approach and laboratory experimentation.

Importance of Sutitable Gradation

Aggregate gradation refers to the arrangement of particle sizes in an aggregate, expressed as a percentage of the total weight[4] . It is a crucial property of aggregates in asphalt mixture, as it significantly impacts the properties and performance of hot mix asphalt (HMA) mixtures [4,5]. These characteristics include workability, permeability, durability, stiffness, air voids, stability, resistance to fatigue, resistance to friction, resistance to moisture damage, as well as rutting resistance of asphalt concrete under traffic and environmental loads [6]. The impact of gradation variations is very significant when there is a modification in the overall shape of the gradation curve, such as transitioning from coarse-to-fine or fine-to-coarse [7]. The aforementioned parameter holds a significant importance within the realm of mixture design. In the realm of pavement design, it is customary for codes to provide prescribed aggregate gradations denoted by both an upper and lower threshold [8]. In hot mix asphalt (HMA), it is noteworthy that the aggregate content constitutes a significant proportion, exceeding 90% of the overall volume [9]. The gradation of aggregates plays a significant role in influencing the overall performance of HMA.

Introduction to the Bailey Technique

The Bailey Technique is a meticulously devised technique for similar aggregates, which ensures the establishment of aggregate interlock as the structural foundation, while simultaneously achieving a harmonious and evenly distributed gradation of particles to achieve a well-rounded blend [7]. It primarily emphasizes the concept of aggregate packing [10]. The proposed methodology employs dry rodded unit weights of the different materials in order to assess the voids between cells among the particles. The given vacant area is subsequently occupied with the suitable quantity and dimension of material, while ensuring the preservation of the intact interlocking of the larger stones. This methodology offers a comprehensive suite of instruments for assessing the ultimate performance of the mixture. The utilization of these tools facilitates a more comprehensive comprehension of the impact of aggregate gradation on the asphalt mix [11]. Therefore, this approach equips the asphalt mixture with a set of tools to facilitate the development and fine-tuning of the aggregate mixture in order to achieve optimal aggregate packing, meet the required resistance against permanent deformation, and simultaneously fulfill the volumetric characteristics necessary to withstand environmental challenges [12].

Understanding the Bailey Technique

Historical Development and Significance

The Bailey Technique was initially formulated by Mr. Robert Bailey, a retired civil engineer from the esteemed Illinois Department of Transportation, specifically District 5 [7]. The approach employed in this methodology is rooted in the individual's expertise in the realm of asphalt mixture design. Mr. Bailey devised these techniqueologies as a strategy to address the issue of rutting in asphalt mixes while simultaneously upholding the desired durability properties. The techniqueologies initially

devised by Mr. Bailey have undergone enhancements by Dr. Bill Vavrik, an esteemed consultant at ERES and a member of the Division of Applied Research Associates, Inc., along with Mr. Bill Pine from Heritage Research. Together, they have formulated a techniqueical framework for aggregate blending that can be universally applied to all dense-graded asphalt mixtures, irrespective of the maximum aggregate size within the composition [13]. It is compatible with various mix design techniqueologies, such as Superpave, Marshall, or Hveem, among others. The methodology can also be effectively applied in the context of Stone Mastic Asphalt (SMA). The selection of aggregate interlock is considered as a crucial design input in the Bailey Method. The implementation of aggregate interlock within the composition will effectively enhance the resistance of the mixture against rutting. In order to guarantee the presence of sufficient asphalt binder within the mixture, it is imperative to modify the Voids in Mineral Aggregate (VMA) by adjusting the arrangement of the coarse and fine aggregates. By employing the Bailey Technique, it is possible to enhance the structural integrity of asphalt mixtures, thereby ensuring heightened stability, while also ensuring the presence of sufficient VMA (voids in mineral aggregate) to promote optimal durability. The aggregate blending procedures mentioned have undergone validation through rigorous laboratory analysis and extensive field trials [13]–[16]. The laboratory experiments conducted thus far encompass a multitude of mixture designs employed within the state of Illinois, under the guidance of Mr. Robert Bailey. Mr. Bailey diligently employed this methodology to enhance the overall functionality of Illinois highways, albeit without formally documenting his research findings. Moreover, the correlations between the aggregate gradation and the resultant volumetric characteristics of the mixture have been extensively documented in the research conducted by Vavrik [16].

Principles of the Bailey Method

The Bailey Technique uses two principles that are the basis of the relationship between aggregate gradation and mixture volumetric parameters[13].

1) Aggregate packing, as a function of type and amount of compaction energy, shape of the particles, surface texture of the particles, gradation and strength of the particles

2) Coarse and fine aggregate definition:

• Coarse Aggregate (CA): Larger aggregate particles which create voids in a unit volume.

• Fine Aggregate (FA): Aggregate particles fill voids between the coarse aggregates.

In the Bailey technique, CA and FA are separated by the primary control sieve (PCS). In contrast to the traditional definition of CA and FA separated by No.4 sieve, the Bailey technique defines the line between CA and FA relative to the (nominal maximum particle size) NMPS. PCS is identified using Formula (1).

$$PCS = NMPS * 0.22 \quad \text{Formula (1)}$$

To evaluate the packing properties, for each of the coarse aggregate stockpiles, the loose and rodded unit weights (LUW, RUW) must be identified; RUW is required for each of the fine aggregate stockpile. LUW is assumed to be the lowest unit weight of CA with particle-to-particle contact. The CA LUW is used to identify “fine” and “coarse” mixtures. In the Bailey analysis, the percent of the CA LUW is termed the “chosen unit weight”. If the CA chosen unit weight is below the LUW, then the coarse aggregate particles are not in particle-to-particle contact. As a result, the fine aggregate skeleton will develop and encompass the CA in the mix. The properties of such blends are primarily associated with the fine aggregate characteristics. The RUW is assumed as the highest achievable unit weight without degrading the CA. This magnitude is typically near 110% of the LUW. Mixtures with chosen CA unit weight close to RUW are normally hard to compact and unstable. If a coarse-dense-graded mixture is desired, then the CA unit weight should be chosen within the range of LUW±5% to ensure some degree of CA interlock. For fine-dense-graded mixtures, the chosen unit weight should be less than 90% of the LUW in order to let the FA skeleton control the mixture properties[17].

Applications of Bailey method in the asphalt mixture

Based on a small investigation carried out in 2002 by the esteemed Ontario Ministry of Transportation (MTO), it was observed that this proposition is likely to hold true for the traditional mix kinds. However, it should be noted that achieving the desired volumetric properties for the premium mixes utilized in high traffic applications would pose a more challenging task. This tool possesses the capability to facilitate the formulation and assessment of aggregate blends in accordance with various mix design technologies, including but not limited to Marshall and Superpave. The provided empirical rules facilitate the management of mixture volumetric characteristics, ensuring ideal field performance and compactness [18]. It also includes:

- Conducting laboratory and field-based investigations to develop and evaluate hot asphalt mixes.

- Enhancing the air voids, VMA (voids in mineral aggregate), and the overall workability of the mixture.
- Conducting a comprehensive assessment of aggregates and aggregate blends through meticulous analysis of their volume and weight properties.
- Incorporating measures to accommodate the utilization of Reclaimed Asphalt Pavement (RAP).
- Combining various aggregates in order to satisfy the volumetric requirements of any given methodology.

Comparison with Traditional Gradation Technique

The Bailey method and the traditional methods for HMA mixture design differ in:

Approach: Bailey suggested a particular approach for gradation analysis of asphalt mixtures, known as the Bailey method of gradation. It entails calculating the aggregate particle size distribution with the idea of a "maximum density curve." Using sieves, conventional asphalt engineering gradation methods like the Superpave system and sieve analysis physically separate and measure various aggregate particle sizes.

Gradation Criteria: The Bailey method of gradation aims to achieve an aggregate particle size distribution that corresponds to the maximum density curve. Traditional gradation techniques, such as the Superpave system, utilize specific gradation criteria defined by standards or specifications to ensure desirable engineering properties of the asphalt mixture, such as sufficient voids, workability, and performance.

Industry Acceptance and Standardization: The Bailey method of gradation is not widely recognized or standardized within the asphalt engineering industry. Traditional gradation techniques, such as the sieve analysis and the Superpave system, have been extensively used and are widely accepted as standard methods in many regions.

Limitations and Criticisms: As the Bailey method of gradation is not widely known or applied, there is limited information available regarding its limitations or criticisms. Traditional gradation techniques, on the other hand, have been subject to extensive research, and their limitations and areas for improvement are well-documented.

In the end, the Bailey technique applies to many kinds of asphalt mixtures, focuses on aggregate packing, and offers insights into mix workability. The conventional method for HMA mixture design is based on volumetric analysis and takes a more comprehensive approach.

Advantages and Limitations of the Bailey Technique

Enhanced Performance

The Bailey Technique provides several advantages for designing asphalt mixes, including**:**

1.Better control of volumetric properties: The Bailey Technique allows for a better control of the volumetric properties of asphalt mixes, which can lead to enhanced performance.

2.Resistance to permanent deformation: The Bailey Technique allows the designer to select an aggregate skeleton that will be more resistant to permanent deformation

3.Adjustments to mix design: When combined with adjustments to the mix design, the Bailey Technique can be used to enhance air voids, VMA, and the overall workability of mix

4.Appreciation of aggregate packing: The Bailey Technique gives designers and contractors a better appreciation of aggregate packing and its influence on mix volumetric and compatibility

5.Systematic approach: Bailey's techniques have been refined by several researchers to provide a systematic approach to blending aggregates to meet the volumetric criteria for any technique.

Addressing Environmental and Sustainability Concerns

Sustainability encompasses the harmonious fulfillment of human requirements and the progression of technology, while striving to minimize both the environmental and economic burdens. Transportation, being an essential requirement for human beings, necessitates the development of sustainable transportation infrastructure, which is a matter of utmost importance [19]. In consideration of the environmental aspect, diligent researchers have been actively exploring solutions to mitigate air pollution and reduce the depletion of natural resources associated with asphalt production. In a recent observation conducted at the Mauna Loa Observatory, a significant milestone was reached as a CO2 reading exceeding 410 parts per million (ppm) was recorded for the first time in history[20]. Here are some ways in which the Bailey method can help to address the environmental and sustainability concerns:

1. Enhanced mix design: The Bailey Technique provides a starting point for mix design, It could result in more effective asphalt combinations. By achieving better compaction and workability.
2. Use of Reclaimed Asphalt Pavement (RAP): The Bailey Technique makes provision for the use of Reclaimed Asphalt Pavement (RAP). Incorporating RAP into asphalt mixtures reduces

the demand for virgin aggregates and helps to conserve natural resources. It also reduces the amount of waste sent to landfills. Yang Xiaoli[21] employed the Bailey approach to enhance the gradation of a cold recycled mixture by incorporating RAP material, consequently leading to enhanced pavement characteristics. He examined that the pavement attributes of the enhanced cold recycled mixture, derived through aggregate screening of RAP material, exhibit superior qualities.

3. Research and refinement: The Bailey Technique has been refined by researchers to provide a systematic approach to blending aggregates to meet volumetric criteria. Ongoing research and refinement of the technique can lead to further enhancements in asphalt mix design and performance, including addressing environmental and sustainability concerns.

It is important to note that while the Bailey Technique can contribute to more sustainable asphalt mix designs, it is just one aspect of a broader approach to sustainable pavement construction and maintenance. Other factors such as the use of recycled materials, energy-efficient production techniques, and proper pavement management strategies also play a crucial role in achieving sustainable outcomes.

Case Studies

Successful Implementations of the Bailey Method

Numerous investigations were conducted pertaining to the Bailey Technique of gradation. A mix design procedure was employed to formulate stone mastic asphalt (SMA) in accordance with the Bailey Technique, which was subsequently adapted. The outcome of this process showcased commendable rutting characteristics [22]. The findings of a comprehensive study conducted in Oregon to examine the efficacy of the Bailey Technique in the design and analysis of dense-graded Hot Mix Asphalt (HMA) have suggested that a modified Bailey Technique analysis ought to be employed as a supplementary instrument for the formulation and selection of trial blends in the design process of dense-graded mixtures [7]. Numerous investigations have been undertaken to analyze the correlation between aggregate gradation and the ability of HMA to withstand permanent deformation. The lab analysis conducted focused on investigating the impact of different maximum aggregate sizes on the rutting potential and other characteristics of asphalt aggregate mixtures [23]. The findings revealed mixtures incorporating larger aggregate sizes, while maintaining that a consistent air void amount of 4%, usually exhibited a greater resistance to permanent deformation compared to mixtures containing smaller aggregates. According to additional research findings, it has been observed that mixtures with finer gradations or excessive sand content tend to exhibit a higher vulnerability to permanent deformation [24]. Table 1 presents the esteemed individuals who have graciously undertaken the task of reviewing the Bailey Technique in its literal form.

Table 1. literal reviewers on bailey technique

Authors	Year	methodology	Summary	Reference
William R. Vavrik, William J. Pine, G Huber, Samuel H Carpenter, R Bailey	2001	They examine different gradations and their effects on the density and voids of the mineral aggregate.	The Bailey technique of gradation analysis considers packing characteristics of aggregates. The experiment showed the response of aggregate packing to different gradation criteria.	[14]
Kareem Othman	2021	The paper discusses the methodology of the Bailey technique and its effectiveness in achieving desired mixture properties	- 14% of samples satisfy Bailey technique guidelines - 80% of mixes are prone to segregation	[25][11]
Wayne Jones	2006	The paper highlights the significance of proper aggregate gradation in achieving desired HMA volumetric properties and field compaction	Bailey technique predicts changes in HMA volumetrics. Workshop teaches participants to predict packing properties.	[26]
Aurilio, WJ Pine, P Lum	2005	The authors explore how the Bailey technique can be used to optimize the aggregate gradation of HMA mixtures to achieve specific volumetric properties and compaction characteristics	Bailey technique is a practical tool for mix design - Bailey technique helps in enhancing air voids and workability	[27]
Wu Jian	2003	Bailey technique is used for gradation selection and evaluation	Bailey technique is useful in gradation selection and evaluation during Superpave mixture design.	[28]

			- The application of Bailey technique to the mixture gradation evaluation of Kai Yang Expressway is discussed	
Malluru Swathi, Thavamani Andiyappan, Gurunath Guduru, M. Amaranatha Reddy, Kranthi Kuna	2021	The paper proposes using the Bailey technique of gradation selection to design asphalt mixes with steel slag aggregates, which can produce mixes with similar properties to natural aggregate mixes.	- Bailey technique can be used to design asphalt mixes with a high proportion of slag steel aggregate (SSA) SSA mixes have a higher resilient modulus and resistance to rutting and moisture damage.	[29]
Yasir Mohammed Jebur, Abdulhaq Hadi Abedali	2020	The paper presents the findings of laboratory testing and discusses the implications for asphalt mixture design and performance.	Bailey technique enhances asphalt mixture performance - Excel spreadsheet developed to save time and reduce errors	[30]
Manh Tuan Nguyen	2020	Laboratory tests including Marshall stability, indirect tensile strength, and rut depth from wheel tracking test.	The Bailey Technique is a gradation design of asphalt concrete that forms a strong aggregate skeleton for enhanced rutting resistance and long-term performance	[31]
Aravind Krishna Swamy, Karanjeet Kaur Sandhu, Jennifer	2017	The Bailey technique of gradation considers aggregate ratios and limits to control the volumetric properties of asphalt concrete mixtures.	Chance constrained programming produces fewer failures - Lower cost and better quality control achieved	[32]
Poornachandra Dev	2014	The work used conventional technique of gradation	- Bailey technique provides strong aggregate skeleton for durability. - Rutting characteristics of both gradations are modeled.	[33]
Andrea Graziani, Gilda Ferrotti, Emiliano Pasquini, Francesco	2012	Sieves and aggregate sizes are adopted in the USA	Bailey Technique criteria can be applied in European practice - European sieves can be used for mixtures grading	[34]
Hasan Al-Mosawe	2016	To investigate the impact of aggregate packing on permanent deformation and stiffness, a surface course layer featuring a maximum aggregate size of 14 mm was chosen for analysis.	The approach could be used for field rutting prediction if appropriate data were supplied	[35]

Performance Assessment in Various Climate Conditions

The Bailey Technique was implemented in a lab asphalt research program conducted in Dubai, United Arab Emirates, with the aim of enhancing the rutting performance of their asphalt mixtures on a global scale. Field trials have been strategically deployed in prominent locations such as Dubai, France, Canada, and various regions across America. The findings derived from these comprehensive lab and field trials shall be duly disseminated through publication as soon as they become accessible [36]. Through the foregoing, we find that there is a large difference in temperatures between those countries and between one season and another, or even between night and day. Nevertheless, the Bailey technique has proven a high efficiency and a satisfactory general performance. However, it's important to note that the performance of asphalt mixtures under specific climate conditions is influenced by various other factors beyond gradation analysis. These factors include binder selection, volumetric properties, asphalt contentz, compaction techniques, and environmental conditions like temperature and moisture. Therefore, a comprehensive performance assessment of asphalt mixtures in different climate conditions requires considering multiple parameters, including those related to the Bailey technique's analysis output.

Cost-Effectiveness and Economic Consideration

In order to enhance the structural and functional aspects of asphalt pavements, a series of novel asphalt mixtures have been developed. These innovative mixtures aim to provide substantial cost savings while simultaneously improving various key factors such as durability, friction, noise reduction, resistance to rutting, resistance to cracking, and resistance to moisture susceptibility [37]. The utilization of the Bailey design technique was employed in order to guarantee the appropriate

arrangement of aggregates within the fine dense-graded mixture gradation. This, in turn, facilitates the achievement of optimal compactability at a reduced layer thickness [22]. A comprehensive cost-benefit analysis was conducted to assess the cost efficiency of the bailey technique, taking into account its performance in relation to the control mixes. The existing techniqueologies for cost analysis primarily prioritize life-cycle cost analysis, which typically employs the international roughness index as a performance indicator for estimating the longevity of pavements [38]. The study conducted by Son and Al-Qadi demonstrates, based on the findings from both laboratory and field performance tests, observed that the Bailey mixtures exhibited superior performance and demonstrated enhanced cost-effectiveness in comparison to the control mixes [38]. The utilization of Bailey's technique exhibits a certain degree of cost-effectiveness in comparison to the application of polymers on asphalt binder for the purpose of achieving optimal performance.

Recent Innovations and Future Prospects

Integration of Technology and Automation

The Bailey technique is in direct contact with modern technology through the use of software in calculations and analysis.An Excel spreadsheet was developed to assist the designer with the analysis (Microsoft, 2003)[39]. Aurilio use the worksheets to design mixes by Bailey method [27]. The integration of the Bailey technique of gradation analysis with technology and automation can significantly enhance the efficiency, accuracy, and speed of the analysis process.

Potential Enhancements to the Bailey Technique

While the Bailey Technique has been successfully utilized in the lab and field, there may be potential enhancements that can further enhance its effectiveness. Here are some potential enhancements to consider:

1. **Enhanced aggregate characterization**: Enhancements could be made to better understand the characteristics of different aggregates and their impacts on the overall mix design. This could involve more detailed analysis of particle size distribution, shape, and angularity.

2. **Refined mix design parameters**: The Bailey Technique currently considers parameters such as air voids, VMA (voids in mineral aggregate), and workability. Further research could explore additional mix design parameters that can optimize the performance of asphalt mixes, such as rutting resistance, fatigue life, and moisture susceptibility.

3. **Incorporation of sustainable materials**: With the growing emphasis on sustainability, there is an opportunity to explore how the Bailey Technique can be adapted to incorporate alternative materials, such as recycled asphalt pavement (RAP) and reclaimed asphalt shingles (RAS). This would help in designing asphalt mixes that are environmentally friendly without compromising performance.

4. **Validation through field performance**: Conducting field trials and monitoring the performance of asphalt mixes designed using the Bailey Technique can provide valuable feedback for further enhancements. This would involve evaluating factors such as rutting, cracking, and durability to ensure that the technique produces long-lasting and high-performing asphalt pavements.

Anticipated Trends in Asphalt Mixture Gradation

While there is no specific information on anticipated trends of the Bailey technique in asphalt mixture gradation, it is possible that the technique could be enhanced to better understand the characteristics of different aggregates and their impacts on the overall mix design[11]. Additionally, the Bailey technique could be refined to consider additional mix design parameters that can optimize the performance of asphalt mixes, such as rutting resistance, fatigue life, and moisture susceptibility. There may also be a trend towards using data-driven approaches, such as machine learning, to identify the optimal aggregate gradation for specific performance requirements[40]. Overall, the Bailey technique remains a valuable tool for developing and analyzing hot asphalt mixes, and there may be potential enhancements to the technique that could further enhance its effectiveness in optimizing asphalt mixture gradation.

Conclusion

The Bailey method of gradation analysis is used in the field of asphalt engineering.for evaluating and designing asphalt mixtures based on the particle size distribution. After reviewing the various aspects of the Bailey technique, the following conclusions can be drawn:

- The Bailey method aids in the management and comprehension of volumetric properties.
- CUW has a notable impact on VMA and Marshall stability.
- Utilizing the Bailey method enhances the performance of asphalt mixtures.
- The use of an Excel spreadsheet is timesaving and minimizes errors.

- The Bailey Method contributes to improved rutting performance in asphalt mixtures.
- The Bailey method provides a more insightful understanding of aggregate gradation. It results in enhanced dynamic stability and an improved tensile strength ratio.
- Modifying gradation leads to improvements in Marshall properties, ITS, and resistance to creep.

In summary, the Bailey method for gradation analysis serves as a valuable asset in the field of asphalt engineering, playing a significant role in tasks such as mix design, quality control, and the evaluation of performance. When combined with other tests and analytical methods and integrated with technological advancements, this approach offers valuable insights for the enhancement of asphalt mixtures and the overall improvement of asphalt pavement performance.

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