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Influence of the Bailey Gradation Method on the Mechanical Behavior of Asphalt Mixture Containing Steel Slag as an Alternative Aggregate

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Abstract: This study evaluates the feasibility of reusing steel slag aggregates in asphalt concrete, analyzing the impact of different gradation methods (Bailey method and conventional Brazilian method) on the mechanical properties of the mix. Using the Marshall methodology and Petroleum Asphalt Concrete (PAC) 30/45, parameters such as Marshall stability, indirect tensile strength, resilient modulus, fatigue life through diametral compression, and permanent deformation (Flow Number) were investigated. Additionally, a simulation for a hypothetical section in the city of Rio de Janeiro, Brazil, was performed using the mechanistic-empirical pavement design software, Medina. The results showed that the mixture produced by the Bailey method outperformed the others in all analyses. This method led to a more compact mix, providing significant advantages, including up to a 35% reduction in final pavement thickness and a 110.6% increase in Flow Number (FN), enabling the mix to withstand extremely heavy traffic, as reported in the literature. Regarding fatigue life, the Bailey mixture achieved a fatigue class of 4, compared to the conventional mixture class 1. These findings indicate that using the Bailey gradation method for producing asphalt mixtures with steel slag can optimize binder content and improve resistance to permanent deformation and fatigue, making it a viable and sustainable alternative for asphalt pavements.

Keywords: alternative aggregate; steel slag; Bailey method; asphalt mixture; mechanical behavior



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1. Introduction

There is currently a significant concern about environmental degradation, given that available natural resources are finite and the generated waste must be properly managed to minimize negative impacts on nature. The dependence on natural resources in the road construction sector is undeniable. Crushed materials are used in almost all the layers that make up a pavement.

The construction of pavements involves high costs, particularly when conventional materials are used for the structural layers [1,2]. In this context, steel slag has increasingly been considered an effective alternative to replace conventional materials, contributing to the reduction in environmental impacts caused by the extraction of natural resources. Nascimento [3] and Wang [4] report the use of steel slag by various countries (England, Germany, Poland, France, Japan, etc.) since the early 20th century for various purposes, and in Brazil, data on the use of this material in paving have been available since the 1970s [5]. Moreover, the European Union (EU) recommends prioritizing the reuse of these wastes as byproducts, given their contribution to sustainability and the reduction in environmental impacts, provided they possess the necessary technical characteristics for their intended

applications [6,7]. The global production of steel, which has been increasing in countries such as China, the USA, Brazil, Australia, and several EU nations, generates large quantities of steel slag [7], motivating research into its utilization in various applications [8–16].

Studies show that steel slag possesses favorable mechanical characteristics, offering adequate strength and structural performance for different applications, such as railway ballast and road pavements. The mechanical characterization and study of permanent deformation behavior of alternative materials for paving are essential for evaluating their long-term effectiveness [17]. In this context, steel slag stands out by exhibiting robust performance when subjected to cyclic loading, demonstrating significant energy dissipation capacity and resistance to permanent deformation. These attributes are crucial for ensuring the durability and stability of infrastructures over time, without compromising the integrity of the structural layers [8,9,16,18–21]. Furthermore, recent studies have reinforced the potential of steel slag as a viable alternative material for hot mix asphalt. Kumar and Varma [22] emphasize that when properly integrated into asphalt mixtures, steel slag not only meets the required volumetric and mechanical performance standards but also contributes to enhanced durability and performance in road construction. Steel slag, a byproduct of the steel industry, possesses properties that make it a viable alternative to conventional aggregates in the production of asphalt mixtures. Applications in asphalt mixtures have been successfully tested by several studies, such as those presented by Guimarães [23], Loures et al [24], Guimarães et al. [9], Pasetto et al [25], Nascimento [3], and Plati et al. [26]. However, it became evident that special precautions need to be taken when using this type of material in asphalt mixtures, but the mechanical results are encouraging.

Various asphalt mixture designs aim to achieve properties such as durability, permeability, strength, stability, fatigue, and stiffness. A crucial factor influencing these properties is the gradation of the aggregates, including shape, size, angularity, and the flat-elongated characteristic, all of which directly affect the resistance and stability of the mixture [27]. Since aggregates form the skeleton of the asphalt mixture, a well-interlocked structure is essential to withstand most of the traffic load on the pavement. The gradation of the aggregates also plays an important role in the performance of the mixture. For example, an increase in the void content raises the porosity and permeability, negatively impacting tensile strength and pavement durability [28]. Furthermore, the characteristics of the aggregates, such as resistance and shape, directly influence the internal structure of the mixture, impacting its service life [29]. Different gradation types alter the average contact number and internal structure index, affecting both short- and long-term mechanical properties [30]. Gradation is also a determining factor in the fracture performance of the asphalt mixture, with the microstructure of coarse aggregates significantly affecting fracture performance, especially when they have the same gradation [31].

Contrary to conventional volumetric mix design methods, such as Marshall and Superpave, which consider aggregate characteristics indirectly and through trial and error, the Bailey Method proposes particle interlock through a continuous and balanced gradation. Sulaiman [32] highlights that this method optimizes asphalt mixtures to achieve the desired performance characteristics, ensuring consistency during asphalt production. Rahi [33] states that the Bailey method improves stability and resistance to permanent deformation, resulting in better performance and greater resistance to wear in pavements. Additionally, Rafeez [34] emphasizes that the method enhances aggregate compaction, promoting superior performance compared to conventional gradations. Developed by the Illinois Department of Transportation (IDOT), the Bailey method has been used and refined since the 1980s. Several studies confirm its effectiveness in designing ideal mixtures (Komba et al. [35]; Blaauw et al. [36]; Horak et al. [37]; Ghuzlan and Al-mestarehi [38]; Imaninasab [39]); Alsheyab et al. [40]; Joulablatt et al. [41]).

Alongside the recycling of aggregates, the reuse of asphalt binder has gained increasing importance in the pursuit of more sustainable practices in pavement construction. Recent studies have emphasized the role of recycled asphalt binders in reducing the demand

for virgin materials, enhancing the sustainability of pavement systems while maintaining performance standards [42–44]. Integrating these practices with alternative aggregates, such as steel slag, further promotes the circular economy in road construction, aligning with global sustainability goals.

The objective of this study was to assess the technical feasibility of using 100% steel slag in asphalt paving by comparing asphalt mixtures designed with the Brazilian conventional method (trial and error method) and the Bailey method for determining the mineral skeleton. To evaluate the performance of these mixtures, tests for indirect tensile strength (ITS), resilient modulus (RM), fatigue life (FL), and permanent deformation (PD) were conducted. Additionally, a simulation for a hypothetical section in the city of Rio de Janeiro, Brazil, was performed using the mechanistic-empirical pavement design software, Medina (v 1.5.0).

2. Gradation Selection Methods

2.1. Bailey Method

The Bailey method was conceived in the 1980s to meet the demands of American agencies regarding the need to provide asphalt coatings with resistance to permanent deformations, fatigue cracks, and wear. This method aims to achieve these objectives through the systematic selection of the gradation of asphalt mixtures. Its primary purpose is to combine aggregates in such a way that, when necessary, interlocking occurs between them, thus forming the structural skeleton of the layer, in addition to employing a continuous and balanced gradation to complete the mixture, as highlighted by Vavrik et al. [45].

The method presents a different way of classifying coarse and fine aggregates based on the Nominal Maximum Size (NMS) of the mixture, defining coarse aggregates as those that form voids when placed in a defined volume and fine aggregates as those capable of filling the voids created by the coarse aggregates present in the mixture.

2.2. Aggregate Size Definition for the Bailey Method

$$PCS = NMS \times 0.22 \quad (1)$$

PCS: Primary Control Sieve.

NMS: Nominal Maximum Size.

Through two-dimensional (2D) and three-dimensional (3D) analyses of the arrangement of aggregates of different shapes, factors ranging from 0.18 to 0.28 were identified for use in Equation (1), without affecting the gradation analysis. However, a standardized value of 0.22 was adopted (Vavrik et al. [45]). Coarse aggregates are those retained on the PCS and are referred to as the Coarse Aggregate Proportion (CA Proportion). The material passing through the PCS represents the fine aggregates, which are further divided into two proportions: the Coarse Portion of the Fine Aggregate (CPFA Proportion) and the Fine Portion of the Fine Aggregate (FPFA Proportion). To determine the two fractions of fine aggregates, the Secondary Control Sieve (SCS) is used, as defined by Equation (2).

$$SCS = PCP \times 0.22 \quad (2)$$

where

SCS: Secondary Control Sieve;

PCS: Primary Control Sieve.

In addition to the two sieves determined previously, we can also mention the following sieves: the median sieve (MS), which is the one closest to half of the nominal maximum size (NMS); and the tertiary control sieve (TCS), which is obtained by multiplying the secondary control sieve (SCS) by a factor of 0.22. With the determination of aggregate fractions and control sieves, the aggregate proportions can be determined using Equations (3)–(5)

$$CA \text{ Proportion} = \frac{\% \text{ passing through MS} - \% \text{ passing through PCS}}{100\% - \% \text{ passing through MS}} \quad (3)$$

$$\text{CPFA Proportion} = \frac{\% \text{ passing through SCS}}{\% \text{ passing through PCS}} \quad (4)$$

$$\text{FPFA Proportion} = \frac{\% \text{ passing through TCS}}{\% \text{ passing through SCS}} \quad (5)$$

According to Vavrik et al. [45], the values for these aggregate proportions should fall within the ranges indicated in Table 1. Mixtures whose values for these proportions do not align with the recommendations of this author may become unstable and exhibit compaction difficulties in the field, for instance.

Table 1. Aggregate proportion relative to nominal maximum size (NMS) in mm.

Aggregate Proportion	Nominal Maximum Size (NMS), in mm					
	37.5	25.0	19.0	12.5	9.5	4.75
CA	0.80–0.95	0.70–0.85	0.60–0.75	0.50–0.65	0.40–0.55	0.30–0.45
CPFA	0.35–0.50	0.35–0.50	0.35–0.50	0.65–0.50	0.35–0.50	0.35–0.50
FPFA	0.35–0.50	0.35–0.50	0.35–0.50	0.35–0.50	0.35–0.50	0.35–0.50

Densities of Coarse Aggregate

After determining the loose bulk density (LBD) and compacted bulk density (CBD) of the coarse aggregate according to AASHTO T-19 [46], the next step is to determine the chosen bulk density of the coarse aggregate, which is essentially the selection of the void content of the mixture. This choice leads to determining the volume of coarse aggregate and also the degree of interlocking of the mixture. With the determination of the CBD, it is also determined whether the mixture is coarse, where the skeleton is formed by the coarse aggregate, or if it is fine, when the amount of coarse aggregate is not sufficient to form the skeleton and it is formed by fine aggregate [45].

Considerations for determining the LBD, which must align with the desired gradation of the mixture, are illustrated in Figure 1. For dense-graded mixtures, values should be between 95% and 100% of the LBD. Values between 90% and 95% of the LBD should be avoided as they may exhibit significant variation in the degree of interlocking of coarse aggregates in the field. Values above 105% should also be avoided due to the increased risk of aggregate degradation and the difficulty of field compaction.



Figure 1. Steel slag used in this research. (a) In wet form; (b) in dry form.

2.3. Conventional Trial-and-Error Method

The term “conventional method” or “trial-and-error method” refers to a widely used approach in asphalt mix design, where the designer selects the aggregate gradation based on practical experience and the characteristics of available materials. Although the specific application of this method in Brazil is regulated by the National Department of Transport Infrastructure (DNIT), this approach is globally recognized and applied, regardless of national standards.

In the conventional method, the process of determining the aggregate gradation involves choosing particle size ranges for the aggregates based on project requirements and material specifications. The designer defines the gradation to be used after analyzing characteristics such as the specific gravity and absorption of the aggregates. Then, the binder content is adjusted based on the aggregate characteristics and the selected gradation.

According to Bernucci et al. [47], the specific gravities of the constituent materials of the mixture should first be determined, as well as the particle size distribution of the aggregates to be used. After that, a gradation range is selected according to predetermined intervals or based on the designer’s practical experience, ensuring it meets the project’s requirements. The binder content is then adjusted to ensure the desired performance of the mixture.

Bernucci et al. [47] further explain that once the appropriate gradation range is selected, the composition of the aggregates must be determined, meaning the mass percentage of each type of aggregate in the mixture. The designer ensures that the percentages of each material fall within the selected range, with permissible variations in the field, according to the specifications.

3. Materials and Methods

To assess the feasibility of using the Bailey Method in asphalt mixtures containing steel slag, two asphalt concrete mixtures were prepared: one in which the mineral skeleton was dosed using the conventional trial-and-error method [48], and another in which the Bailey Method was used to determine the mineral skeleton.

3.1. Material

The slag used in this study is Linz–Donawitz steel slag, supplied by the Ternium steel company located in the Santa Cruz neighborhood in the city of Rio de Janeiro. The particle size distribution analysis of the steel aggregate was conducted according to the DNER-ME 083 standard [49]. Figure 1 presents the slag in wet and dry forms, and Figure 2 represents the particle size distribution curve of the slag used.

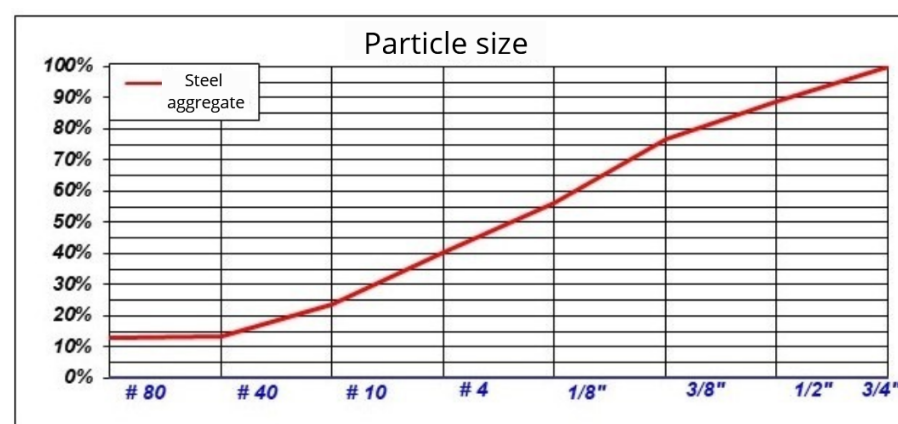


Figure 2. Particle size distribution curve of the steel slag used in this research.

For the characterization of the slag, tests were conducted for density [50], absorption [51], sand equivalent [52], and adhesivity [53], following the technical specifications [54].

The environmental suitability of the steel slag used in this study was assessed by the supplier through standardized tests, which confirmed compliance with all relevant technical and environmental standards, including evaluations of potential leachates. Additionally, expansion tests were conducted, and the results met the limits established by current standards [55], ensuring the material's stability and safety for application in asphalt mixtures.

In addition, tests related to the slag's resistance were conducted, such as the evaluation of shock loss using the Treton equipment [56], and the Los Angeles abrasion test [57].

The asphalt binder used in this research is the Petroleum asphalt concrete (PAC) 30/45, supplied by the Asphalt Plant of Caju (Rio de Janeiro City Hall), as it is the most commonly used type in asphalt pavement works in the region. The characteristics of the binder are presented in Table 2.

Table 2. Characterization tests as per the National Agency of Petroleum, Natural Gas, and Biofuels.

Test	Unit	PAC 30/45 Limit	Standard
Flash Point, min.	°C	min 235	DNER-ME 148 [58]
Penetration (100 g, 5 s, 25 °C)	0.1 mm	30 to 45	DNIT ME 155 [59]
Softening Point	°C	min 52	DNIT ME 131/10 [60]
Thermal Susceptibility Index	-	(−1.5) to (+0.7)	–
Rotational Viscosity	cP	min 374	NBR 15184 [61]
		min 203	
		76–285	
Residue After RTFOT Tests			ASTM 2872 [62]
Mass Variation	% mass	≤ 0.5	–
Softening Point Variation	°C	max 8	DNIT ME 131 [60]
Penetration Retained	%	min 60%	DNIT ME 155 [59]

3.2. Method

To prepare the mixture containing 100% steel slag aggregates, the initial dosing aimed to fit the aggregate gradation into the C range, as specified in the Brazilian standard [48]. The C range refers to a specific gradation interval that ensures the aggregates meet the requirements for optimal performance in asphalt mixtures. This classification defines the particle size distribution, with the objective of achieving proper compaction, adequate void distribution, and good binder adhesion. The ranges listed specify the percent passing through particular sieve sizes, ensuring that the mix is balanced for the intended layer thickness, typically requiring the compacted layer to be at least 2.5 times the nominal maximum particle size of the selected gradation.

Thus, the decision was made to fractionate the raw slag, resulting in the slag being divided into coarse slag I (passing through #3/4 and retained on #1/2), coarse slag II (passing through #1/2 and retained on #10), and fine slag (passing through #10), with their respective particle size distributions presented in Figure 3.

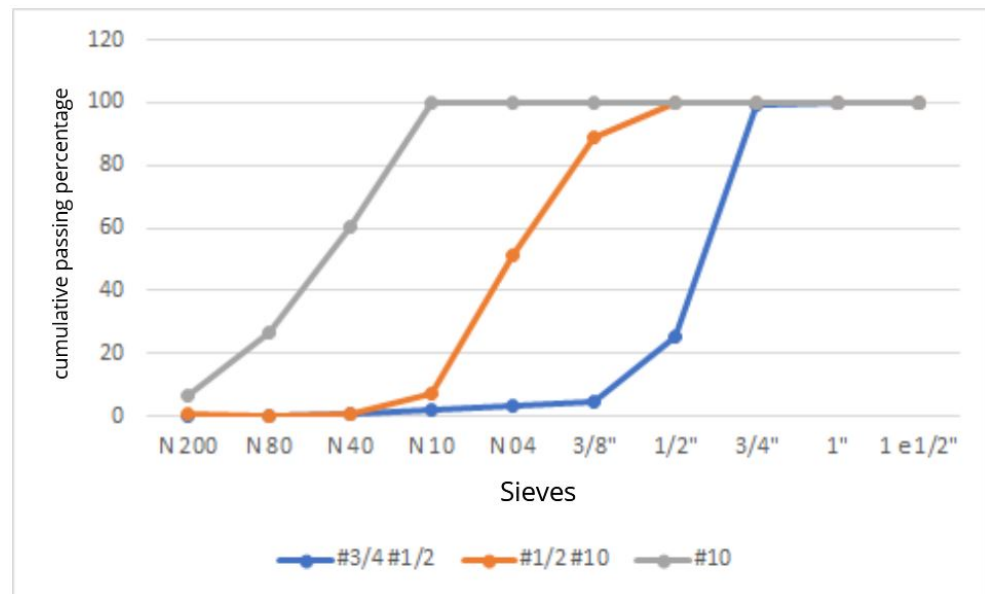


Figure 3. Particle size distributions of the materials used in this study.

The proportioning of aggregates was determined through the trial and error method and was denoted as the conventional mixture. From this conventional mixture, modifications were made following the suggestions of the Bailey method, resulting in a new mixture designated as the Bailey mixture. In the Bailey mixture, it was necessary to add 1.7% limestone filler. The resulting particle size distributions are presented in Table 3.

Table 3. Percentage composition of components for conventional and Bailey mixtures.

Mixture	Coarse Slag I (%)	Coarse Slag II (%)	Fine Slag (%)	Filler (%)
Conventional Mixture	12	60	28	-
Bailey Mixture	24.8	49	24.5	1.7

Table 4 presents the granulometric parameters indicated by the Bailey method for the studied Bailey mixture. It is noted that the mixture exhibited a proportion of coarse aggregate in fine aggregate (GAF) higher than desirable. However, even with the non-compliance of this proportion, it was decided to proceed with the experimental procedures.

Table 4. Aggregate distribution for Bailey mixture with acceptance limits.

Parameter/Mixture	CA	FCA	FFA
Bailey Mixture	0.57	0.56	0.45
Limit	0.50–0.65	0.35–0.50	0.35–0.50

To establish the optimal design contents for both mixtures (conventional mixture and Bailey mixture), we followed the Marshall method [63], with the application of 75 blows per face. The final results indicated design contents of 8% and 6.5% for the conventional mixture and Bailey mixture, respectively. These values were determined based on a voids condition of 4%, as analyzed in volumetric studies conducted by Coelho [64], which employed the Marshall methodology as a reference.

The results in Tables 3 and 4 highlight the distinct aggregate distribution achieved using the Bailey method compared to the conventional method. Despite the GAF proportion exceeding the desirable range for the Bailey mixture, the decision to proceed with the experimental procedures underscores the adaptability of the Bailey method. The optimized

gradation allowed for a lower binder content (6.5%) compared to the conventional mixture (8%), demonstrating its efficiency in achieving target volumetric properties. These findings reinforce the method's potential to accommodate variations in granulometric parameters while maintaining its design principles.

It is worth noting that the conventional mixture failed to meet the required value for voids in bituminous mix (VBM). However, it exceeded the minimum stability specified by the methodology, and the other volumetric parameters were within the recommended limits.

With the determined optimum contents, tests were carried out for indirect tensile strength (ITS), resilient modulus (RM), permanent deformation (PD), and fatigue life (FL) as per the methods outlined in DNIT 136 [65], DNIT 135 [66], DNIT 184 [67], and DNIT 183 [68], respectively. The moisture damage resistance of compacted asphalt mixture was investigated by the ITS test. They were both conducted according to AASHTO T 238 standard methods. In the ITS test, Marshall samples were averagely divided into two groups. One was the control group, and the other was conditioned. The conditioned group was subjected to moisture freeze-thaw damage, as shown in Figure 4. All samples were sent to equipment to measure the tensile strength under room temperature about 25 °C. The tensile strength ratio (TSR) was computed according to Equation (6).

$$\text{TSR} = \frac{\text{TSh}}{\text{TSo}} \times 100\% \quad (6)$$

where TSo is the average tensile strength of the control group, MPa; e TSh is the average tensile strength of the conditioned group after freeze-thaw damage, MPa.

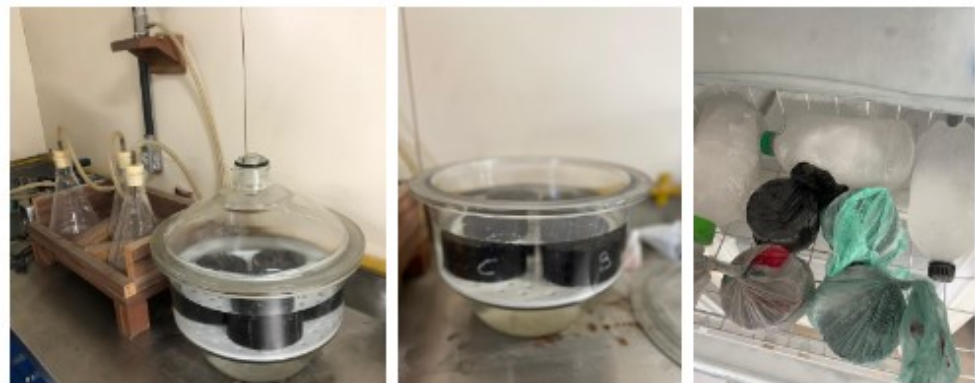


Figure 4. Specimens used in the freeze-thaw cycles.

Mechanistic Analysis

For the analysis and comparison of the mechanical behavior of a flexible pavement structure composed of the studied mixtures (conventional mixture and Bailey mixture), the Brazilian National Pavement Design Method, Medina, was utilized. Medina is the result of research developed between 2015 and 2018 by the Road Research Institute—IPR and the Alberto Luiz Coimbra Institute of Postgraduate and Research in Engineering, Federal University of Rio de Janeiro—COPPE, with the collaboration of the Petrobras Research Center—CENPES and several universities in Brazil. Additionally, it is an update of the SISPAV program developed by Franco [69] in his doctoral thesis.

The software uses as input data the dimensions of the layers, the mechanical properties of the materials (RM, FL model, PD model, and Poisson's ratio) composing the layers and the loads generated by the passage of vehicles. Once the stresses, strains, and displacements are calculated, the software verifies whether the number of load applications will lead to excessive cracking of the asphalt pavement or cemented layers, or to rutting in the wheel track exceeding the established limit.

Moreover, based on the regression coefficients obtained from the fatigue test, the software automatically calculates a fatigue factor of the mixture (FFM) for each model

inserted. Comparing this value with the resilient modulus of the mixture, the fatigue class (FC) of the material is calculated. According to the Medina manual [70], the higher the FC (ranging from 1 to 4), the better the mechanical behavior of the asphalt mixture.

The hypothetical structure of the flexible pavement will be composed according to the scheme presented in Table 5, taking into account the characteristics of the base, sub-base, and subgrade materials of the pavement. These characteristics were selected for a standard Brazilian single-wheel axle load and considering a design life of 10 years, based on representative traffic data obtained in Loures' research [24]. The asphalt pavement will be a mixture commonly used in Rio de Janeiro, while the studied slag mixtures will also be incorporated into the design.

Table 5 presents the hypothetical structure of the flexible pavement adopted for analysis, considering the characteristics of the base, sub-base, and subgrade materials, as well as the standard Brazilian single-wheel axle load. A design life of 10 years was assumed, with hypothetical traffic levels representing low, medium, and high traffic volumes. These scenarios were defined to evaluate the adaptability of the mixtures under varying demands, inspired by representative data from Loures' research [24]. For comparison purposes, the RJ PAC 30/45 #12.5mm Sepetiba (M0) mixture, available in the MeDiNa program database, was selected as a reference. The physical and mechanical characteristics of the pavements are presented later in Table 5.

The hypothetical nature of this analysis allows for its application in other countries or regions, providing a basis for future research or as a framework for evaluating similar pavement designs and mixtures in diverse traffic and environmental conditions.

Table 5. Characteristics of materials and traffic for road pavement design.

Layers	Type	RM (MPa)	Thickness (cm)
Base	Granular Material (Gneiss C1)	259	15
Sub-base	Fine, silty, or clayey soil	189	15
Subgrade	Fine, silty, or clayey soil	189	-
Standard Brazilian Road Axle Data			
Axle load (tonf)		8.2	
Tire pressure (MPa)		0.56	
Traffic Characteristics			
Light Traffic		(9.96×10^5)	
Medium Traffic		(5×10^6)	
Heavy Traffic		(5×10^7)	

4. Results and Discussion

4.1. Physical Characterization

The results presented in Table 6 demonstrate that the studied steel slag follows the characteristics determined by the standard, except for absorption, which shows higher values than the standardized ones.

Table 6. Results of physical and mechanical properties tests.

Test	Result
Real Density (g/cm ³)	3.30
Apparent Density (g/cm ³)	2.62
Absorption (%)	3.60
Sand Equivalent (%)	68.52
Adhesivity	Satisfactory
Expansion (%)	1.24

In addition, tests for impact loss and Los Angeles abrasion were conducted, and the results are presented in Table 7, demonstrating compliance with the standards used.

Table 7. Results of impact loss and Los Angeles abrasion tests.

Test	Result
Impact Loss (%)	9.20
Los Angeles Abrasion (%)	21.57

4.2. Tensile Strength and Resilient Modulus

Table 8 presents the results of the tests, based on the average (three replicates) values found for each mixture. The ITS values showed no significant differences but met the minimum criterion of the standard (0.65 MPa).

Table 8. RT and RM values for conventional and Bailey mixtures.

Mixture	ITS (MPa)	RM (MPa)
Conventional Mixture	1.16	8700
Bailey Mixture	1.09	10,693

The high RM values observed in this study, ranging from 8700 to 10,693 MPa, underscore the superior stiffness of mixtures with a high steel slag aggregate (SSA) compared to mixtures of natural aggregate (NA), as discussed by Swathi et al. [71]. Prior findings from Swathi et al. [71] indicate that incorporating SSA, due to its high impact resistance and cubic particle shape, substantially enhances stiffness relative to NA, with SSA mixtures exhibiting RM values approximately 1.4 to 1.8 times higher than those of NA mixtures. The notable stiffness difference in our results can probably be attributed not only to the high content of SSA (88.3% to 100%) but also to the use of a stiffer binder (PAC 30/45), both contributing to the observed increase in RM values.

Previous studies, such as those by Xie et al. [72] and Kavussi and Qazizadeh [73], identified significant limitations in using 100% SSA in asphalt mixtures, including increased binder demand and voids in mineral aggregate (VMA) when conventional weight-based gradation methods are applied. These challenges often lead to higher costs and reduced performance under traffic loading, prompting design guidelines to recommend partial replacement of aggregates instead of full substitution [74–76]. Our study addresses this gap by demonstrating that the Bailey method effectively solves these issues, allowing the use of 100% SSA while achieving RM values significantly higher than those reported for NA mixtures. This finding highlights the potential of the Bailey method to improve sustainability and performance in asphalt pavement design by optimizing gradation for high SSA content mixtures.

The Bailey method mixture specifically demonstrated an increase in stiffness in comparison to conventional mixtures, as reflected in these higher RM values. However, it is important to note that a higher stiffness alone does not guarantee better performance in asphalt mixtures. For optimal performance, these mixtures must balance rigidity with flexibility to accommodate deformations and maintain sufficient tensile strength, thus preventing cracking and rupture. In addition, the stiffness of the mixture should align with the structural needs of other layers of the pavement to ensure overall durability and compatibility.

In comparison, Cavalcante et al. [77], using the Superpave methodology, found an RM value of 2241 MPa for HMA containing 57% steel slag, demonstrating a substantial difference from our findings, likely due to the lower content of slag and the different binder used in their studies.

Furthermore, Coelho et al. [78] investigated HMA containing 40% reduction ferromagnetic slag (RFNS) applied in an experimental parking lot, achieving an RM value of

6323 MPa through the Marshall methodology. Their study confirmed the durability of RFNS as an alternative aggregate, with visual inspections four years later indicating that the pavement remained in excellent condition. This RM value, although lower than those in our study, supports the feasibility of using alternative aggregates in asphalt mixtures.

Finally, Guimarães et al. [23] evaluated mixtures containing 20% and 17% mining waste, producing RM values of 5137 MPa and 5244 MPa, respectively. Their findings demonstrated that substituting fine aggregate with mining waste in asphalt concrete is viable for local roads without compromising pavement support capacity, although their RM values are also significantly lower than those found in our study with higher slag content.

4.3. Permanent Deformation

Permanent deformation was evaluated using the Flow Number (FN) test. The FN value was obtained by averaging three specimens for each mixture. In Figure 5, the characteristics of the mixtures can be analyzed according to the limit criteria proposed by Nascimento [79] and Bastos [80].

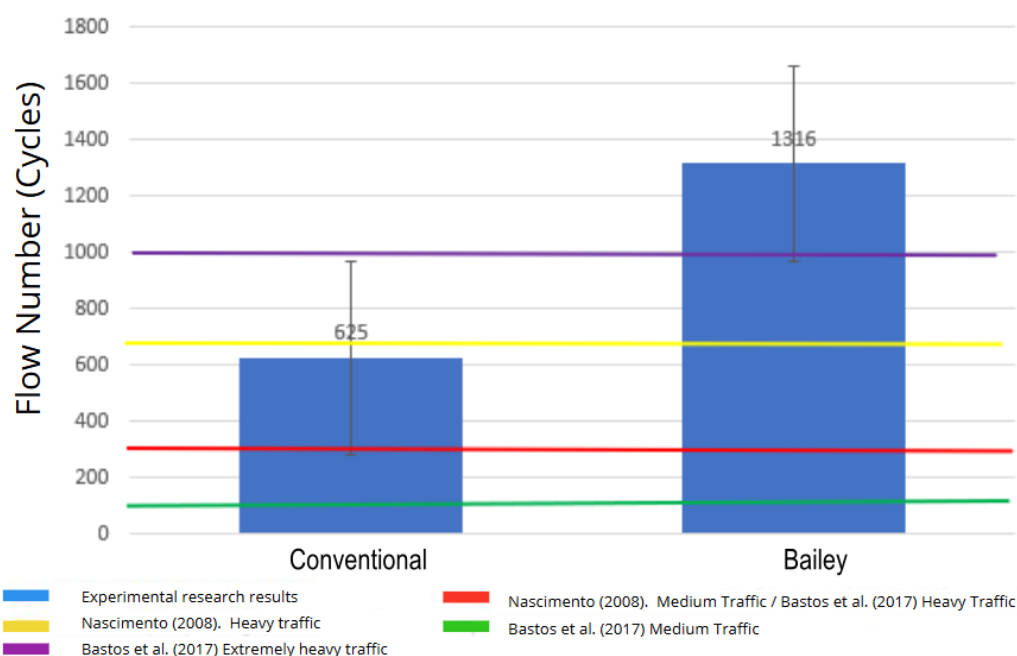


Figure 5. Comparison of FN values obtained for each method compared to the limits proposed by Nascimento [79] and Bastos [80].

According to Medina and Motta [81], the FN is higher the coarser the aggregate gradation and the more consistent (lower penetration) the asphalt binder.

Considering the FN results for the tested mixtures, the conventional mixture showed a considerable value, with a tendency towards medium-to-heavy traffic. However, the FN result for the Bailey mixture, which uses the same steel slag aggregates and the same compaction method, demonstrates the positive influence of the granulometric method on permanent deformation behavior and consequently on wheel track rutting (WTR) defect, resulting in an FN number related to extremely heavy traffic limits, according to Nascimento's research [79].

Additionally, after modeling the deformation curves using the Francken model, the FN results, permanent deformation at FN ($\epsilon_{p(FN)}$), and FN Index were extracted, as shown in Table 9.

Table 9. Flow number test results for conventional and Bailey methods.

Method	FN (Cycles)	$\epsilon_{p(FN)}$ (Microstrains)	FN INDEX (Microstrains/Cycles)
Conventional	625	7564.30	12.10
Bailey	1316	8018.10	6.10

It is observed that the Bailey mixture accumulated approximately two times less plastic deformation per cycle than the conventional mixture. This behavior can be attributed to the strength characteristics of the steel slag aggregate combined with the interlocking effect provided by the Bailey gradation. Supporting this finding, Ghuzlan et al. [38] and Golalipou et al. [82] noted that mixtures with finer aggregate arrangements systematically interlocked with coarse aggregates exhibit lower deformation values under loading. This configuration helps distribute stresses more effectively among the coarse aggregates, enabling the mixture to withstand higher load cycles.

Conversely, Ouza and Abdolsamed [83] observed that coarse Bailey mixtures demonstrated superior rutting resistance compared to finer ones, highlighting the influence of gradation design on performance. Despite these differing observations, the results of this study align with findings from Shang et al. [84], Manjunath and Poornachandra [85], and Denneman et al. [86], which collectively emphasize that Bailey gradation mixtures outperform conventional designs such as Superpave and Asphalt Institute gradations. This superiority underscores the effectiveness of the Bailey method in enhancing the structural and functional performance of asphalt mixtures.

4.4. Fatigue Life Analysis

The fatigue life test was conducted in the pavement laboratory of the Military Institute of Engineering, Rio de Janeiro, Brazil, following the standard (DNIT-ME 183 [68]), without the use of LVDT sensors. The test was performed for specimens molded at the determined optimum content for each mixture and subjected to the fatigue test by diametrical compression with the variation in stress level in the range of 15% to 30% of the ITS.

Thus, it was possible to establish the stress difference ($\Delta\sigma$) curves in relation to the number of cycles to failure (Nf). When considering the resilient characteristic of each mixture through the RM, a relationship of resilient strain (ϵ_r) was also established with Nf. The regression coefficients and correlation coefficients are presented in Table 10.

Table 10. Regression parameters of fatigue life curves for the mixtures in this study.

Mixture	Nf = a1 ($\Delta\sigma$) b1			Nf = a1 (ϵ_r) b2		
	a1	b1	R^2	a2	b2	R^2
Conventional	35,511	−4.619	0.868	2.00×10^{-14}	−4.059	0.868
Bailey	184,436	−2.682	0.9782	7.00×10^{-8}	−2.682	0.9782

Analyzing Table 10, it can be observed that the values exhibit good determination coefficients R^2 , indicating the quality of fit of the models to the observed points. The values obtained from the Bailey method showed less dispersion, i.e., R^2 values closer to 1, while the conventional method values yielded more conservative results.

Júnior [87] explains that the coefficient “b” indicates the slope of the curve, and for stress difference graphs, “b1” indicates susceptibility to stress conditions, meaning higher values indicate greater sensitivity of fatigue behavior of mixtures to variations in stress difference. Thus, according to the data in Table 10, the conventional mixture presents higher values of “b1”, therefore being considered more susceptible to variations in stress conditions.

According to Medina and Motta [81], comparing fatigue curves should only be conducted when mixtures exhibit similar stiffness or resilience modulus, since stiffer mixtures

“absorb” more stress, resulting in higher tensile stresses as well. Thus, for the same structure (thicknesses and materials of other layers), differences in MR in the pavement will lead to different stress difference values ($\Delta\sigma$).

Given that the RM of the Bailey mixture is approximately 22.9% higher than that of the conventional mixture, it indicates that the mixtures have different moduli. To better understand the fatigue behavior characteristics of these mixtures, a simulation of the design was performed using the Medina software (v 1.5.0) for an arbitrary pavement containing the studied mixtures of HMA with steel slag compared to conventional HMA from the city of Rio de Janeiro/RJ. This simulation can be verified in Section 4.7.

4.5. Influence of the Granulometric Method on Fatigue and Permanent Deformation

With the results of permanent deformation from the FN test and the regression parameters “b1” obtained from the fatigue curves of the mixtures, an analysis of the average effects and interactions among the variable “method” was conducted, guided by the factorial experimental design. This study was parameterized based on the reference variable (conventional method), as observed in Table 11.

Table 11. Comparison of methods for assessing susceptibility to stress state and average flow number effect.

Method	Susceptibility to Stress State	Percentage Over Reference	Average Effect Flow Number	Percentage Over Reference
Conventional	4.059		625	
Bailey	2.682	−34%	1316	110.6%

In relation to the average effects, it can be stated, according to Table 11, that the variation in granulometric composition is a factor that significantly influences the mixture’s resistance to permanent deformation and its susceptibility to fatigue life. Overall, the variation from the conventional granulometric method to the Bailey method resulted in a 110.6% increase in the FN.

Regarding its role in fatigue life, it appeared to be more predominant, albeit indicating sensitivity to fatigue through the slope of the curve represented by the parameter “b1”. The variation from the conventional granulometric method to the Bailey method made the mixture 34% less susceptible to stress conditions, meaning lower values of “b1” indicate less sensitivity of the mixture’s fatigue behavior to variations in stress difference.

These findings have practical implications for the design and durability of asphalt pavements. The increased FN observed with the Bailey method suggests a higher resistance to permanent deformation, which could lead to improved performance under heavy traffic loads and in regions subject to high temperatures. In contrast, the reduced sensitivity to fatigue in the Bailey method indicates that these mixtures may exhibit better long-term performance in terms of fatigue cracking, which is a critical consideration for the design of pavements in areas subjected to repeated traffic stresses. Therefore, the choice of granulometric method significantly impacts the durability and maintenance needs of asphalt pavements, influencing both the fatigue and deformation behavior of the mixture over time.

4.6. Evaluation of Freeze-Thaw Cycle Damage Resistance

Moisture damage in asphalt mixtures is intrinsically linked to the degradation of asphalt mastic and the interface between mastic and aggregate, with these effects being exacerbated under freeze-thaw cycles. The tensile strength of asphalt mixtures is influenced by various factors, such as aggregate properties, binder characteristics, and gradation; however, the behavior of the aggregate-binder interface is particularly critical [88].

In this study, mixtures produced using the Bailey method and the conventional method exhibited significant differences in the results of the moisture-induced damage test. The

Bailey method showed higher tensile strength in the conditioned state ($T_{Sh} = 0.55$ MPa) compared to the conventional method ($T_{Sh} = 0.32$ MPa), indicating better retention of strength after freeze-thaw cycles. Conversely, mixtures produced with the conventional method presented higher tensile strength in the dry state ($T_{So} = 1.06$ MPa vs. 0.88 MPa for the Bailey method), suggesting better initial performance, although this did not translate into improved durability. The TSR was significantly higher for the mixtures produced with the Bailey method (62.5%) compared to the conventional method (30.18%), highlighting greater stability against moisture-induced damage.

These findings align with the work of Guo et al. [89], who demonstrated that the steel slag content significantly influences the long-term water stability of asphalt mixtures. Their results suggest that an optimal steel slag content can enhance resistance to water-induced damage over extended periods. The incorporation of such materials contributes to the improvement of the aggregate-binder interface, supporting the superior performance observed in the mixtures designed using the Bailey method.

Overall, these results emphasize the effectiveness of the Bailey method in optimizing aggregate gradation, promoting better interlocking among particles, and ensuring a more uniform stress distribution within the asphalt matrix. Consequently, mixtures produced using the Bailey method exhibit a greater capacity to mitigate the progressive degradation caused by moisture, making it a more robust alternative for regions with adverse climatic conditions.

4.7. Mechanistic Analysis

As observed in Table 12, the characterization of each asphalt mixture in Medina's database shows a significant influence of gradation composition on the fatigue characteristics of the mixtures. Notably, M2 achieved a fatigue class of 4, indicating superior mechanical performance. In contrast, M1 and M0 exhibited fatigue classes of 1 and 2, respectively.

Table 12. Characteristics added to the Medina software for the analyzed mixtures.

Asphalt Concrete	RJ PAC 30/45 #12.5 mm Sepetiba Reference (M0)	Slag (Conventional Method) (M1)	Slag (Bailey Method) (M2)
Parameters			
Poisson's Ratio	0.30	0.30	0.30
Modulus (MPa)			
Constituent Model Modulus (MPa)	Linear Resilient 9000	Linear Resilient 8700	Linear Resilient 10,693
Characteristics			
Type of Binder (PAC)	30/45 - PG 70-16	30/45	30/45
Specific Gravity (g/cm^3)	2.4	2.766	2.792
Tensile Strength (MPa)	2.08	1.16	1.09
Asphalt Content (%)	6	8	6.5
Void Volume (%)	5	3.6	4.1
Gradation Size	#12.5 mm	#12.5 mm	#12.5 mm
Los Angeles Abrasion (%)	40	-	-
Standard or Specification	DNIT ES 31 [48]	DNIT ES 31 [48]	DNIT ES 31 [48]
Fatigue Curve			
Constituent Model	$K1 (\epsilon t^{k2})$	$K1 (\epsilon t^{k2})$	$K1 (\epsilon t^{k2})$
Regression Coefficient (k1)	5.00×10^{-14}	2.00×10^{-14}	7.00×10^{-8}
Regression Coefficient (k2)	-3.992	-4.059	-2.682
Fatigue Class	2	1	4
FFM	0.75	0.69	1.21

In Table 13, a summary of the designed structures for light, medium, and heavy traffic is presented, considering a 95% confidence level for the various mixtures evaluated in this study.

Table 13. Cracked area (CA), rut depth (RD), and thickness values of the pavements under analysis.

Light Traffic ($N = 9.96 \times 10^5$)			Layer Thickness			Total Thickness
Mixture	% CA	RD (mm)	Surface	Base	Sub-Base	
M0	12.3	6.3	5 cm	15 cm	15 cm	35 cm
M1	14.2	6.3	5 cm	15 cm	15 cm	35 cm
M2	5.2	6.1	5 cm	15 cm	15 cm	35 cm

Medium Traffic ($N = 5 \times 10^6$)			Layer Thickness			Total Thickness
Mixture	% CA	RD (mm)	Surface	Base	Sub-base	
M0	29.1	4.0	10 cm	15 cm	15 cm	40 cm
M1	26.3	3.6	11 cm	15 cm	15 cm	41 cm
M2	15.4	6.8	5 cm	15 cm	15 cm	35 cm

Heavy Traffic ($N = 5 \times 10^7$)			Layer Thickness			Total Thickness
Mixture	% CA	RD (mm)	Surface	Base	Sub-base	
M0	28.6	2.4	20.3 cm	20 cm	20 cm	63.0 cm
M1	28.5	2.2	22.1 cm	20 cm	20 cm	62.1 cm
M2	28.9	3.5	12.1 cm	15 cm	15 cm	42.1 cm

It is observed that, for the traffic level of $N = 9.96 \times 10^5$ (Light Traffic) with 95% reliability, the pavements had the same layer thicknesses. However, using the asphalt coating with the Bailey method, the pavement showed the best performance in terms of CA and RD, with 5.2% and 6.1 mm, respectively.

Considering a 95% reliability level and $N = 5 \times 10^6$ (Medium Traffic), the conventional mixture would require a 10 cm surface layer, and the slag mixture using the conventional method would need an 11 cm surface layer. Both showed similar performance in terms of the percentage of cracked area and rut depth. Meanwhile, the Bailey mixture would meet the same criteria with a 5 cm surface layer, presenting the lowest percentage of cracked area.

For the reliability level of 95% and $N = 5 \times 10^7$ (Heavy Traffic), the conventional mixture would meet the design criteria with a surface layer thickness of 20.3 cm and a Base + Sub-base of 40 cm; the slag mixture using the Trial method would need a surface layer thickness of 22.1 cm and a Base + Sub-base of 40 cm. Meanwhile, the Bailey mixture would require a 12.1 cm surface layer and a Base + Sub-base of 30 cm. Even with a lower final pavement thickness, the Bailey mixture demonstrated the best performance in terms of pavement CA and RD over the 10-year project analysis period.

In the hypothetical pavement evaluation conducted in this study, the Bailey-graded mixture demonstrated superior performance under varying traffic levels and reliability requirements, achieving lower cracked areas and rut depths with reduced surface layer thicknesses compared to conventional and conventional-graded slag mixtures. Similarly, Swathi et al. [71] highlighted the benefits of SSA in asphalt mixtures, noting that its high impact resistance and cubic shape contribute to reduced rutting potential and improved durability under heavy loads. These findings align with the improved performance observed in the Bailey mixture, which exhibited optimal structural efficiency, supporting its potential as a sustainable alternative for high-traffic pavements. Furthermore, Luan et al. [90] also observed that modifying the aggregate gradation can enhance the use of steel slag in asphalt mixtures. Their study, utilizing a modified Marshall mix design, showed that steel slag mixtures demonstrated superior rutting resistance and low-temperature crack resistance, particularly in stone matrix asphalt (SMA) mixtures. This supports the idea that adjusting gradation, similar to the Bailey method applied in this study, can optimize the use of alternative aggregates like slag, improving both mechanical properties and environmental sustainability of asphalt pavements.

5. Summary and Conclusions

This study aimed to evaluate the feasibility of reusing 100% steel slag aggregates in asphalt concrete, comparing the Bailey and conventional Brazilian gradation methods. Through laboratory testing and a simulation for a hypothetical section in Rio de Janeiro, Brazil, using the Medina software, the following conclusions were drawn:

- The mixture with steel slag produced using the conventional Brazilian method achieved a Resilient Modulus (RM) of 8700 MPa, while the mixture prepared with the Bailey method showed a significantly higher RM of 10,693 MPa. This indicates that the Bailey Method resulted in a stiffer mixture, which is expected to provide improved performance, especially under heavy traffic conditions. These findings highlight the effectiveness of the Bailey Method in enhancing the mechanical properties of steel slag-based asphalt mixtures, making it a promising approach for optimizing pavement design.
- The Bailey mixture under study showed better performance in terms of permanent deformation, with a 110.6% increase in the flow number (FN), making the mixture capable of withstanding extremely heavy traffic, according to the literature. Regarding fatigue life, the Bailey mixture achieved the best result, with a fatigue class of 4, while the conventional mixture obtained a fatigue class of 1.
- Comparing the application of the asphalt mixtures under study in the pavement structure and traffic levels presented, using the Medina software, the Bailey mixture showed the best performance in all analyses conducted. That is, for the same traffic level (light, medium, or heavy), confidence level (95%), and pavement structure from the research, the lowest final asphalt coating layer thicknesses, as well as the lowest overall pavement thicknesses, were obtained.
- In comparison to the control mixture, which contains only natural aggregates, the use of the Bailey method with 100% steel slag resulted in a reduction of up to 35% in the final pavement thickness.
- While this study primarily focused on the technical feasibility of using steel slag in asphalt mixtures, it is worth noting that reducing binder content and reusing steel slag can provide environmental and economic benefits, such as lower material costs and reduced greenhouse gas emissions. These aspects warrant further exploration in future research, including life cycle assessments and cost-benefit analyses.

This demonstrates that steel slag mixtures produced using the Bailey gradation selection method can have advantages in terms of improved fatigue life and permanent deformation, as well as the potential for reducing the binder content in these mixtures. Thus, it is suggested to increase research on gradation selection methods in mixtures with steel aggregates, as well as to study the behavior of these mixtures using the Superpave methodology.

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