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Dynamic semicircular bending testing for asphalt mixture fatigue evaluation

Ensaio semicircular bending dinâmico para avaliação da fadiga em misturas asfálticas

Karolayne Peres de Melo[1], **Jamilla Emi Sudo Lutif Teixeira**[2], **Lilian Ribeiro de Rezende**[1]

[1]Federal University of Goiás, Goiânia, Goiás, Brazil
[2]University of Nebraska–Lincoln, Lincoln, Nebraska, United States

Contact: karolaynepm@ufg.br, (KPM); jamilla.teixeira@unl.edu, (JESLT); lrezende@ufg.br, (LRR)

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ABSTRACT
Determining the fatigue life of asphalt mixtures is an important step in predicting the performance of flexible surface courses, and it is necessary to use laboratory tests that adequately represent the mechanisms that lead to the failure of mixtures due to fatigue. Currently, methods such as Indirect Tensile Test (IDT), Four-Point Beam Bending (4PB) and Direct Tension (DT) are used for this purpose. Due to their practicality and speed, static fracture tests such as Semi-Circular Bending (SCB) are also widely used, but they do not allow fatigue life to be determined. This study aims to investigate the viability of the dynamic SCB test as an alternative for obtaining fatigue life coefficients in order to optimize the analyses required for the mechanistic-empirical design of sidewalks. Initially, two systematic mappings were carried out to support the methodological decisions. Static and dynamic SCB tests and IDT fatigue tests were then carried out on two asphalt mixtures. The results were statistically compared to assess the agreement between the methods and indicated that, although there were differences in the fatigue curve coefficients obtained by the dynamic SCB and IDT tests, this was not statistically significant and both had similar fatigue performance ratings. This suggests that dynamic SCB tests are an interesting tool for evaluating fatigue and can optimize asphalt pavement design. The study highlights the importance of developing simplified and effective test methods to ensure sustainability, efficiency and safety in transportation infrastructure projects.

RESUMO
A determinação da vida de fadiga de misturas asfálticas é uma etapa importante para a previsão de desempenho de revestimentos flexíveis, sendo necessário empregar ensaios laboratoriais que representem adequadamente os mecanismos que levam à ruptura de misturas por fadiga. Atualmente, métodos como Tração Diametral à Tensão Controlada (IDT), Flexão em Viga Quatro Pontos (4PB) e Tração Direta (TD) são utilizados para esta finalidade. Devido à praticidade e rapidez, ensaios de fratura estáticos, como o Semi-Circular Bending também são amplamente utilizados, porém não permitem determinar a vida de fadiga. Este estudo objetiva investigar a viabilidade do ensaio SCB dinâmico como alternativa para obter os coeficientes de vida de fadiga de forma a otimizar as análises necessárias ao dimensionamento mecanístico-empírico de pavimentos. Inicialmente, foram realizados dois mapeamentos sistemáticos para respaldar as decisões metodológicas. Na sequência, foram realizados ensaios SCB estáticos e dinâmicos e ensaios de fadiga IDT em duas misturas asfálticas. Os resultados foram comparados estatisticamente para avaliar a concordância entre os métodos e indicaram que, embora houvesse diferenças nos coeficientes da curva de fadiga obtidos pelos ensaios dinâmicos SCB e IDT, ela não é estatisticamente significativa e ambos apresentaram classificações semelhantes quanto ao desempenho à fadiga. Isso sugere que os ensaios SCB dinâmicos são uma ferramenta interessante para avaliação da fadiga, podendo otimizar o dimensionamento de pavimentos. O estudo destaca a importância de desenvolver métodos de ensaio simplificados e eficazes para garantir sustentabilidade, eficiência e segurança nos projetos de infraestruturas de transporte.

1. INTRODUCTION

The implementation of fatigue tests to evaluate asphalt mixture cracking behavior is essential, as it indicates the asphalt mixture's response to repeated loads before failure. The main test outcomes include parameters such as the reduction in mixture's initial stiffness and fatigue life curve with stress or strain parameters. In Brazil asphalt mixture fatigue life is determined based on the diametral compression fatigue test, also known as indirect tensile test (IDT), according to ME - 183 (DNIT, 2018a).

In addition to the Brazilian standard, international guidelines for fatigue studies include TP 107-14 (AASHTO, 2018) for Direct Tension (DT) and T321-14 (AASHTO, 2017) for Four-Point Beam Bending (4PB). Outputs from DT, for example, are used to fit model parameters based on the Simplified Viscoelastic Continuum Damaged (S-VECD) theory, determining damage characteristic curves. The 4PB test provides a fatigue life curve similar to the IDT that can also be used to determine the samples' flexural stiffness. However, this test is more time consuming due to the need for specialized equipment to fabricate beam samples and the long test duration. Although SCB testing also requires specific equipment, the fabrication of 4PB specimens demands significantly larger saws and a different compaction process. Unlike SCB specimens, which can be compacted in SGC, 4PB specimens require compaction using roller compactors, which are considerably more expensive and need a larger amount of material and space. These factors make 4PB testing substantially more resource-intensive than SCB testing.

Fatigue life analysis generally reveals three distinct stages of material behavior, i.e., crack initiation, propagation, and final failure. Studies have explored the difference between the stress- or strain-controlled fatigue tests, highlighting the relationship between the damage observed under varying conditions (Medina and Motta, 2015). Additionally, in Brazil, Fritzen et al. (2019) advanced in fatigue life studies and proposed the Fatigue Factor of Asphalt Mixtures (FFM), which is derived from resilient modulus values and fatigue performance analysis based on Wöhler curves, providing an additional approach to assess the material's fatigue behavior.

Besides fatigue test protocols, static tests are commonly used to evaluate the cracking resistance of asphalt mixtures due to their practicality and shorter testing time. Many studies have reported a good correlation between index parameters obtained from static tests and the fatigue life of pavements (Ozer et al., 2018; Zhou et al., 2023). One of the most popular static tests to assess cracking resistance of asphalt mixtures is the Semi-Circular Bending (SCB) test, initially developed to study rock materials and has been widely used for asphalt mixture cracking assessment (Saha and Biligiri, 2016). Parameters like fracture energy and flexibility index are used as cracking indicators in current balance mix design (BMD) approaches. International standards such as EN 12697-44 (CEN, 2010), AASHTO TP 124 (AASHTO, 2016) and TP105 (AASHTO, 2013) have been created to standardize the SCB test and its applications have proved valuable in assessing the fatigue resistance of asphalt mixtures. Falchetto et al. (2018) used the static SCB test at low temperature to evaluate the fracture properties and strength of asphalt mixtures. The authors pointed out that the test accurately reflected the crack evolution in the mixtures and presented a strong correlation with the asphalt mixtures' performance. Similar results were found in other studies, such as Hu et al. (2022) and Radeef et al. (2021; 2022) for an intermediate temperature of 25 °C.

Furthermore, SCB test has easier protocol for sample manufacture, applicability to field samples, and good results' repeatability (Aragão et al., 2014; Gao et al., 2016; Saha and Biligiri, 2016). Studies have explored how different characteristics of asphalt mixtures, such as binder type, grain size and aggregate type, affect results (Li and Marasteanu, 2010; Freire et al., 2014; Godoi, 2017). Temperature and loading speed also affect the results, with lower temperatures causing higher peak loads (Chen, 2019).

Teixeira et al. (2023) proposed to adopt the dynamic SCB test to assess asphalt mixtures' fatigue strength. The authors found good correlations between the SCB and IDT results. The differences in fatigue life values were attributed to differences in geometry and energy dissipation mechanisms. Nonetheless, both tests were able to discriminate different fatigue responses, depending on aggregate type, which was one of the goals.

However, Teixeira et al. (2023) did not establish whether SCB results could reliably substitute IDT results for fatigue characterization. The main objective of the present study is to evaluate the viability of the dynamic SCB test as an alternative to the IDT for assessing asphalt mixtures' fatigue strength. This study advances the discussion by providing a more detailed statistical comparison between SCB and IDT, considering a broader dataset and different testing conditions. By addressing this gap, the research aims to assess the potential of SCB as a reliable alternative to IDT, contributing to a deeper understanding of the influence of test geometry and loading conditions on asphalt mixture performance.

2. RESEARCH OBJECTIVES AND SCOPE

The development of fatigue test protocols, investigating different test methods and their variations, is essential for advancing asphalt mixtures performance evaluation and creating more resilient pavement structures. In this sense, this study aims to evaluate the applicability of dynamic Semi-Circular Bending (SCB) testing as an alternative method for fatigue performance assessment of asphalt mixtures, in comparison to the standard Indirect Tensile Test (IDT) commonly used in Brazil. To achieve this main goal, the study is developed through the following specific objectives:

1) To conduct a systematic mapping to verify the state of the art regarding fatigue testing worldwide, to assess the most used tests and the best protocol to prepare the SCB samples.
2) To investigate the use of dynamic SCB tests for optimizing fatigue life determination. The dynamic SCB test protocol is further statistically compared with the standard IDT method, currently adopted in Brazil.
3) To verify the MeDiNa response in the pavement layer design when using the coefficients obtained from the dynamic SCB and its similarity or not to the layers designed using the IDT coefficients.

3. MATERIALS AND METHODS

3.1. Systematic mapping of literature

A systematic literature mapping was performed to identify the most used methods for determining the fatigue life of asphalt mixtures, as well as the methodologies for producing and cutting SCB specimens. At the end of this step, it was noted that a second in-depth mapping of the SCB tests would be necessary to satisfactorily identify the methodology used to obtain the samples. Both phases were structured using the PICOC methodology (Population, Intervention, Comparison, Results, Application) adapted from Wohlin et al. (2012) (Table 1).

Table 1: Description of the PICOC Components of the Systematic Mappings

Acronym	Definition	Description and application: Generalized Mapping	Description and application: Refined Mapping
P	Population	Journal articles in English or Portuguese found in the four databases cited that present the method for obtaining the fatigue curve of at least one asphalt mixture.	Journal articles in English or Portuguese found in the four databases cited that present the method for obtaining asphalt mixture specimens for the static or dynamic SCB test.
I	Intervention	Inclusion and exclusion criteria were defined, covering topics such as the focus of the study, the type of study and the level of detail of the methodology.	
C	Comparison	Not applicable.	
O	Outcomes	It was hoped to obtain a survey of fatigue life curve determination methods in the world.	It was hoped to obtain a survey of the methods used to obtain the asphalt mix samples.
C	Context	Determine which method is most widely used worldwide and nationally to justify the one used as a comparison in this research.	Determine which method is most used and justified and use it to base the methodology for cutting samples for SCB tests.

The mappings were refined using the search strings *("fatigue test" OR "fatigue analysis" OR "fatigue evaluation" OR "fatigue behavior") AND "asphalt mixtures" AND ("methodology" OR "protocol" OR "technique" OR "procedure")* for the generalized mapping and *(Semi-circular bending OR SCB) AND asphalt AND fatigue AND cracking* for the SCB-focused mapping. A time frame of five years (2020 to 2024) was used for the first search and two years (2022 to 2023) for the second. The search covered the Engineering Village, Science Direct, Scopus and Web of Science databases. The exported papers were analyzed using the online tool Parsif.al (2021) and spreadsheets were created in Microsoft Excel. The images relating to the search results were generated using codes written in the RStudio software (CRAN, 2024).

4. EXPERIMENTAL EVALUATION

4.1. Materials

For the experimental analysis, two asphalt mixtures were considered varying the binder type. They were previously designed by Silva (2022). To produce the studied mixtures, mica schist aggregates were used. The aggregate gradation for both mixtures was the same as defined by Silva (2022), using the Bailey and Dominant Aggregate Fractions (FAD) methodologies. Figure 1 shows the particle size distribution adopted.

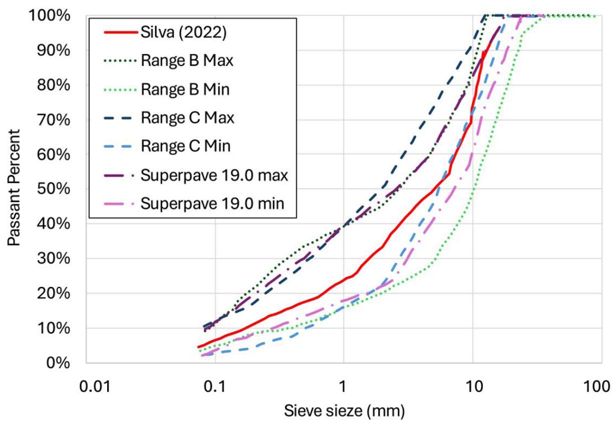

Figure 1. Aggregates grain size distribution curve [adapted from: Silva, 2022].

Two asphalt binders, CAP 50/70 and AMP 60/85-E, were used. Their PG classifications were previously determined as PG 64-XX and PG 70-XX, respectively (Curado, 2024; Miranda, Curado and Rezende, 2024). The volumetric parameters of the mixtures are shown in Table 2.

Table 2: Characteristics of the mixtures used for fatigue fatigue testing (Silva, 2022)

Misture	G_{mb} (g/cm³)	G_{mm} (g/cm³)	Binder Content (%)	AV (%)	VMA	VFA
SP4-CAP5070	2.45	2.57	4.5	4.1	14.4	72.3
SP4-AMP6085E	2.47	2.57	4.7	3.9	14.0	71.5

Note: Gmb = Bulk specific gravity of compacted mixture; Gmm = Maximum specific gravity of loose mixture; AV = Air voids; VMA = Voids in the mineral aggregate; VFA = Voids filled with asphalt.

4.2. Sample preparation

The specimens produced for IDT tests were compacted in the Superpave Gyratory Compactor (SGC) with 100 mm of diameter, approximately 64 mm of height, and 1200 g of mass, to meet the air void (AV) design. On the other hand, the SCB samples production was obtained by consolidating the results of the systematic mapping, the guidelines of the AASHTO TP 124 standard (AASHTO, 2016) and the most optimal use of the equipment available in the laboratory where the study was carried out. First of all, the SCB specimens were compacted in the SGC with a diameter of 150 mm and approximate 160 mm of height. Unlike the specimens for the IDT test, which were compacted to an AV design, the aim was to obtain samples with AV of 7% ± 0.5, as recommended by AASHTO TP 124 (AASHTO, 2016) for the static test. Next, the top and bottom of the specimens were removed, resulting in a 115 mm central cylinder with regularized and leveled faces. The cylinder was cut into two smaller cylinders with 50 mm of height, keeping the flat surfaces. Finally, each cylinder was cut into two semicircles. The last stage consisted of making a notch with a depth of 15 mm and a thickness of 1.5 mm. All the steps are shown in Figure 2.

During the process of preparation and cutting of specimens, several challenges were encountered. Initially, it was necessary to find a larger saw with a blade capable of cutting specimens with a 150 mm diameter. Additionally, a thinner blade – less than 1.5 mm thick – was required to create the 15 mm notch while maintaining sufficient strength and size. In both cases, the selected saws needed a water cooling system to preserve the integrity of the specimens during cutting.

Despite these precautions, some modifications were still required. To ensure that all the specimens were cut with the same dimensions in the used saws and that the surfaces were completely flat, various supports were designed and made on a 3D printer. A custom support was designed to allow the notch-cutting blade to pass freely through the entire specimen, preventing curvature in the notch (Figures 3e and 3f). Another set of supports was created to eliminate the need to rotate larger specimens in the large-scale saw, ensuring straight cuts (Figures 3a, 3b and 3c). Lastly, an additional support was developed to guarantee that every cut was of uniform size and that all specimen surfaces were completely flat (Figure 3d). In total, six models were manufactured, two of which were used for regularizing the base and top, one for cutting the cylinders, one for cutting the semicircles and two for making the notch.

4.3. IDT and SCB fatigue tests

The specimens were pre-conditioned at 25 °C for 4 hours for IDT and for 2 hours for SCB into the Universal Testing Machine (UTM), as recommended by the DNIT ME - 183 standard for IDT and the AASHTO TP 124 standard for SCB. Thus, the tests were carried out in accordance with

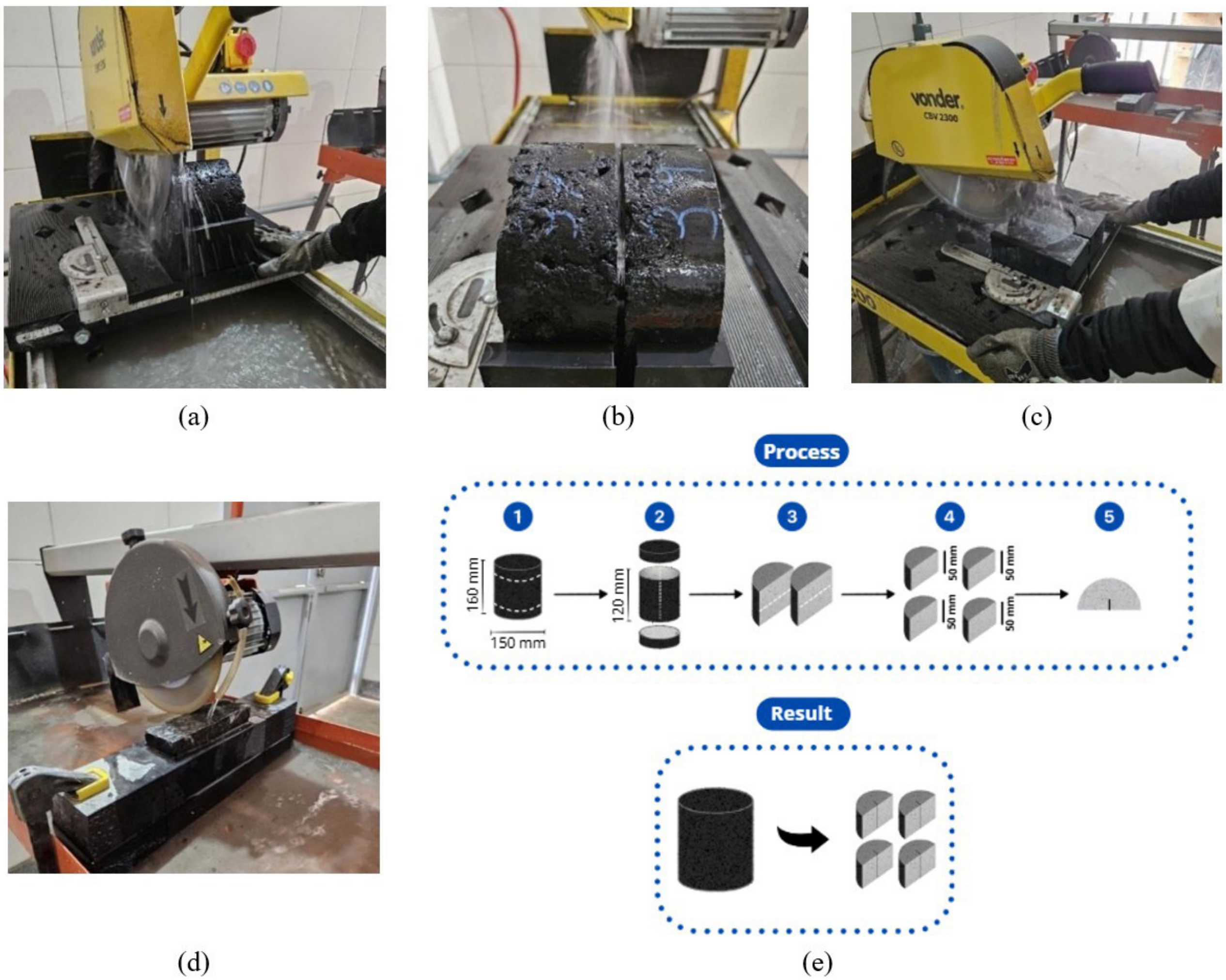

Figure 2. SCB sample cutting steps: (a) leveling of top and base; (b) cutting into cylinders; (c) cutting into semicircles; (d) notch cutting; (e) Cutting steps and sample preparation process.

IDT standard ME - 183 (DNIT, 2018a) and SCB static test TP 124 (AASHTO, 2016) with a loading rate of 50 mm/min. The dynamic SCB tests were carried out following the protocol adopted by Gao et al. (2016), Godoi (2017) e Teixeira et al. (2023). This consists of applying dynamic loading at a frequency of 10 Hz to the semicircular specimens until the maximum displacement of the static SCB test is reached, here considered to be the complete rupture of the specimen. The applied load consisted of 4 stresses, with the magnitude varying between 15% and 35% of the maximum strength found in the static test.

For the construction of the fatigue life curves, the resilient strain was obtained differently depending on the test method. In the case of the IDT tests, the resilient strain was calculated from the horizontal displacements measured by LVDT sensors fixed to the specimen, as required by the Brazilian standard DNIT ME - 183 (2018). These displacements were used to estimate the initial resilient strain in the horizontal direction at the center of the specimen, considering its geometry.

For the SCB dynamic tests, the resilient strain was indirectly estimated by assuming linear elastic behavior and uniform stress distribution in the region between the notch tip and the base of the specimen. The nominal tensile stress (σ_{max}) was calculated from the peak load (P_{max}) and specimen geometry using the Equation 1 below, which was adapted from AASHTO TP 124 (2016):

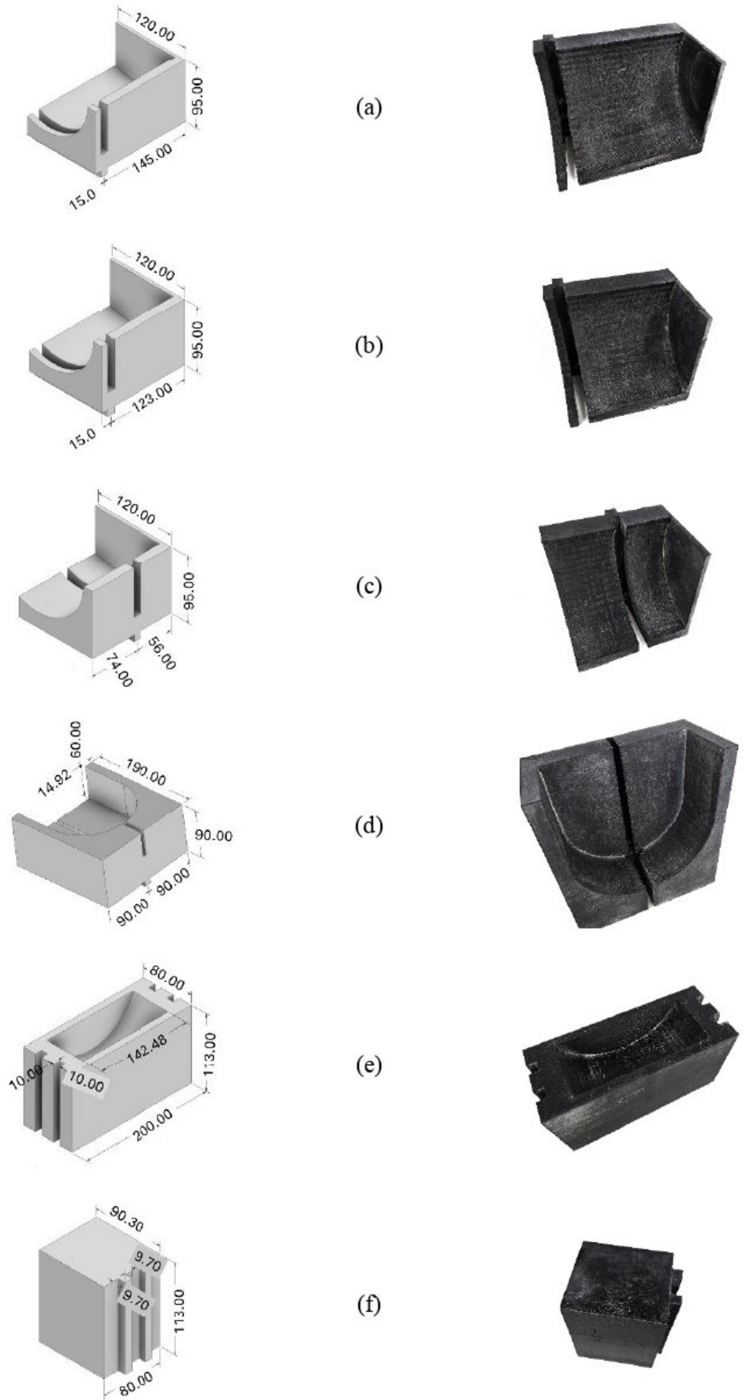

Figure 3. 3D designed supports (dimensions in millimeters): (a) and (b) support for cutting the ends; (c) support for cutting into circles; (d) support for cutting into semicircles; (e) module 1 of the support for notching; (f) module 2 of the support for notching.

$$\sigma_{max} = \frac{4.8 \cdot P_{max}}{D \cdot t} \quad (1)$$

where: σ_{max} is the nominal tensile stress (MPa); P_{max} is the peak load (N); D is the specimen diameter (mm); and t is the specimen thickness (mm).

The initial resilient modulus (MR) was obtained in a separate test following DNIT ME – 135 (DNIT, 2018b), using specimens compacted to the same air void content (7%) as those used in the SCB test. The tensile stress (σ_t) used in the calculation corresponded to the applied load in the dynamic test. The resilient strain (ε_i) was then estimated using the Equation 2:

$$\varepsilon_i = \frac{\sigma_t}{MR} \quad (2)$$

Where: ε_i is the initial resilient strain; σ_t is the tensile stress applied during the SCB dynamic loading (MPa); and MR is the resilient modulus of the asphalt mixture (MPa).

This method assumes that MR remains constant and does not account for damage accumulation during the test, which represents a limitation. It follows the procedure recommended by DNIT 183 for situations where direct measurement of resilient strain is not feasible, enabling comparison with the IDT-derived curves under similar assumptions.

The data was statistically analyzed using the RStudio software. The data normality was checked using the Shapiro-Wilk test. Next, analysis of variance (ANOVA) with a 95% confidence interval was applied to a range of data generated by the power regression of each fatigue life curve, considering the null hypothesis that there is no significant difference between the data. In other words, if the p-value is less than 0.05, this hypothesis should be rejected and the data should be considered significantly different.

4.4. Mechanistic-empirical evaluation using MeDiNa

After generating all the fatigue curves and, consequently, the k_1 and k_2 fatigue coefficients for each mixture and for each determination method, the MeDiNa software was applied to check the influence of the method used to obtain the coefficients on the structure designed. A main arterial system was considered, with a design period of 10 years and a total number of standard axle passes (N) of 6.85×10^7, considering severe traffic conditions.

The subgrade consists of a saprolitic soil, and the base layer is a tropical granular soil with a thickness of 15 cm. Both were previously studied by Freitas et al. (2020), Cavalcante (2022), and Lima et al. (2023). For the binder and the surface course were considered the mixtures investigated in this study and their thickness varied in the design process. The analysis in the software was carried out in two stages: the first consisted of dimensioning the thicknesses of the layers and the second in evaluating the performance of the structure generated in terms of crack area over time.

It is worth noting that the MeDiNa software was calibrated based on fatigue data obtained through the IDT method. Thus, results using fatigue parameters from other test types should be interpreted considering possible discrepancies and interference resulting from this calibration method.

5. RESULTS AND DISCUSSIONS

5.1. Systematic mappings

The study carried out in the four databases chosen for the systematic mappings initially returned 165 and 432 papers in English or Portuguese for the generalized and the refined searches, respectively. After removing duplicate documents, review papers, numerical simulation and papers with incomplete methodology or that did not provide the necessary information for this study, the number of papers selected for full reading was 58 in the first mapping and 39 in the second (Table 3).

Table 3: Papers selected for this study

	Generalized Mapping	Refined Mapping
Criterion	**Number**	
Obtained Results	+165	+432
Duplicates	-81	-309
Review papers	-3	-2
Inaccessible	-6	0
Numerical simulation	-2	-2
The focus of the article is not SCB	Not applicable	-80
No fatigue testing was conducted for the asphalt mixture	-13	Not applicable
The methodology for obtaining the fatigue curve is not described	-2	Not applicable
Complete reading	+58	+39

In addition, the Venn diagrams in Figures 4a and 4b show the number of adherent papers found in each database and those found in two or more databases. In both cases, the largest intersection is the one that encompasses all four databases, i.e., there is uniformity in the indexing of publications relevant to the object of study. Even so, the presence of single publications in most of the databases highlights the importance of a comprehensive approach to the literature review and the search for relevant papers to include as many significant publications as possible.

The reading of the 58 papers included in the first mapping showed that the search was successful in collecting information from four continents: Oceania; Central, South and North America; Europe and Asia. The papers presented 10 different methodologies for determining the fatigue life of asphalt mixtures, but when checking the predominance of tests by country, it was found that 4 of them are most widely (DT, 4PB, IDT and SCB), while the others 6 (2PB, 3PB, CPBFT, DWT, Overlay Test and Shear-torque) were cited only once or in less quantity than the others in the same region, as shown in Table 4. Figure 4 also shows 5 incidence maps relating to the 4 predominant tests. Figure 4c illustrates which test predominates in each country analyzed and the others show the percentage of how much each of the 4 tests was cited in each country.

The test used in most papers was 4PB (21), followed by IDT (14) and DT (13). The Dynamic SCB was used in 8 papers, mainly in China, but with 100% incidence in papers from Malaysia. IDT is widely used in South America, mainly in Brazil, Chile and Colombia, but it is also used in China and Iran. 4PB and DT are used with the same frequency in Australia, Brazil and France, with percentages varying between 20% and 50%. In China, Costa Rica, India, Iran, Iraq and Serbia, the use of 4PB stands out, while in the United States and Norway DT is more used.

This analysis might present some limitations because of the restricted number of papers available per country and test type. For example, French data indicate 2PB as common practice and DT as state-of-the-art. However, these findings derive from a small sample, and the sole 4PB mention relates to reinforced slabs, possibly reflecting practical applications, with comparable DT studies also identified. Therefore, these percentages should be considered with caution.

Thus, considering the Brazilian standard for fatigue life of asphalt mixtures (DNIT, 2018a) as the predominant use of IDT in Brazil and South America, the use of this as a comparative test with SCB in this study is justified.

Table 4: Details of the analyzed articles

Study	Country	Test	Study	Country	Test
Abhijith et al. (2023)	IND	4PB	Nguyen et al. (2021)	FRA	4PB
Adnan et al. (2024)	CHN	IDT	Oliveira et al. (2022)	BRA	DWT
Ahmed et al. (2020)	IRQ	2PB and 4PB	Orešković et al. (2024)	SRB	4PB
Alamnie et al. (2023)	NOR	DT	Radeef et al. (2021)	MYS	SCB
Alikhani and Latifi (2022)	IRN	4PB	Ragni et al. (2020)	ITA	Shear-torque
Bai (2024)	CHN	SCB	Ren et al. (2024)	CHN	SCB
Bai et al. (2022)	CHN	SCB	Saleh et al. (2020)	USA	DT
Barghabany et al. (2020)	USA	4PB	Seitllari and Kutay (2023a)	USA	3PB
Benaboud et al. (2021)	FRA	2PB	Seitllari and Kutay (2023b)	USA	3PB
Beyene et al. (2024)	USA	DT	Shan et al. (2022)	CHN	IDT
Bueno et al. (2022)	BRA	DT	Silva et al. (2024)	BRA	DT and IDT
Covilla-Varela et al. (2023)	COL	IDT	Su and Nikraz (2022)	AUS	4PB and DT
Cruz et al. (2022)	BRA	IDT	Valdés-Vidal et al. (2020)	CHL	IDT
Dong et al. (2021)	CHN	IDT	Wang et al. (2020)	CHN	IDT
Dyer et al. (2021)	BRA	4PB and IDT	Wei et al. (2023)	CHN	4PB
Elwardany et al. (2024)	USA	DT	Williams et al. (2024)	FRA	DT
Feng et al. (2021)	CHN	4PB	Xia et al. (2021)	CHN	DT and IDT
Guabiroba et al.(2023)	BRA	IDT	Xu et al. (2022)	CHN	SCB
Jeong et al. (2022)	USA	DT	Yang et al. (2023)	CHN	IDT
Jia et al. (2022)	CHN	DT	Ye et al. (2023)	CHN	4PB
Kabir et al. (2023)	USA	4PB	Zhang et al. (2022)	CHN	3PB
Keshavarzi and Kim (2020)	USA	DT	Zhang et al. (2020a)	CHN	4PB
Kuchiishi et al. (2023)	USA	DT	Zhang et al. (2020b)	CHN	4PB
Li et al. (2024)	CHN	CPBFT	Zhang et al. (2023)	CHN	4PB
Liang et al. (2022)	CHN	3PB, 4PB and IDT	Zhang et al. (2024a)	CHN	SCB
Liu et al. (2023)	CHN	4PB	Zheng et al. (2023)	CHN	4PB
Liu et al. (2020)	CHN	3PB	Zhu et al. (2022)	CHN	4PB
Lopes et al. (2021)	BRA	4PB	Zhu et al. (2020)	CHN	SCB
Mora Valverde et al. (2021)	CRI	4PB, Overlay Test and SCB	Ziari et al. (2021)	IRN	IDT

In the second mapping, the results showed that most of the studies used the SGC to produce the specimens, except only 2 studies that used Marshall compaction. The specimens' dimensions were not very uniform, with a predominance of 150 mm in diameter, while there was greater variation for heights. The execution of the notch also varied between the studies, especially in the work by Yao et al. (2023), which opted not to make notches and did not detail the justification or influence of this decision on the results obtained.

The papers' systematic analysis revealed a wide range of methodological approaches, reflecting a diversity of experimental techniques and field test parameters. On the other hand, there was a tendency for certain parameters, such as sample size and equipment, to be repeated in several studies, suggesting a consensus on the most suitable conditions for producing and cutting SCB samples.

Summarizing, the steps required to obtain asphalt mixture specimens for static or dynamic SCB tests were already illustrated in Figure 2e. The main difference in the methodology adopted in this study lies in the fact that, in the papers mapped, the larger cylinder was first sliced into semicircles, and then the height was reduced. This approach seems to consider the possibility that cutting the cylinder directly at a height of 50 mm could cause crushing or other alterations to the sample due to the saw type used. However, in this study, this problem was eliminated with the use of special supports as presented in Figure 3, which ensured the total integrity of the specimens throughout the cutting process.

5.2. Experimental assessment of fatigue behavior

Figures 5a and 5b show the obtained fatigue curves, and Figure 5c presents the representation of the mixtures based on FFM values. The slopes of the curves are similar, although there is a shift between the SCB and IDT curves, especially for the SP4-AMP6085E sample. The FFM values varied between 1.05 and 1.40, resulting in Class 4 identification for both mixtures studied. These values are similar to those obtained by Guabiroba et al. (2023) considering the IDT data for MB (Mica schist Bailey) and MCS (Mica schist Range C Superpave) mixtures, produced with the same aggregate and CAP 50/70.

Teixeira et al. (2023) used a similar approach to determine the fatigue curve with the Dynamic SCB test and compare it with the IDT, verifying the proximity of the two curves when plotted together, as shown in Figure 5d. The difference in the method used by these authors and the one used in this study is how the resilient strain was calculated. In this study, the calculation was made by using the resilient modulus value obtained from specimens with a void volume of 7%, like those used in the SCB tests, while in the aforementioned paper the calculation was made by using the resilient modulus with a void of 4%. Even so, both curves have slopes similar to those of the IDT and R^2 values above 0.8, which were also observed in this study. This finding corroborates with the hypothesis that the two tests used to obtain the fatigue life curves are comparable and that the dynamic SCB test can provide reliable curves.

In order to advance in the study and in the methods comparison, it is necessary to statistically analyze the variance of the fatigue coefficients, k_1 and k_2, obtained by IDT and SCB tests. Thus, after performed the Shapiro-Wilk test to confirm the normality of the data, ANOVA was carried out on a range of data varying in × from 1×10^{-5} to 1×10^{-3} with a step of 1×10^{-5}, which results in an analysis with 198 degrees of freedom (Df). Table 5 shows that the sum of the squares (Sum Sq) is close to 1×10^{-27} and the mean squares (Mean Sq) is 1×10^{-30} for both cases. It is also clear that the p-value is much higher than 0.05, which indicates that the two models are not statistically significantly different.

Other authors have used the SCB test to determine the fatigue life of asphalt mixtures (Mora Valverde et al., 2021; Radeef et al., 2021; Ren et al., 2024; Xu et al., 2022; Zhang et al., 2024b) and have focused on various factors, such as crack propagation, effect of the energy dissipation on fatigue life and the size of the notch on the variability of the results. There is a smaller number of studies that present the fatigue life curve in the same format as that presented in this study (Bai et al., 2022; Bai, 2024), and it should be noted that in these studies the R^2 obtained for all the fatigue life curves plotted was above 0.9. Thus, the test is replicable and the type of regression required to obtain the fatigue life coefficients provides a good fit of data and captures the trend of data variability.

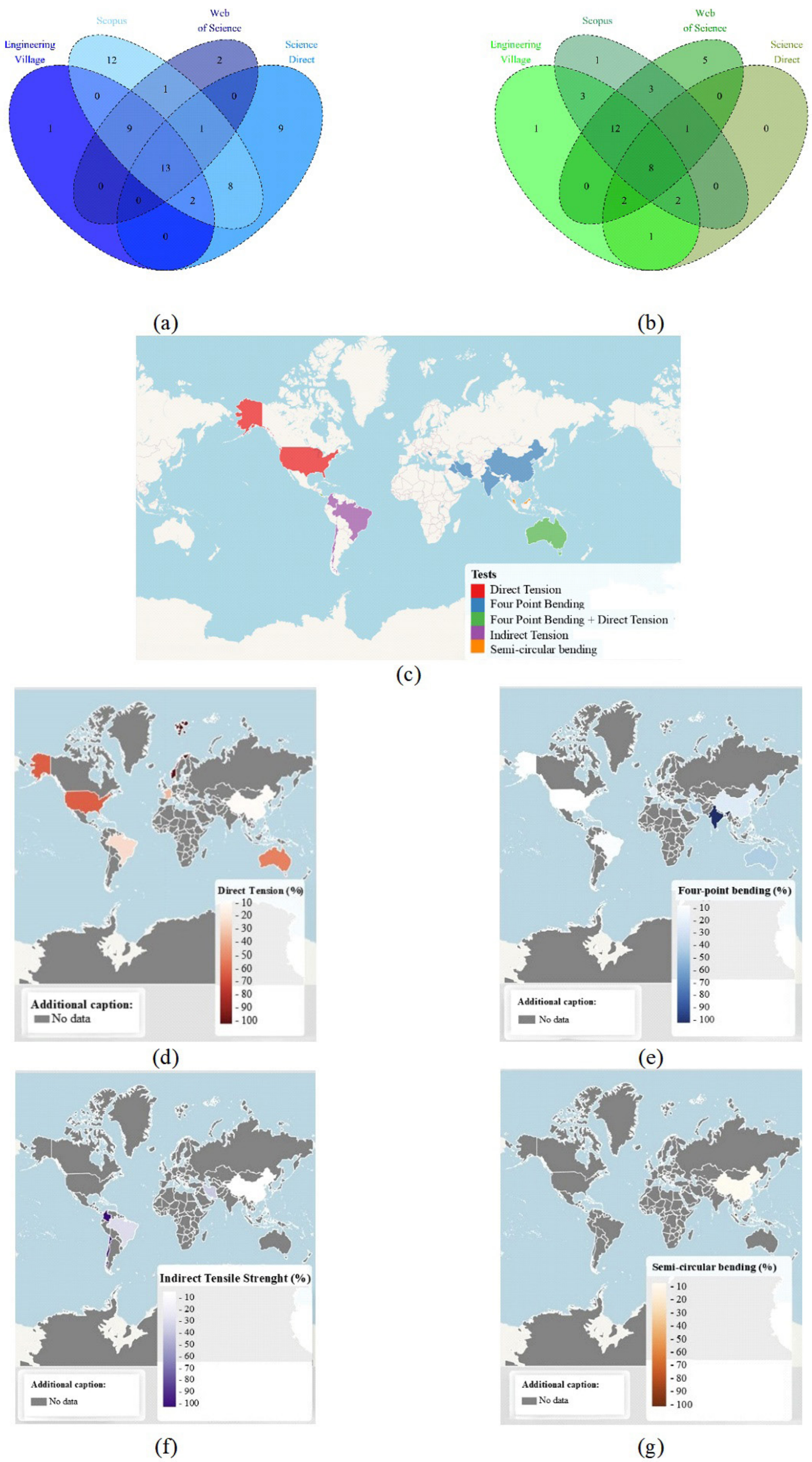

Figure 4. Systematic Mappings results: (a) Venn diagram of accepted papers - generalized mapping; (b) Venn diagram of accepted papers - refined mapping; (c) Predominant test in each country; (d) DT map; (e) 4PB map, (f) IDT map; (g) SCB map.

5.3. Mechanistic-empirical analysis

Table 6 and Figure 6 show a comparison of the structure design by varying only the asphalt concrete. When comparing the structure generated with the same material, but with k_1 and k_2 coefficients values altered to match each fatigue life curve test type, the thicknesses obtained for surface course with dynamic SCB data (SP4-CAP5070 SCB, AMP6085E SCB) were smaller than those obtained with IDT data (SP4-CAP5070 IDT, AMP6085E IDT). However, the magnitude of these differences is relatively small and, in some cases, the curves appear to be nearly superimposed (Figure 6b), suggesting that the practical impact on thickness design may be limited. This difference was more notable for the mixture with polymer modified asphalt binders (SP4-AMP6085E), which could potentially generate construction savings.

To explain the discrepancy observed in the thickness of the designed layers, it can be considered the fact that the MeDiNa software was calibrated with mixtures that had their fatigue life and class curves determined with data from the IDT, and not from the SCB test. Therefore, its lab-to-field transfer function is inherently dependent on this methodological choice. The use of different fatigue characterization methods, such as the SCB, introduces a source of inconsistency in the predictive capacity of the model.

At the same time, it should be noted that lower stress levels such as those used in the dynamic SCB generate greater precision in determining the slope of the fatigue curve (DNIT, 2020). This occurs because, when SCB specimens are used, it is possible to work with lower loading levels due to the shape of the sample, which generates a different loading distribution when compared to the sample used in IDT. In other words, while SCB may offer a more mechanically representative evaluation of fatigue, especially under low-stress conditions, the differences observed in this study's simulations between SCB and IDT results were smaller than initially expected. Therefore, the direct application of SCB-derived coefficients in MeDiNa simulations should be interpreted with caution, as the actual differences in pavement design parameters may be subtle.

Ideally, a new calibration of the transfer function would be required for SCB-based fatigue curves to maintain the consistency of predictions with field-observed performance. However, this study does not aim to change MeDiNa's modeling, but rather to investigate the implications of using fatigue parameters from different test types under the current calibration framework. This simulation exercise, therefore, provides valuable insight for ongoing discussions in Brazil on improving the reliability of mechanistic-empirical design by aligning test methods with field performance.

Another aspect that should be further evaluated is the fact that the most significant discrepancy was observed in the mixture with polymer modified asphalt binders. Considering that the IDT can indicate higher fatigue resistance results than those observed in the field, especially in mixtures with materials less susceptible to excessive creep (Medina and Motta, 2015; Oliveira et al., 2023), this may indicate that the IDT does not faithfully represent the fatigue in this type of mixture. To better understand the divergence between the obtained results, it is necessary to carry out studies with a greater number and types of mixtures.

Even so, when looking at the cracked area expected in the end-life pavement (Table 5 and Figure 6), the IDT and SCB results were similar. In general terms, the performance of the mixtures studied in this study surpasses those studied by Guabiroba et al. (2023), a fact that is explained by the better fit of the granulometric curves, the use of polymer modified asphalt binders and the improvement in adhesiveness by using lime in the mix design.

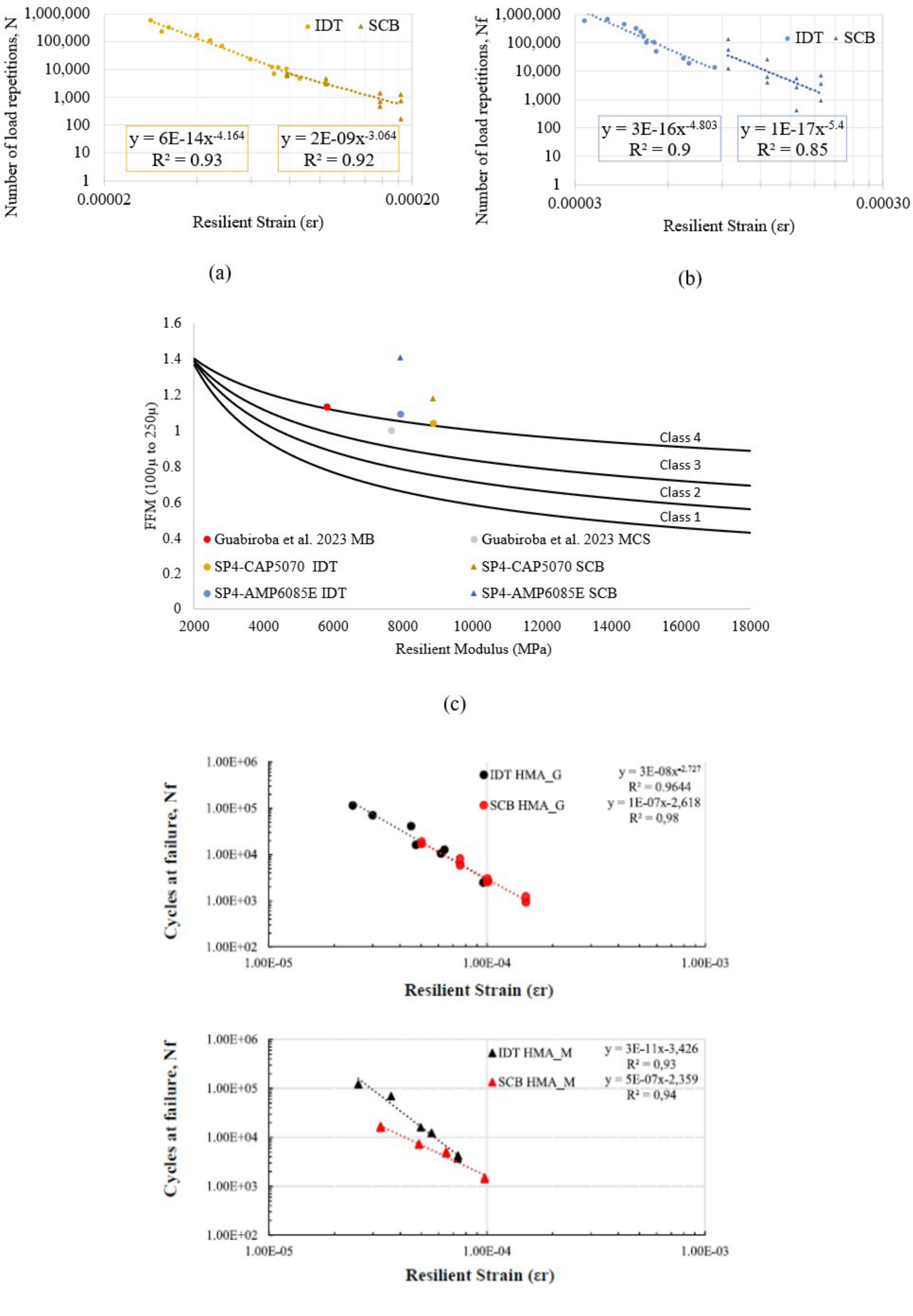

Figure 5. Fatigue curves: (a) SP4-CAP5070; (b) SP4-AMP6085E; (c) Representation of the mixture class regarding fatigue performance; (d) Comparison of fatigue curves [adapted from: Teixeira et al., 2023].

Table 5: Summary of ANOVA results

Mixture	Df	Sum Sq	Mean Sq	P-value
SP4-CAP5070	198	$1.705{\times}10^{-27}$	$8.609{\times}10^{-30}$	0.999
SP4-AMP6085E	198	$1.739{\times}10^{-27}$	$8.781{\times}10^{-30}$	0.999

Table 6: MeDiNa layers input data and structures designed for each asphalt mixture type

Layer	Input Data k_1 = 590.35 k_2 = 0.683 k_3 = 0.101			
Subgrade	k_1 = 590.35 k_2 = 0.683 k3 = 0.101			ψ_1 = 0.493 ψ_2 = −0.555 ψ_3 = 1.428 ψ_4 = 0.027
Base (15 cm)	k_1 = 476.32 k2 = 0.465 k3 = 0.103			ψ_1 = 0.098 ψ_2 = 0.873 ψ_3 = 1.650 ψ_4 = 0.098
Binder and Surface Course				
SP4-CAP5070 IDT	MR = 8869 MPa			k_1 = 6×10 {−14} k_2 = −4.164
SP4-CAP5070 SCB	MR = 8869 MPa			k_1 = 2×10 {−9} k_2 = −3.064
SP4-AMP6085E IDT	MR = 7930 MPa			k_1 =3×10 {−16} k_2 = −4.803
SP4-AMP6085E SCB	MR = 7930 MPa			k_1 =1×10 {−17} k_2 = −5.4
Guabiroba et al. (2023) MB	MR = 5805 MPa			k_1 =6×10 {−8} k_2 = −2.647
Guabiroba et al. (2023) MCS	MR = 7658 MPa			k_1 = 3×10 {−11} k_2 = −3.426
Mixture	**Design thicknesses (cm)**			**Crack area (%)**
	Binder	**Surface course**	**Total**	
SP4-CAP5070 IDT	10	11.2	21.2	28.2
SP4-CAP5070 SCB	10	10.4	20.4	28.3
SP4-AMP6085E IDT	10	10.7	20.7	28.1
SP4-AMP6085E SCB	10	6.0	16.0	29.2
Guabiroba et al. (2023) MB	15	13.2	28.2	28.7
Guabiroba et al. (2023) MCS	15	10.7	25.7	28.8

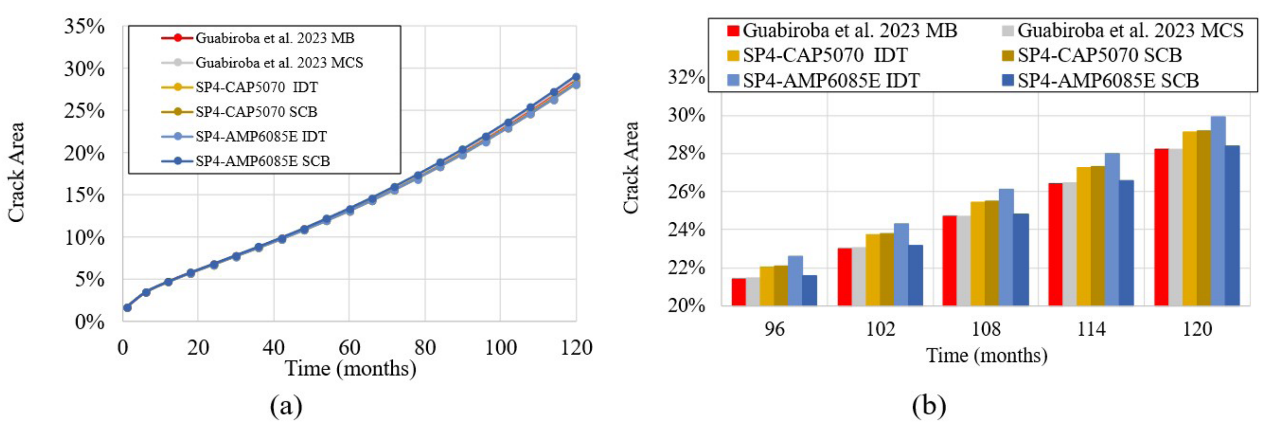

Figure 6. Mixtures' performance in terms of crack area: (a) whole period; (b) last 24 months.

6. CONCLUSIONS

This study has shown that dynamic Semi-Circular Bending (SCB) tests have potential as an alternative method for determining fatigue life coefficients in asphalt mixtures. For that, two systematic mappings were conducted to guide the methodology. Then, experimental evaluation of dynamic SCB and IDT tests was done and a statistical analysis was performed to evaluate the differences among fatigue model parameters obtained from both tests. Finally, the mechanistic-empirical approach using MeDiNa was carried out with the laboratory results. The main conclusions were drawn as follow:

- The systematic mappings point that in the region where this study was conducted, the IDT is the most commonly used test for determining fatigue life, and that around the world there is a preferred order to cut the SCB samples: first into semicircles and then by reducing their height.
- IDT and dynamic SCB tests showed similar fatigue curves slopes, but with a shift between the curves, particularly for the polymer modified asphalt binder mixture. Statistical analysis of the fatigue coefficients (k1 and k2) revealed minimal differences between the two methods which do not reject the hypothesis that the curves are similar.
- Despite these differences, both methods classified the mixtures in terms of fatigue performance as Class 4, and the mechanistic-empirical analysis indicates the same evolution for crack area.
- In the MeDiNa software design, the SCB-derived coefficients resulted in less thickness for the surface course compared to the IDT-derived coefficients, especially for mixture with polymer modified asphalt binder, probably because of differences on the loading distribution that occur in SCB and IDT specimens tests, and also the concern that IDT test can indicate higher fatigue strength results than those observed in the field.

To really implement SCB testing as a reliable alternative for determining fatigue life, future studies should focus on developing suitable safety or factors for the SCB-derived coefficients, carrying out additional validation studies with different types of mix, and investigating the relationship between sample geometry and test results. This study has contributed to the advancement of mechanistic-empirical asphalt pavement design by investigating an innovative testing methodology that can potentially optimize laboratory protocols while maintaining accuracy in fatigue life prediction. The results support the continued development of simplified but effective testing methodologies for the design of durable and cost-effective pavement structures.

AUTHORS' CONTRIBUTIONS

KPM: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing; JESLT: Conceptualization, Supervision, Visualization, Writing – original draft, Writing – review & editing; LRR: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

CONFLICTS OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

USE OF ARTIFICIAL INTELLIGENCE-ASSISTED TECHNOLOGY

The DeepL tool was used to assist in the translation of the manuscript into English , which was verified and approved by all authors. ChatGPT was used to support the creation of RStudio code for plot generation. The plots created with this code were verified by all authors. The authors assume responsibility for all content generated with the assistance of these technologies.

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