




Using a hybrid multi-criteria analysis method to classify hot mix asphalt regarding permanent deformation

Uso de método de análise multicritério híbrido para classificação de misturas asfálticas a quente quanto à deformação permanente

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ABSTRACT

The new Brazilian pavement design method (MeDiNa) defines the Flow Number as an indicator of permanent deformation of asphalt mixtures, which is adapted to traffic by trial and error, as there is no established combination of parameters in the literature for its prediction. In this sense, multi-criteria decision-making support methodologies can help improve the mix composition process by simultaneously combining simplified indicators. Therefore, this study used a hybrid multi-criteria method (SMART and TOPSIS) to classify asphalt mixtures by combining parameters obtained in the design of these materials, comparing them with the ranking found by Flow Number. Based on the relative importance assigned by a panel of experts, it was found that it is possible to obtain a ranking statistically similar to that of Flow Number using only data from softening point and viscosity of the binder, granulometric range, shape index of the aggregate fraction #3/4 and binder content. The method is more effective for traffic of less than $6.8E+07$ repetitions of standard axis under normal conditions. Therefore, the research has shown that it is feasible to simplify the design of mixtures for surfacing flexible pavements by filtering out the mixtures sent for more laborious tests such as Flow Number, limiting the number of tests to only the best-placed test mixtures. It also makes it possible to rationalize the design of low-traffic roads where there are no resources to carry out the test proposed by MeDiNa, helping designers to make decisions based on simplified indicators.

RESUMO

O novo método de dimensionamento de pavimentos brasileiro (MeDiNa) define o Flow Number como indicador de deformação permanente das misturas asfálticas, cuja adequação ao tráfego é realizada por tentativa e erro, pois não há estabelecido na literatura uma combinação de parâmetros para sua previsão. Nesse sentido, metodologias multicritério de apoio à tomada de decisão podem auxiliar na otimização do processo de composição das misturas pela combinação simultânea de indicadores simplificados. Assim, este trabalho utilizou um método multicritério híbrido (SMART e TOPSIS) para classificar misturas asfálticas pela combinação de parâmetros obtidos na concepção desses materiais, comparando com o ranking encontrado pelo Flow Number. A partir das importâncias relativas atribuídas por um painel de especialistas, verificou-se que é possível obter um ranking estatisticamente semelhante ao do Flow Number apenas com dados de ponto de amolecimento e viscosidade do ligante, faixa granulométrica, índice de forma da fração #3/4 do agregado e teor de ligante. O método é mais eficaz para tráfegos inferiores a $6,8E+07$ repetições do eixo-padrão em condições normais. Portanto, a pesquisa mostrou viabilidade para simplificação do projeto de misturas para o revestimento de pavimentos flexíveis, por filtrar as misturas encaminhadas para testes mais laboriosos como o Flow Number, limitando o número de ensaios apenas às misturas-teste mais bem colocadas. Além disso, possibilita a racionalização do projeto de vias de baixo tráfego em que não haja recurso para execução do ensaio proposto pelo MeDiNa, auxiliando projetistas na tomada de decisão a partir de indicadores simplificados.

1. INTRODUCTION

Permanent deformation in flexible pavements is a phenomenon closely linked to the quality of the asphalt mix used. The occurrence of plastic rutting, in addition to impairing rolling comfort for users, can compromise safety due to the accumulation of water (Balbo, 2007; Papagiannakis and Masad, 2008). Therefore, it is imperative to adapt the asphalt mixture to the traffic and climate expected for the planned road, and this selection is currently carried out by the new Brazilian pavement design method (MeDiNa) using the Flow Number (FN) parameter from uniaxial cyclic repeated load test (DNIT, 2018).

The design of an asphalt mixture involves the use and composition of materials with satisfactory properties, in order to avoid some pathological manifestations (Yoder and Witczak, 1975; Medina and Motta, 2015). In addition, suitable designs, from material selection to mix design, increase the likelihood that they will achieve good performance levels in permanent deformation damage tests, and should be chosen according to the intended project (Bernucci et al., 2022; Balbo, 2007). Thus, controlling a small set of properties may help to predict the behavior observed by FN, avoiding successive errors in the planning of asphalt mixtures.

The adoption of scientific multiple criteria (based on the use of decision support methodologies) in the evaluation or ordering of alternatives in the paving scenario, and in the selection of asphalt materials, can already be found in the literature (Dell'Acqua et al., 2012; Moretti et al., 2013; Noori et al., 2014; Iwański et al., 2016; Santos et al., 2017; Torres-Machi et al., 2019; Nizamuddin et al., 2021; Rassafi et al., 2021), and few studies use hybrid techniques, i.e. using one technique for weighing criteria and a different one for assessing (ordering, selecting or classifying) alternatives (Jato-Espino et al., 2018; Gupta et al., 2021; Alharbi et al., 2022; Ismael et al., 2023). Notwithstanding this, no studies were observed in the literature using hybrid multi-criteria techniques to rank asphalt mixtures in terms of permanent deformation. Bearing in mind the need to improve the design process of asphalt mixtures in relation to this failure mechanism, it is interesting to apply rational support methodologies to identify whether a combination of indicators can predict the ranking of asphalt mixtures using uniaxial cyclic repeated load test.

Thus, given the growing need to enhance the design process of flexible pavements, especially in contexts with limited resources and time, it is crucial to develop a simplified preliminary methodology for selecting asphalt mixtures based on permanent deformation, one of the main distresses observed on highways. In asphalt mixture design, decision-support methods can address multi-criteria problems using simplified parameters, particularly for permanent deformation, as it is closely linked to pavement surface properties.

This type of decision is also based on the principles of data science, already widely mentioned in the literature for solving a range of engineering problems (Magalhães and Oliveira, 2020; Becker et al., 2021; Damirchilo et al., 2021; Grimm and Brito, 2022; Okte and Al-Qadi, 2022; AzariJafari et al., 2023; Ding et al., 2023; Mansour et al., 2023). The structured organization and analysis of data can guide decisions in the paving sector with reasonable reliability when a large amount of information is used.

On the other hand, scientific research produced by specialized working groups, especially in universities, can generate extensive amounts of data. Structuring and modeling this information allows researchers, industry and public management to gain new insights into the study topic and have their decisions guided by technical and scientific criteria. Therefore, the aim of this study is to rank hot-mix asphalt mixtures produced in the field and in laboratory in Rio Grande do Sul (southern Brazil) in terms of their behavior to permanent deformation, by using a hybrid multi-

criteria method to a combination of different indicators. Moreover, the study tests if the hierarchy obtained is similar to the ranking by FN parameter.

It is relevant to highlight the advantage of employing a hybrid decision-making approach, demonstrated by the integration of SMART (Simple Multi-Attribute Rating Technique) and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) in this study. TOPSIS is a robust and widely recognized ranking technique within the American school of thought (complete aggregation methods). However, its effectiveness is strongly influenced by the reliability of the input weights, which can be a limitation due to the potential subjectivity involved in their determination.

To address this issue, the weights were derived using the SMART method, which is also a compensatory technique within the same methodological family. SMART is known for its simplicity and effectiveness, and its application in this study was enhanced through consultation with a panel of experts. This integration reduces the subjectivity of the assigned weights and ensures a more balanced and reliable decision-making process. It not only streamlines the mixture selection approach but also supports more informed decisions at early design stages, reducing the number of mixtures subjected to more time-consuming and costly tests like the Flow Number.

Since the selection of asphalt mixtures regarding permanent deformation is imperative for the performance and safety of roads, the application of the hybrid method proposed in this study aims to verify whether it is possible to rank asphalt mixtures for permanent deformation based on simplified indicators naturally obtained by design phase, without having to subject all the test mixtures to the FN test, so that the mix composition during the asphalt surfacing design becomes less laborious. As Meroni et al. (2021) point out, it is important to combine the different testing levels in the design of asphalt mixtures, since simplified tests are advantageous due to their low cost and execution time, and robust and fundamentalist tests are more reliable due to their better correlation with the field. In addition, the research aims to advance the application of multi-criteria decision methodologies in the paving context, allowing for the rationalization and assertiveness of road projects.

2. THEORETICAL BACKGROUND

Paving can benefit greatly from data science. Several research projects, based on the data naturally collected in scientific studies, have used analysis, modeling and even machine learning techniques to solve a wide variety of engineering problems.

In this sense, data science can help, for example, in evaluating functional conditions of roads (Damirchilo et al., 2021; Magalhães and Oliveira, 2020), and propose less expensive methodologies; in verifying the real load conditions of commercial vehicles traveling on pavements (Grimm and Brito, 2022); in creating tools for predicting the performance of asphalt concretes in field (Mansour et al., 2023); in analyzing repeatability and reproducibility of laboratory tests (Ding et al., 2023); in searching for more sustainable paving solutions, with reduced carbon emissions (Azarijafari et al., 2023); in assessing the impact of different types of vehicles on flexible pavement design (Okte and Al-Qadi, 2022), among others. The literature is vast in this area, but there is still room for the application of data analysis tools for other purposes.

2.1. Indicators that influence the permanent deformation of asphalt mixtures

The selection of asphalt mixtures by MeDiNa, based on the FN indicator, takes into account the characterization of these materials by the uniaxial repeated load test (DNIT, 2023). The method recommends a minimum number of cycles to be achieved for each traffic level or condition.

The design of a hot-mix asphalt mixture that meets the criteria established by MeDiNa depends on the adjustment of a series of indicators, ranging from selection of the materials used to the combination between them (Bernucci et al., 2022). From this perspective, it should be noted that the input selection is deeply conditioned by the region where the construction site will be located, and it is up to the designer to adjust other characteristics to fit the material into minimum project requirements.

The National Department of Transport Infrastructure (DNIT), through its service specification for asphalt concrete (DNIT, 2006a), defines minimum requirements to be met. In addition to general provisions, such as acceptable climatic conditions for execution and the need for certification of asphalt binders received at the plant, the regulation establishes that the binders must meet the pertinent material specifications (i.e., DNIT, 2006b, 2009, 2011, 2013).

Regarding aggregates, DNIT also demands minimum values for shape index and sand equivalent; maximum values for wear by Los Angeles abrasion and durability loss; and satisfactory results for adhesion to the asphalt binder. The aggregate combination must fall within one of the ranges standardized by the same specification. Finally, with regard to asphalt mix design, the standard defines acceptable ranges for voids percentage and bitumen/voids ratio, as well as minimum limits for mix stability, static diametral compressive tensile strength and mineral aggregate voids. All these parameters must be controlled when designing the asphalt mix, but the specification does not guarantee a certain Flow Number level by controlling these indicators.

There are other indices mentioned in scientific studies that can influence the permanent deformation (PD) of asphalt mixtures, described in Table 1 (Almeida Jr., 2016; Boeira, 2018; Chkaiban et al., 2022; Domingos et al., 2017; Ferreira et al., 2020; Gomes et al., 2021; Schuster et al., 2023). The desirable variation direction of these characteristics when dealing with PD, and references to scientific studies, are also presented in Table 1.

Table 1: Indicators that influence the permanent deformation (PD) of mixtures

Indicator	Desirable direction for PD	Indicator type	References
Softening point	Greater	Quantitative maximizing	(Domingos et al., 2017; Gomes et al., 2021)
Brookfield viscosity at 135 °C	Greater	Quantitative maximizing	(Ferreira et al., 2020; Gomes et al., 2021)
Granulometric range	Thicker	Qualitative maximizing	(Almeida Jr., 2016; Boeira 2018)
Shape index #3/4	Greater	Quantitative maximizing	(Schuster et al., 2023)
Binder content	Lower	Quantitative minimizing	(Almeida Jr., 2016; Chkaiban et al., 2022)

The properties of asphalt binders are pointed out as relevant in this regard, such as softening point and Brookfield rotational viscosity, which are indicators that can be easily obtained from reports of these materials. Other mixture characteristics can also alter the result of uniaxial cyclic repeated load tests. Examples include the granulometric range and shape index of the #3/4 aggregate fraction and the binder content, which are also easily obtained during the process of selecting materials and designing the asphalt mix.

2.2. Decision support methodologies applied to paving

Decision-making involves choosing one or more alternatives to solve a problem, either directly or indirectly (Gomes, 2007). Rational decision support methods apply to various fields, including humanities and engineering, and are categorized into mono-criteria or multi-criteria methods. Multi-criteria methods can be either discrete or continuous. Multi-criteria methodologies are useful in engineering because of the common presence of conflicting evaluation attributes (Gomes and Gomes, 2014). While no single solution exists, decision-makers' preferences are crucial in selecting the most suitable alternative.

Decision support techniques enhance choices in asphalt paving and address various technical issues. Studies employ hybrid multi-criteria and fuzzy methods, such as the multilayer dual hesitant fuzzy weighted zero inconsistency (DH-FWZIC) method and dual hesitant fuzzy decision by opinion score method (DH-FDOSM) to evaluate pavement sustainability (Ismael et al. 2023). Other research uses concordance analysis (CA) for the improved selection of asphalt mixtures, including reinforcements like rubber powder and carbon fibers, or for decisions on paving low-traffic roads (Dell'Acqua et al., 2012; Gupta et al., 2021; Rassafi et al., 2021).

Delphi methods associated with techniques such as evaluation based on distance from average solution (EDAS), ordering of the preference by similarity to ideal solution (TOPSIS) and weighted aggregated sum product assessment (WASPAS) are also used to assess additives for porous mixtures, considering mechanical, hydraulic, economic, and environmental criteria (Gupta et al., 2021).

Hybrid techniques, including expert panels and methods like AHP (Analytic Hierarchy Process) and TOPSIS, are useful for selecting wearing course mixtures for high-traffic roads (Jato-Espino et al., 2018). TOPSIS has also been applied to evaluate various road construction and maintenance scenarios (Santos et al., 2017).

Several techniques assess the environmental impact of various asphalt mixtures (Moretti et al., 2013). Harrington's multi-criteria technique, using a utility function, has been applied to improve cold recycled asphalt mixtures with gabbro rock dust and foamed bitumen (Iwański et al., 2016).

In addition, comparisons between sustainable maintenance techniques, such as cold in situ recycling, and conventional alternatives (milling and applying a new asphalt layer) have also been identified in the literature, using different techniques such as VIKOR fuzzy (Alharbi et al., 2022) or the AHP itself and the choosing by advantages (CBA) technique (Torres-Machi et al., 2019), by evaluating criteria such as economic, environmental and social. In summary, the use of multi-criteria decision-making methodologies is increasing in paving, highlighting the need to consider multiple parameters when tackling more complex challenges. Even so, the application field for these methodologies is vast, and different combinations of selection, ordering, classification or description techniques can be explored.

From the literature presented, it is clear that decision support methodologies are contributing to solving engineering problems. However, there are still no studies that use the hybrid method of this paper (SMART+TOPSIS) to rank hot-mix asphalt mixtures in relation to permanent deformation. Therefore, it is hoped that this research may contribute to the design and selection of asphalt mixtures for pavement surfacing.

3. MATERIALS AND METHODS

3.1. Characterization of asphalt binders and mixtures to obtain the indicators

The research data consists of a database with 178 hot-mix asphalt mixtures produced in the field and in a laboratory from Rio Grande do Sul, Brazil. Literature correlations between indicators and the FN parameter guided the selection of parameters for ranking mixes based on permanent deformation (Almeida Jr., 2016; Boeira, 2018; Chkaiban et al., 2022; Domingos et al., 2017; Ferreira et al., 2020; Gomes et al., 2021; Nunes-Ramos, 2023; Schuster et al., 2023). The selected characteristics are binder content, granulometric range, softening point, Brookfield viscosity at 135 °C, and shape index #3/4 (Table 1).

The softening point and Brookfield viscosity at 135 °C are standard for characterizing asphalt binders, as per Brazilian regulations. The softening point, determined by the Ring and Ball test, is the maximum temperature a binder can support a standardized sphere (DNIT, 2010), and viscosity measures the torque needed to rotate a spindle in the binder at a given speed (ABNT, 2021). Higher values are preferred for better permanent deformation performance.

The granulometry of mixtures in the database (DNIT, 2019) is identified by one of the DNIT or DAER/RS ranges (Autonomous Highway Department of Rio Grande do Sul) (DNIT, 2006a; DAER RS, 1998). In addition, some mixtures fall within the DERSA - Road Development (DERSA, 2005) ranges specific company ranges like EGL-19 and BN25-D ranges. These ranges determine aggregate size distribution, affecting whether mixtures are coarser or finer. For permanent deformation, mixtures with larger aggregates generally perform better when other indicators are fixed.

The shape index of the #3/4 aggregate fraction is measured using rectangular reducing sieves (DNIT, 2020). Higher values are preferred, indicating more cubic aggregates with better interlocking and mechanical resistance. Binder content is the percentage of binder relative to the mixture's mass, which is determined after batching (Marshall – DNER, 1995 - or Superpave – AASHTO, 2022). Lower binder contents generally lead to better performance regarding permanent deformation.

Other factors influencing permanent deformation include voids in mineral aggregate (VMA), aggregate texture, Los Angeles abrasion, and the filler/bitumen ratio. However, using too many parameters could complicate the differentiation between them. Multi-criteria decision-making methods use weighing factors to address this, as discussed in section 3.2, though variations may be minimal. The study focused on parameters with the greatest impact on PD, based on literature correlations. Table 1 lists the selected indices, their nature (qualitative or quantitative), and their preferred direction of variation regarding PD (maximizing or minimizing).

3.2. Hybrid multi-criteria analysis method for classifying asphalt mixtures

The quantitative modeling conducted in this research is classified by Bertrand and Fransoo (2002) as empirical, as it focuses on real-world data and observations to validate the application of theoretical models to practical engineering problems. Also, according to the authors, this work can be classified as normative, as it uses knowledge about permanent deformation generated in descriptive research to recommend a new strategy to speed up the selection of asphalt mixtures. Thus, it develops strategies to improve current situations.

The study's methodology followed Becker et al. (2021), using the TOPSIS method to rank asphalt mixtures based on similarity to an ideal solution (Hwang and Yoon, 1981). The similarity ratio ($S_{TOPSISj}$) (Equation 1) is calculated using the weighted Euclidean distance between each alternative

from the positive ideal solution (D_j^+) (Equation 2), and the negative ideal solution (D_j^-) (Equation 4). The ideal solutions are constructed from normalized and weighted criteria values among all the alternatives evaluated. For the positive ideal solution (PIS), the maximum value is used for maximizing criteria and the minimum for minimizing criteria (Equation 3). The negative ideal solution (NIS) uses the least desirable results for each criterion (Equation 5). In this study, four criteria are maximizing indicators, and only binder content is minimizing.

$$S_{TOPSIS\ j} = \frac{D_j^-}{D_j^+ + D_j^-} \quad (1)$$

$$D_j^+ = \sqrt{\sum_{i=1}^n (PIS - y_{ij})^2}, j = 1, \dots, m \quad (2)$$

$$PIS = \{\max y_{ij} (i = 1, \dots, n), \text{if criterion } i \text{ is maximizing}, \min y_{ij} (i = 1, \dots, n), \text{if criterion } i \text{ is minimizing}\} \quad (3)$$

$$D_j^- = \sqrt{\sum_{i=1}^n (NIS - y_{ij})^2}, j = 1, \dots, m \quad (4)$$

$$NIS = \{\min y_{ij} (i = 1, \dots, n), \text{if criterion } i \text{ is maximizing}, \max y_{ij} (i = 1, \dots, n), \text{if criterion } i \text{ is minimizing}\} \quad (5)$$

where $S_{TOPSIS\ j}$: similarity ratio to the ideal of alternative j ;

D_j^+ : distance of normalized and weighted performances to the positive ideal solution;

D_j^- : distance of normalized and weighted performances to the negative ideal solution;

PIS: positive ideal solution;

NIS: negative ideal solution;

$i = 1, \dots, n$: criteria;

$j = 1, \dots, m$: alternatives;

y_{ij} : normalized and weighted value of alternative j in relation to criterion i , obtained as $y_{ij} = w_i * x_{ij}'$, with w_i being the weight of criterion i , and x_{ij}' the normalized evaluation of the alternative j regarding the criterion i .

Before sorting, the technique requires normalizing the evaluation matrix x_{ij} . Thus, qualitative indicators, like granulometric range, were converted into numerical values. Mixtures were categorized into DNIT, DAER/RS, DERSA ranges, and company specifications (EGL-19, BN25-D). Values from 3 to 7 were assigned, with 3 for the thinnest range (DAER range A) and 7 for the thickest (BN25-D range). Values starting with 1 were avoided to prevent analysis distortion, as class 2 ranges would not necessarily be 2 times thicker than class 1 ranges. Similar ranges received the same value: 4 for ranges C DNIT, III DERSA, and B DAER, 5 for C DAER and EGL-19, and 6 for B DNIT. Class 7 is the most desirable for mitigating permanent deformation.

The weights (w_i) for each criterion were determined using the Simple Multi-Attribute Rating Technique (SMART), chosen for its simplicity and compensatory nature (Edwards, 1977). The compensatory nature of the SMART method allows not only for the determination of the relative importance of each criterion but also for the identification of trade-offs between them. In this way, poor performance in one criterion can be offset by strong performance in another,

which aligns with the ongoing balance between the properties of asphalt mixtures concerning their permanent deformation behavior.

Data for SMART was gathered through a virtual questionnaire (Turoff, 1970) answered by 17 experts (thus exceeding the minimum value set) from various Brazilian universities (Rio Grande do Sul, Santa Catarina, Goiás, São Paulo, Rio de Janeiro, and Ceará), reflecting great representativeness in the academic knowledge of Brazilian asphalt paving. Moreover, the expert panel comprised respondents with advanced academic qualifications: 4 held a Master's degree, and 13 held a Doctorate. The age distribution was diverse, with 41% aged between 26 and 35 years, 18% between 36 and 45 years, 29% between 46 and 55 years, 6% between 56 and 65 years, and 6% between 66 and 75 years. Regarding professional experience in the field of pavement engineering, 47% reported between 5 and 14 years of experience, 29% between 15 and 24 years, and 24% between 25 and 35 years. This composition highlights the high level of expertise among the respondents and reflects a diverse and representative population aligned with the study's objectives.

For the variables selected in this study, the questionnaire required respondents to assign scores (whole numbers) ranging from 0 to 20, where 0 represented the least importance and 20 the greatest importance in influencing the permanent deformation of asphalt mixtures. Respondents were also instructed to assign identical scores to variables they deemed to have an equal impact on permanent deformation (PD) of asphalt mixtures, if applicable.

In the SMART method, weights are assigned to each criterion based on their relative importance (Edwards, 1977). These weights can be determined through pairwise comparisons or the normalized average of the scores given by a panel of experts, as in the case of this study (Equation 6).

$$w_i = \frac{\bar{s}_i}{\sum \bar{s}_i} \times 100\% \quad (6)$$

where w_i : weight of criterion i ;

\bar{s}_i : average of the scores given by the experts to criterion i .

3.3. Comparing rankings

After ranking asphalt mixtures with TOPSIS, the results were compared to the FN rankings from MeDiNa. Shapiro-Wilk and Levene tests checked for normality and homogeneity of TOPSIS and FN data. Friedman's non parametric test compared the rankings, with similarity ratio values from TOPSIS and FN standardized as per Equation 7.

$$Z = \frac{v - \mu}{\sigma} \quad (7)$$

where Z : standardized value;

v : gross value;

μ : sample mean;

σ : sample standard deviation.

A 95% reliability level was set for the analyses. The null hypotheses were: Shapiro-Wilk test (H0) - data follows a normal distribution; Levene test (H0) - data groups have equal variances; Friedman test (H0) – there is no difference between classifications.

To assess the hybrid method's robustness, a sensitivity analysis varied expert scores in six scenarios: (a) $s_{ik} + 1$; (b) $s_{ik} + 2$; (c) $s_{ik} + 3$; (d) $s_{ik} - 1$; (e) $s_{ik} - 2$; and (f) $s_{ik} - 3$, where s_{ik} is the score for a given parameter i by the expert k . The Friedman test was re-applied to compare the resulting rankings.

4. RESULTS AND DISCUSSIONS

4.1. Sample description

To use the TOPSIS technique for ranking asphalt mixtures, adjustments were made to the study's database. Mixtures missing two or more indicator values were discarded to avoid inconsistent weighing of other criteria. Mixtures without FN characterization were also excluded.

Thus, 121 out of the initial 178 mixtures were used, each with a maximum of one missing value in either Brookfield viscosity or shape index. The indicators for softening point, granulometric range, and binder content were complete for all mixtures. For mixtures with missing data, the weights of the remaining indicators were normalized so that their sum equaled 100%.

The nomenclature of the selected mixtures remains as proposed by the original authors. The 121 mixtures feature diverse aggregate sources, grain sizes, and mix design characteristics, including various modified (especially polymer) and unmodified binders. The binder type is expected to be a key factor in the ranking since the selected aggregates were of good quality, and binder changes can significantly improve the final mix. Thus, the results for each criterion cover a wide range of values.

4.2. Ranking asphalt mixtures using the hybrid multi-criteria method

Weights for each criterion were calculated using the SMART method based on expert panel scores (Table 2). There was no significant discrepancy in the criteria's importance, but binder content was highlighted as the most important indicator for permanent deformation behavior, according to the experts and the selected criteria.

Table 2: Weights found by the SMART method

Criteria	Average score (\underline{s}_j)	Weight (w_j)
Binder content	15.65	26.10%
Granulometric range	13.47	22.47%
Softening point	11.06	18.45%
Brookfield viscosity at 135 °C	9.94	16.58%
Shape index #3/4	9.82	16.39%
Total:	59.94	100.00%

The performance matrix values, converted from qualitative to quantitative data, were normalized as per the methodology. After weighing the criteria, mixtures were ranked based on performance

(S_{TOPSIS}) (Table 3), which also shows the FN-based classification. The table presents the mixtures ordered by their S_{TOPSIS} values, thereby reflecting the ranking derived from the hybrid methodology. Additionally, it provides readers with insight into the magnitude of the TOPSIS performance values and enables a preliminary comparison between the rankings obtained through the hybrid method (SMART and TOPSIS) and the Flow Number values. The hybrid multi-criteria approach shows that mixtures with modified binders (polymer or tire rubber) or stiffer binders (RAP or lower penetration) generally rank higher, confirming the FN-based order.

Table 3: Ranking of mixtures against permanent deformation found by TOPSIS and FN

Nomenclature	S_{TOPSIS}	FN	Order	
			TOPSIS	FN
BN25-D - A - 10/20 (Nunes-Ramos, 2023)	0.846	1485	1	19
BN25-D - B - 10/20 (Nunes-Ramos, 2023)	0.832	1140	2	21
EGL-19 - B - 10/20 (Nunes-Ramos, 2023)	0.723	1004	3	24
EGL-19 - A - 10/20 (Nunes-Ramos, 2023)	0.706	484	4	48
S BAI FX B HIMA (Boeira, 2018)	0.638	7200	5	1
S CON FX B HIMA (Boeira, 2018)	0.636	7200	6	1
U5-DAER-FXB-ECO (Faccin, 2018)	0.616	175	7	69
M BAI FX B HIMA (Boeira, 2018)	0.61	7200	8	1
M CON FX B HIMA (Boeira, 2018)	0.61	7200	9	1
TLAF (Vestena, 2021)	0.58	7200	10	1
TLAF lab (Ilha, 2022)	0.58	6950	11	3
S CON FX C HIMA (Boeira, 2018)	0.575	7200	12	1
S BAI FX C HIMA (Boeira, 2018)	0.573	7200	13	1
M BAI FX C HIMA (Boeira, 2018)	0.564	7200	14	1
M CON FX C HIMA (Boeira, 2018)	0.56	7200	15	1
HIMA (Vestena, 2021)	0.539	6070	16	5
HIMA lab (Ilha, 2022)	0.539	5064	17	9
U5-DNIT-FXB-60/85 (Faccin, 2018)	0.532	37	18	96
U12-DAER-FXC-60/85 (Faccin, 2018)	0.493	986	19	25
BN25-D - A - TLA (Nunes-Ramos, 2023)	0.491	3821	20	10
S BAI FX B 60/85 (Boeira, 2018)	0.49	5528	21	6
S CON FX B 60/85 (Boeira, 2018)	0.486	5165	22	8
DERSA - FX III - 60/85E B (Nunes-Ramos, 2023)	0.485	7200	23	1
BN25-D - B - TLA (Nunes-Ramos, 2023)	0.483	1215	24	20
M BAI FX B 60/85 (Boeira, 2018)	0.468	2976	25	11
U2-DNIT-FXC-65/90 (Faccin, 2018)	0.466	1033	26	22
M CON FX B 60/85 (Boeira, 2018)	0.465	2244	27	14
U12-DAER-FXB-60/85 (Faccin, 2018)	0.457	923	28	26
U9-DNIT-FXC-TLAF (Faccin, 2018)	0.454	2001	29	16
S BAI FX C 60/85 (Boeira, 2018)	0.449	6300	30	4
S CON FX C 60/85 (Boeira, 2018)	0.443	5367	31	7

Table 3:Continued...

Nomenclature	S_{TOPSIS}	FN	Order	
			TOPSIS	FN
M7-PG64-SBS-12.5 (Schuster, 2023)	0.441	597	32	34
S CON FX C 50/70 (Boeira, 2018)	0.438	444	33	52
M BAI FX C 60/85 (Boeira, 2018)	0.432	2945	34	12
BC 60/85 (Barboza Jr., 2018)	0.43	719	35	29
U14-DNIT-FXC-60/85 (Faccin, 2018)	0.426	7200	36	1
M4-PG70-SBS-12.5 (Schuster, 2023)	0.426	2072	37	15
M CON FX C 60/85 (Boeira, 2018)	0.426	1742	38	18
GC 60/85 (Barboza Jr., 2018)	0.425	431	39	53
DERSA - FX III - 60/85E A (Nunes-Ramos, 2023)	0.422	464	40	49
S BAI FX B 50/70 (Boeira, 2018)	0.416	597	41	35
U6-DNIT-FXC-60/85 (Faccin, 2018)	0.413	7200	42	1
SBS (Vestena, 2021)	0.412	7200	43	1
SBS lab (Ilha, 2022)	0.412	7037	44	2
U7-DNIT-FXC-60/85 (Faccin, 2018)	0.41	7200	45	1
S CON FX B 50/70 (Boeira, 2018)	0.408	662	46	30
AR (Possebon, 2021)	0.406	124	47	83
U2-DNIT-FXC-60/85 (Faccin, 2018)	0.402	7200	48	1
GS 60/85 (Barboza Jr., 2018)	0.401	316	49	58
M BAI FX B 50/70 (Boeira, 2018)	0.398	370	50	54
M CON FX B 50/70 (Boeira, 2018)	0.398	314	51	59
BS 60/85 (Barboza Jr., 2018)	0.397	509	52	42
M5-PG70-SBS-12.5 (Schuster, 2023)	0.395	1764	53	17
M30 (Luzzi, 2019)	0.391	309	54	60
M20 (Luzzi, 2019)	0.388	455	55	50
M10 (Luzzi, 2019)	0.384	590	56	36
S BAI FX C 50/70 (Boeira, 2018)	0.379	492	57	46
M BAI FX C 50/70 (Boeira, 2018)	0.366	449	58	51
DERSA - FX III - 50/70 PA 85 (Nunes-Ramos, 2023)	0.365	636	59	33
M CON FX C 50/70 (Boeira, 2018)	0.363	329	60	57
M2-PG64-SBS-19 (Schuster, 2023)	0.362	645	61	32
ECOFLEX B-3G (Oliveira, 2019)	0.361	124	62	84
EGL-19 - A - TLA (Nunes-Ramos, 2023)	0.359	2473	63	13
EGL-19 - B - TLA (Nunes-Ramos, 2023)	0.359	1011	64	23
U9-DNIT-FXC-60/85 (Faccin, 2018)	0.357	647	65	31
BC 50/70 (Barboza Jr., 2018)	0.349	175	66	70
30 RAP 60/85 (Correa, 2020)	0.348	143	67	79
GC 50/70 (Barboza Jr., 2018)	0.344	115	68	85
REF 60/85 (Correa, 2020)	0.339	23	69	101
60/85E (Possebon, 2021)	0.338	158	70	72

Table 3:Continued...

Nomenclature	S_{TOPSIS}	FN	Order	
			TOPSIS	FN
U8-DNIT-FXB-50/70 (Faccin, 2018)	0.334	779	71	28
20 RAP 60/85 (Correa, 2020)	0.327	111	72	86
10 RAP 60/85 (Correa, 2020)	0.327	29	73	98
BS 50/70 (Barboza Jr., 2018)	0.324	65	74	90
AMP 60/85 (Oliveira, 2019)	0.318	158	75	73
GS 50/70 (Barboza Jr., 2018)	0.316	68	76	89
U14-DNIT-FXB-50/70 (Faccin, 2018)	0.311	546	77	39
U5-DNIT-FXB-ECO (Faccin, 2018)	0.311	61	78	91
UFSM 3 - 50/70 12.5 mm(a) (Santos, 2015)	0.307	552	79	38
U13-DNIT-FXB-50/70 (Faccin, 2018)	0.301	336	80	56
50/70 - F (Possebon, 2021)	0.3	233	81	65
30/45 (Possebon, 2021)	0.299	214	82	67
U4-DNIT-FXB-50/70 (Faccin, 2018)	0.299	564	83	37
DERSA - FX III - 30/45 A (Nunes-Ramos, 2023)	0.291	234	84	64
DERSA - FX III - 30/45 B (Nunes-Ramos, 2023)	0.286	517	85	41
UFSM 3 - 50/70 12.5 mm(b) (Santos, 2015)	0.285	501	86	43
U11-DAER-FXA-50/70 (Faccin, 2018)	0.284	226	87	66
U8-DNIT-FXC-50/70 (Faccin, 2018)	0.278	359	88	55
U3-DAER-FXB-ECO (Faccin, 2018)	0.278	158	89	74
50/70 - D (Possebon, 2021)	0.276	132	90	80
50/70 - A (Possebon, 2021)	0.275	128	91	82
U2-DAER-FXB-50/70 (Faccin, 2018)	0.274	262	92	63
M1-PG58-19 (Schuster, 2023)	0.272	497	93	44
M6-PG58-19 (Schuster, 2023)	0.268	155	94	77
50/70 - H (Possebon, 2021)	0.267	165	95	71
50/70 - C (Possebon, 2021)	0.264	176	96	68
U10-DNIT-FXC-50/70 (Faccin, 2018)	0.263	485	97	47
0% Areia (Schuster, 2016)	0.26	51	98	93
2% Areia (Schuster, 2016)	0.26	51	99	94
4% Areia (Schuster, 2016)	0.26	43	100	95
6% Areia (Schuster, 2016)	0.26	29	101	99
U14-DNIT-FXC-50/70 (Faccin, 2018)	0.26	822	102	27
50/70 - B (Possebon, 2021)	0.258	18	103	103
M3-PG58-19 (Schuster, 2023)	0.255	75	104	87
50/70 - E (Possebon, 2021)	0.252	17	105	105
50/70 - I (Possebon, 2021)	0.249	21	106	102
50/70 - G (Possebon, 2021)	0.247	70	107	88
M8-PG64-RUB-12.5 (Schuster, 2023)	0.229	18	108	104

Table 3:Continued...

Nomenclature	S_{TOPSIS}	FN	Order	
			TOPSIS	FN
CAF10 (Centofante, 2016)	0.228	150	109	78
REF 50/70 (Correa, 2020)	0.219	17	110	106
U4-DNIT-FXC-50/70 (Faccin, 2018)	0.214	284	111	61
CAF20 (Centofante, 2016)	0.211	262	112	62
CAF30 (Centofante, 2016)	0.197	540	113	40
10 RAP 50/70 (Correa, 2020)	0.197	16	114	107
CAref (Centofante, 2016)	0.196	60	115	92
20 RAP 50/70 (Correa, 2020)	0.19	26	116	100
CACAMPO (Rossato, 2015)	0.188	158	117	75
U1-DAER-FXA-50/70 (Faccin, 2018)	0.175	132	118	81
UFSM 1 - 50/70 12.5 mm (Santos, 2015)	0.163	497	119	45
30 RAP 50/70 (Correa, 2020)	0.16	34	120	97
CALAB 50/70 (Rossato, 2015)	0.122	158	121	76

4.3. Rankings comparison

Comparing the rankings found by the two rankings visually showed several similarities. However, there are exceptions that do not allow for a clear conclusion as to whether the rankings were indeed similar.

The standardized TOPSIS similarity ratio and FN performance data do not follow a normal distribution (Shapiro-Wilk p-value = 9.137E-14, rejecting the null hypothesis of data normality). Levene's test indicated homogeneity of variances (p-value = 0.1134, 1 degree of freedom). Thus, there is no evidence to reject the null hypothesis of homogeneity of variances. The Friedman test showed no statistical difference between rankings (p-value = 0.1727, 1 degree of freedom), supporting variance homogeneity. Figure 1 confirms this, with similar standardized scores and trends, especially below position 50.

The mixture ranked 50th has an FN of 590 cycles, deemed satisfactory for 6.8E+07 standard axle repetitions under normal conditions, according to MeDiNa Manual (DNIT, 2023). Although Ceratti et al. (2015) classify traffic above 5.0E+07 (calculated using the United States Army Corps of Engineers - USACE - method) as very heavy, Figure 1 indicates that this work better aligns with FN for traffic under 6.8E+07.

In the absence of FN data, a statistically similar classification of asphalt mixtures can be achieved using the five simplified indicators and hybrid multi-criteria approach (TOPSIS with SMART weighting) proposed. These indicators can serve as control parameters to tailor mixtures to the required FN for highway traffic. This method aids initial mix design by ranking mixtures based on binder softening point, rotational viscosity at 135 °C, granulometric curve, aggregate shape index, and binder content, thus prioritizing the best mixtures for FN testing, which is a more laborious protocol (higher costs in terms of time, equipment and labor). It also helps select the most suitable mixtures for lower-traffic roads (such as local roads) where FN testing resources may be limited.

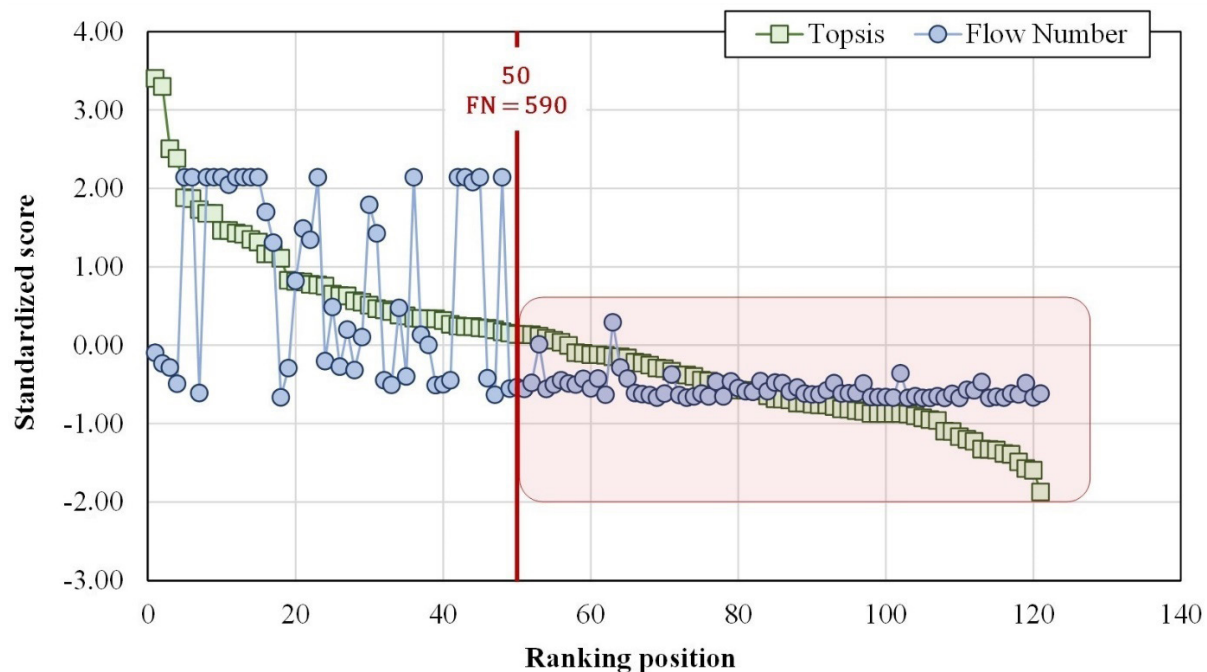


Figure 1. Standardized scores vs. positions in the TOPSIS ranking.

The sensitivity analysis resulted in p-values from **0.008049 to 0.5791** (Figure 2). Variations of up to 2 points higher or 1 point lower in expert scores did not significantly affect rankings (Friedman test p-values > 0.05), indicating that the hybrid multi-criteria method is robust within these limits. This method is valid for initial mix design stages of designing and choosing the surfacing mix, providing reliable results through a simple process, since the sensitivity limitation occurs mainly for higher variations in the expert's scores. For higher traffic levels, increasing the number and types of indicators could enhance the method's robustness.

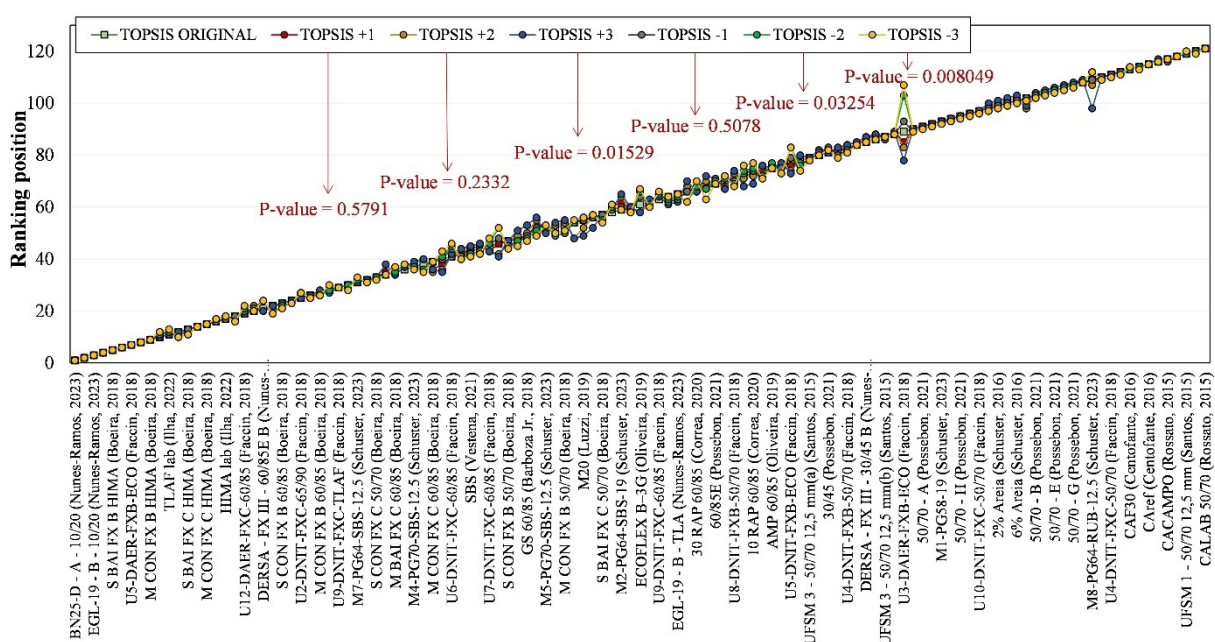


Figure 2. Rankings changes by sensitivity test.

5. SUMMARY OF FINDINGS, CONCLUSIONS AND FUTURE WORK

According to the new pavement design method, the suitability of an asphalt mixture for a road project's traffic and conditions is determined by the Flow Number (FN) from the uniaxial cyclic load test. The mixture composition to meet this criterion is currently determined by trial and error and multi-criteria methodologies can improve this process using structured data. Thus, this study aimed to use a hybrid multi-criteria decision analysis (SMART and TOPSIS) to rank asphalt mixtures using simplified indicators and compare this rank with that based on FN. The proposed methodology was tested on 178 hot-mix asphalt mixtures produced in the field and in a laboratory in Rio Grande do Sul State, Brazil.

Five indicators were selected: softening point and rotational viscosity at 135 °C of binders, granulometric range, shape index of #3/4 aggregate fraction, and binder content. A panel of 17 experts from various Brazilian states evaluated the relative importance, allowing the SMART method to weigh the criteria. Binder content was deemed the most influential for permanent deformation, while the shape index of #3/4 aggregate fraction was the least influential.

The TOPSIS ranking showed that the type of asphalt binder significantly influenced the results. Mixtures with modified binders (SBS polymer or TLAflex) or stiffer binders (oxidized or with lower penetration) ranked highest, consistent with the FN results. The Friedman test showed no statistical difference between the rankings and visual inspection suggests the hybrid method is better for traffic under $6.8E+07$ standard axle repetitions in normal conditions. Also, the method was consistent in sensitivity tests, with variations of +2 and -1 points in expert scores used for weighing criteria.

Thus, in the initial absence of FN results, asphalt mixtures can be classified at the mix design stage using the five selected indicators. This approach reduces the number of FN tests needed, focusing only on the top-ranked mixtures. It is also useful for low-traffic roads with limited resources, allowing selection of the best mixture through the ranking method.

Finally, the hybrid method proved robust, as significant differences only appeared with major changes in weights. While it doesn't predict the exact FN level (not being a regression technique), it is valid for initial pavement surface mix design and selection. Further tests with different indicators can enhance robustness, particularly for high-traffic roads. Additional insights may be gained by observing mixtures from other Brazilian states, using different aggregates, binders with extreme behaviors, or varying field production practices. Finally, future research could consider the use of non-compensatory methods, such as ELECTRE or PROMETHEE techniques, and the definition of minimum performance standards.

The hybrid multi-criteria methodology proposed in this study is promising for asphalt paving decision-making. While increasingly used in engineering, it pioneered the classification of hot-mix asphalt mixtures and can be widely applied in asphalt material studies.

AUTHORS' CONTRIBUTIONS

VNR: Conceptualization, Software, Formal analysis, Investigation, Visualization, Methodology, Writing – original draft; JSV: Formal analysis, Methodology, Writing – original draft; ARP: Conceptualization, Formal analysis, Supervision, Methodology, Project administration, Writing – review & editing; LPS: Conceptualization, Resources, Supervision, Funding acquisition, Methodology, Project administration, Writing – review & editing.

CONFLICTS OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

USE OF ARTIFICIAL INTELLIGENCE-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence tools were used in the research reported here or in the preparation of this article.

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REFERENCES

- AASHTO (2022) *AASHTO M 323: Standard Specification for Superpave Volumetric Mix Design*. Washington: AASHTO.
- ABNT (2021) *ABNT NBR 15184: Materiais Betuminosos – Determinação da Viscosidade em Temperaturas Elevadas Usando um Viscosímetro Rotacional*. Rio de Janeiro: ABNT.
- Alharbi, F.; F. Alshubrumi; M. Almoshaogeh et al. (2022) Sustainability evaluation of cold in-place recycling and hot mix asphalt pavements: a case of Qassim, Saudi Arabia. *Coatings*, v. 12, n. 1, p. 50. DOI: 10.3390/coatings12010050.
- Almeida Jr., P.O.B. (2016) *Comportamento Mecânico de Concretos Asfálticos com Diferentes Granulometrias, Ligantes e Métodos de Dosagem*. Thesis (master's degree). Universidade Federal de Santa Maria. Santa Maria, RS. Available at: <<http://repositorio.ufsm.br/handle/1/7925>> (accessed 04/02/2025).
- Azarijafari, H.; F. Guo; J. Gregory et al. (2023) Solutions to achieve carbon-neutral mixtures for the U.S. pavement network. *The International Journal of Life Cycle Assessment*, v. 28, n. 7, p. 877-890. DOI: 10.1007/s11367-022-02121-1.
- Balbo, J.T. (2007) *Pavimentação Asfáltica: Materiais, Projeto e Restauração* (1. ed.). São Paulo: Oficina de Textos.
- Barboza Jr., V.S. (2018) *Efeito Deletério da Água em Misturas Asfálticas com Adição de Ligante Modificado por Polímero e de Cal*. Thesis (master's degree). Universidade Federal de Santa Maria. Santa Maria, RS. Available at: <<http://repositorio.ufsm.br/handle/1/15871>> (accessed 04/02/2025).
- Becker, R.W.; L.A. Jachstet; A. Dallegrove et al. (2021) Multi-criteria decision-making techniques associated with (Q)SAR risk assessment for ranking surface water microcontaminants identified using LC-QTOF MS. *The Science of the Total Environment*, v. 797, p. 149002. DOI: 10.1016/j.scitotenv.2021.149002. PMID:34303982.
- Bernucci, L.B.; L.M.G. Motta; J.A.P. Ceratti et al. (2022) *Pavimentação Asfáltica: Formação Básica para Engenheiros* (2. ed.). Rio de Janeiro: PETROBRAS/ABEDA.
- Bertrand, J.W.M. and J.C. Fransoo (2002) Operations management research methodologies using quantitative modeling. *International Journal of Operations & Production Management*, v. 22, n. 2, p. 241-264. DOI: 10.1108/01443570210414338.
- Boeira, F.D. (2018) *Estudo da Rigidez, da Deformação Permanente e da Fadiga de Misturas Asfálticas com Ligantes Convencionais e Modificados*. Dissertation (doctoral degree). Universidade Federal de Santa Maria. Santa Maria, RS. Available at: <<http://repositorio.ufsm.br/handle/1/16134>> (accessed 04/02/2025).
- Centofante, R. (2016) *Estudo Laboratorial da Utilização de Material Fresado em Misturas Asfálticas Recicladas a Quente*. Thesis (master's degree). Universidade Federal de Santa Maria. Santa Maria, RS. Available at: <<http://repositorio.ufsm.br/handle/1/7915>> (accessed 04/02/2025).
- Ceratti, J.A.P.; L.B. Bernucci and J.B. Soares (2015) *Utilização de Ligantes Asfálticos em Serviços de Pavimentação*. Rio de Janeiro: ABEDA.
- Chkaiban, R.; E. Hajj and A.J.T. Hand (2022) Influence of balanced mix design approaches on pavement design making through an illustrative example. *Transportation Research Record: Journal of the Transportation Research Board*, v. 2676, n. 10, p. 495-506. DOI: 10.1177/03611981221090238.
- Correa, B.M. (2020) *Análise de Rigidez e Danificação de Misturas Asfálticas Recicladas a Quente com Diferentes Tipos e Teores de RAP*. Thesis (master's degree). Universidade Federal de Santa Maria. Santa Maria, RS. Available at: <<http://repositorio.ufsm.br/handle/1/22199>> (accessed 04/02/2025).
- DAER RS (1998) *DAER-ES-P 16/91: Concreto Asfáltico*. Porto Alegre: Departamento Autônomo de Estradas de Rodagem.
- Damirchilo, F.; A. Hosseini; M. Mellat Parast et al. (2021) Machine learning approach to predict international roughness index using long-term pavement performance data. *Journal of Transportation Engineering, Part B: Pavements*, v. 147, n. 4, p. 04021058. DOI: 10.1061/JPEODX.0000312.
- Dell'Acqua, G.; M. De Luca and F. Russo (2012) Procedure for making paving decisions with cluster and multicriteria analysis. *Transportation Research Record: Journal of the Transportation Research Board*, v. 2282, n. 1, p. 57-66. DOI: 10.3141/2282-07.
- DERSA (2005) *Norma DERSA ET-P 00/027: Concreto Betuminoso Usinado a Quente*. São Paulo: DERSA.
- Ding, J.; J. Jeong; K.C. Lee et al. (2023) Repeatability and reproducibility analysis for functional test results from asphalt mixture performance tester cyclic fatigue test. *Transportation Research Record: Journal of the Transportation Research Board*, v. 2677, n. 9, p. 539-54. DOI: 10.1177/03611981231159409.
- DNER (1995) *DNER 043-ME: Misturas Betuminosas a Quente - Ensaio Marshall*. Rio de Janeiro: DNER.
- DNIT (2006a) *DNIT 031-ES: Pavimentos Flexíveis - Concreto Asfáltico - Especificação de Serviço*. Rio de Janeiro: DNIT.

- DNIT (2006b) *DNIT 095-EM: Cimentos Asfálticos de Petróleo - Especificação de Material*. Rio de Janeiro: DNIT.
- DNIT (2009) *DNIT 111-EM: Pavimentação Flexível - Cimento Asfáltico Modificado por Borracha de Pneus Inservíveis Pelo Processo Via Úmida, do Tipo "Terminal Blending" - Especificação de Material*. Rio de Janeiro: DNIT.
- DNIT (2011) *DNIT 129-EM: Cimento Asfáltico de Petróleo Modificado por Polímero Elastomérico - Especificação de Material*. Rio de Janeiro: DNIT.
- DNIT (2010) *DNIT 131 - ME: Materiais Asfálticos - Determinação do Ponto de Amolecimento - Método do Anel e Bola Método de Ensaio*. Rio de Janeiro: DNIT.
- DNIT (2013) *DNIT 168-EM: Cimento Asfáltico de Petróleo Modificado por Asfalto Natural do Tipo TLA (Trinidad Lake Asphalt) - Especificação de Material*. Rio de Janeiro: DNIT.
- DNIT (2018) *DNIT 184-ME: Pavimentação - Misturas Asfálticas - Ensaio Uniaxial de Carga Repetida para Determinação da Resistência à Deformação Permanente - Método de Ensaio*. Rio de Janeiro: DNIT.
- DNIT (2019) *DNIT 412 - ME: Pavimentação - Misturas Asfálticas - Análise Granulométrica de Agregados Graúdos e Miúdos e Misturas de Agregados por Peneiramento - Método de Ensaio*. Rio de Janeiro: DNIT.
- DNIT (2020) *DNIT 424 - ME: Pavimentação - Agregado - Determinação do Índice de Forma com Crivos - Método de Ensaio*. Rio de Janeiro: DNIT.
- DNIT (2023) *Manual de Utilização do Programa MeDiNa - Versão 1.1.9*. Rio de Janeiro: DNIT.
- Domingos, M.D.I.; A.L. Faxina and L.L.B. Bernucci (2017) Characterization of the rutting potential of modified asphalt binders and its correlation with the mixture's rut resistance. *Construction & Building Materials*, v. 144, p. 207-213. DOI: 10.1016/j.conbuildmat.2017.03.171.
- Edwards, W. (1977) How to use multiattribute utility measurement for social decisionmaking. *IEEE Transactions on Systems, Man, and Cybernetics*, v. 7, n. 5, p. 326-340. DOI: 10.1109/TSMC.1977.4309720.
- Faccin, C. (2018) *Concretos Asfálticos em Utilização no Rio Grande do Sul: Comportamento Mecânico e Desempenho em Campo Quanto à Deformação Permanente*. Thesis (master's degree). Universidade Federal de Santa Maria. Santa Maria, RS. Available at: <<http://repositorio.ufsm.br/handle/1/15888>> (accessed 04/02/2025).
- Ferreira, J.L.S.; L.F.A.L. Babadopulos; J.B.S. Bastos et al. (2020) A tool to design rutting resistant asphalt mixes through aggregate gradation selection. *Construction & Building Materials*, v. 236, p. 117531. DOI: 10.1016/j.conbuildmat.2019.117531.
- Gomes, C.F.S. and L.F.A.M. Gomes (2014) *Tomada de Decisão Gerencial: Enfoque Multicritério* (5. ed.). São Paulo: Editora Atlas.
- Gomes, L.F.A.M. (2007) *Teoria da Decisão* (5. ed.). São Paulo: Cengage Learning.
- Gomes, O.J.F.; J.B. Soares and J.B.S. Bastos (2021) The effect of mix constituents in the permanent deformation resistance of asphalt mixtures. *RILEM Bookseries*, v. 27, p. 1791-1798. DOI: 10.1007/978-3-030-46455-4_227.
- Grimm, H.F. and L.A.T. Brito (2022) Nível de carga de veículos comerciais em rodovias federais concedidas, *Transportes*, v. 31, n. 1, p. 1-15. DOI: 10.58922/transportes.v31i1.2849.
- Gupta, A.; C.J. Slebi-Acevedo; E. Lizasoain-Arteaga et al. (2021) Multi-criteria selection of additives in porous asphalt mixtures using mechanical, hydraulic, economic, and environmental indicators. *Sustainability*, v. 13, n. 4, p. 2146. DOI: 10.3390/su13042146.
- Hwang, C.-L. and K. Yoon (1981) *Multiple Attribute Decision Making: Methods and Applications* (1st ed.). New York: Springer-Verlag. DOI: 10.1007/978-3-642-48318-9.
- Ilha, P.S. (2022) *Caracterização de Rigidez, Deformação Permanente, Fadiga e Análises Mecanicistas de Pavimentos com Misturas Asfálticas Produzidas em Campo e Laboratório*. Undergraduate thesis (bachelor's degree). Universidade Federal de Santa Maria. Santa Maria, RS. Available at: <<http://repositorio.ufsm.br/handle/1/23972>> (accessed 04/02/2025).
- Ismael, S.F.; A.H. Alias; A.A. Zaidan et al. (2023) Toward sustainable transportation: a pavement strategy selection based on the extension of dual-hesitant fuzzy multicriteria decision-making methods. *IEEE Transactions on Fuzzy Systems*, v. 31, n. 2, p. 380-393. DOI: 10.1109/TFUZZ.2022.3168050.
- Iwański, M.; P. Buczyński and G. Mazurek (2016) The use of gabbro dust in the cold recycling of asphalt paving mixes with foamed bitumen. *Bulletin of the Polish Academy of Sciences. Technical Sciences*, v. 64, n. 4, p. 763-73. DOI: 10.1515/bpasts-2016-0085.
- Jato-Espino, D.; I. Indacoechea-Vega; L. Gáspár et al. (2018) Decision support model for the selection of asphalt wearing courses in highly trafficked roads. *Soft Computing*, v. 22, n. 22, p. 7407-21. DOI: 10.1007/s00500-018-3136-7.
- Luzzi, F.C. (2019) *Adaptação de Usina para Reciclagem à Quente e Avaliação Laboratorial das Misturas Asfálticas Produzidas*. Thesis (master's degree). Universidade Federal de Santa Maria. Santa Maria, RS. Available at: <<http://repositorio.ufsm.br/handle/1/19103>> (accessed 04/02/2025).
- Magalhães, L.M. and F.H.L. Oliveira (2020) Identificação de condições funcionais em pavimentos urbanos auxiliada por machine learning. In *Anais do 34º Congresso de Pesquisa e Ensino em Transporte da ANPET*. Rio de Janeiro: ANPET, p. 1070-1080.
- Mansour, E.; M.R. Mousa; H. Dhasmana et al. (2023) Machine-learning-based framework for prediction of the long-term field performance of asphalt concrete overlays in a hot and humid climate. *Transportation Research Record: Journal of the Transportation Research Board*, v. 2677, n. 10, p. 375-85. DOI: 10.1177/03611981231161353.
- Medina, J. and L.M.G. Motta (2015) *Mecânica dos Pavimentos* (3. ed.). Rio de Janeiro: Editora Interciência.
- Meroni, F.; G.W. Flintsch; J. Habbouche et al. (2021) Three-level performance evaluation of high RAP asphalt surface mixes. *Construction & Building Materials*, v. 309, p. 125164. DOI: 10.1016/j.conbuildmat.2021.125164.

- Moretti, L.; P. Di Mascio and A. D'Andrea (2013) Environmental impact assessment of road asphalt pavements. *Modern Applied Science*, v. 7, n. 11, p. 1-11. DOI: 10.5539/mas.v7n11p1.
- Nizamuddin, S.; M. Jamal; J. Santos et al. (2021) Recycling of low-value packaging films in bitumen blends: A grey-based multi criteria decision making approach considering a set of laboratory performance and environmental impact indicators. *The Science of the Total Environment*, v. 778, p. 146187. DOI: 10.1016/j.scitotenv.2021.146187. PMID:33714093.
- Noori, M.; O. Tatari; B.H. Nam et al. (2014) A stochastic optimization approach for the selection of reflective cracking mitigation techniques. *Transportation Research Part A, Policy and Practice*, v. 69, p. 367-378. DOI: 10.1016/j.trra.2014.09.006.
- Nunes-Ramos, V. (2023) *Proposta para Seleção de Ligantes e Misturas Asfálticas Considerando Deformação Permanente e Fadiga*. Thesis (master's degree). Universidade Federal de Santa Maria. Santa Maria, RS. Available at: <<http://repositorio.ufsm.br/handle/1/30248>> (accessed 04/02/2025).
- Okte, E. and I.L. Al-Qadi (2022) Impact of autonomous and human-driven trucks on flexible pavement design. *Transportation Research Record: Journal of the Transportation Research Board*, v. 2676, n. 7, p. 144-160. DOI: 10.1177/03611981221077083.
- Oliveira, A.A. (2019) *Estudo da Rigidez e da Resistência ao Dano de Misturas Asfálticas com Ligantes Modificados por Borracha e Polímero*. Undergraduate thesis (bachelor's degree). Universidade Federal de Santa Maria. Santa Maria, RS. Available at: <<http://repositorio.ufsm.br/handle/1/23473>> (accessed 04/02/2025).
- Papagiannakis, A.T. and E.A. Masad (2008) *Pavement Design and Materials* (1st ed.). New Jersey: John Wiley & Sons, Inc.
- Possebon, E.P. (2021) *Advanced Characterization of Brazilian Bitumens and Mixtures*. Dissertation (doctoral degree). Universidade Federal de Santa Maria. Santa Maria, RS. Available at: <<https://repositorio.ufsm.br/handle/1/22487>> (accessed 04/02/2025).
- Rassafi, A.A.; M. Zarei and A. Dadashi (2021) Application of multi-criteria decision-making in achieving the right mix asphalt mixtures. *Electronic Journal of Structural Engineering*, v. 21, n. 1, p. 55-63. DOI: 10.56748/ejse.21291.
- Rossato, F.P. (2015) *Avaliação do Fenômeno de Fadiga e das Propriedades Elásticas de Misturas Asfálticas com Diferentes Ligantes em Variadas Temperaturas*. Thesis (master's degree). Universidade Federal de Santa Maria. Santa Maria, RS. Available at: <<https://repositorio.ufsm.br/handle/1/7890>> (accessed 04/02/2025).
- Santos, M.S. (2015) *Desenvolvimento de Modelos de Previsão de Desempenho a Partir da Implantação de Trechos Monitorados na Região de Santa Maria - RS*. Thesis (master's degree). Universidade Federal de Santa Maria. Santa Maria, RS. Available at: <<http://repositorio.ufsm.br/handle/1/7886>> (accessed 04/02/2025).
- Santos, J.; G. Flintsch and A. Ferreira (2017) Environmental and economic assessment of pavement construction and management practices for enhancing pavement sustainability. *Resources, Conservation and Recycling*, v. 116, p. 15-31. DOI: 10.1016/j.resconrec.2016.08.025.
- Schuster, S.L. (2016) *Estudo da Influência da Areia Natural nas Deformações Permanentes de Misturas Asfálticas em Laboratório*. Undergraduate thesis (bachelor's degree). Universidade Federal de Santa Maria. Santa Maria, RS.
- Schuster, S.L. (2023) *Investigation of the Aging Phenomenon in Asphalt Binders and Asphalt Mixtures: Linear Viscoelastic Behavior and Performance Properties*. Dissertation (doctoral degree). Universidade Federal de Santa Maria. Santa Maria, RS. Available at: <<http://repositorio.ufsm.br/handle/1/27671>> (accessed 04/02/2025).
- Schuster, S.L.; C. Faccin; F.D. Boeira et al. (2023) Fatigue behaviour of plant produced asphalt mixtures through viscoelastic continuum damage model. *Road Materials and Pavement Design*, v. 24, n. 1, p. 59-85. DOI: 10.1080/14680629.2021.2009011.
- Torres-Machi, C.; F. Nasir; J. Achebe et al. (2019) Sustainability evaluation of pavement technologies through multicriteria decision techniques. *Journal of Infrastructure Systems*, v. 25, n. 3, p. 04019023. DOI: 10.1061/(ASCE)IS.1943-555X.0000504.
- Turoff, M. (1970) The design for a policy delphi. *Technological Forecasting and Social Change*, v. 2, n. 2, p. 149-71. DOI: 10.1016/0040-1625(70)90161-7.
- Vestena, P.M. (2021) *Segmentos Experimentais na BR 116/RS Empregando TLAFlex, HiMA E 55/75-E (SBS): Caracterização Avançada e Monitoramento*. Thesis (master's degree). Universidade Federal de Santa Maria. Santa Maria, RS. Available at: <<http://repositorio.ufsm.br/handle/1/24399>> (accessed 04/02/2025).
- Yoder, E.J. and M.W. Witczak (1975) *Principles of Pavement Design* (1st ed.). New York: John Wiley & Sons. DOI: 10.1002/9780470172919.