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# 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.

$$S_{TOPSIS\ j} = \frac{D_j^-}{D_j^+ + D_j^-} \tag{1}$$

$$D_j^+ = \sqrt{\Sigma_{\mathrm{i}=1}^{n}\left(PIS - y_{ij}\right)^2}, j = 1, \cdots, m \tag{2}$$

$$PIS = \{max\ y_{ij}\left(i = 1, \ldots, n\right), \text{if criterion i is maximizing}, \min \mathrm{y_{ij}}\left(i = 1, \ldots, n\right), \text{if criterion i is minimizing.} \tag{3}$$

$$D_j^- = \sqrt{\Sigma_{\mathrm{i}=1}^{n}\left(NIS - y_{ij}\right)^2}, j = 1, \cdots, m \tag{4}$$

$$NIS = \{min\ y_{ij}\left(i = 1, \ldots, n\right), if \text{ criterion i is maximizing}, \max \mathrm{y_{ij}}\left(i = 1, \ldots, n\right), \text{if criterion i is minimizing.} \tag{5}$$

where $S_{TOPSISj}$: 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, ..., n: criteria;

*j = 1, ..., 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).

$$w_i = \frac{\underline{s_i}}{\sum \underline{s_i}} \times 100\% \qquad (6)$$

where $w_i$: weight of criterion $i$;

$\underline{s_i}$ : 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.

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

where $Z$: standardized value;

$v$: gross value;

$\mu$: sample mean;

$\sigma$: 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 ( $\underline{s_i}$ ) | Weight ($w_i$) |
|---|---|---|
| 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

| | | | Order | |
|---|---|---|---|---|
| **Nomenclature** | $S_{TOPSIS}$ | *FN* | **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 50$^{th}$ 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.

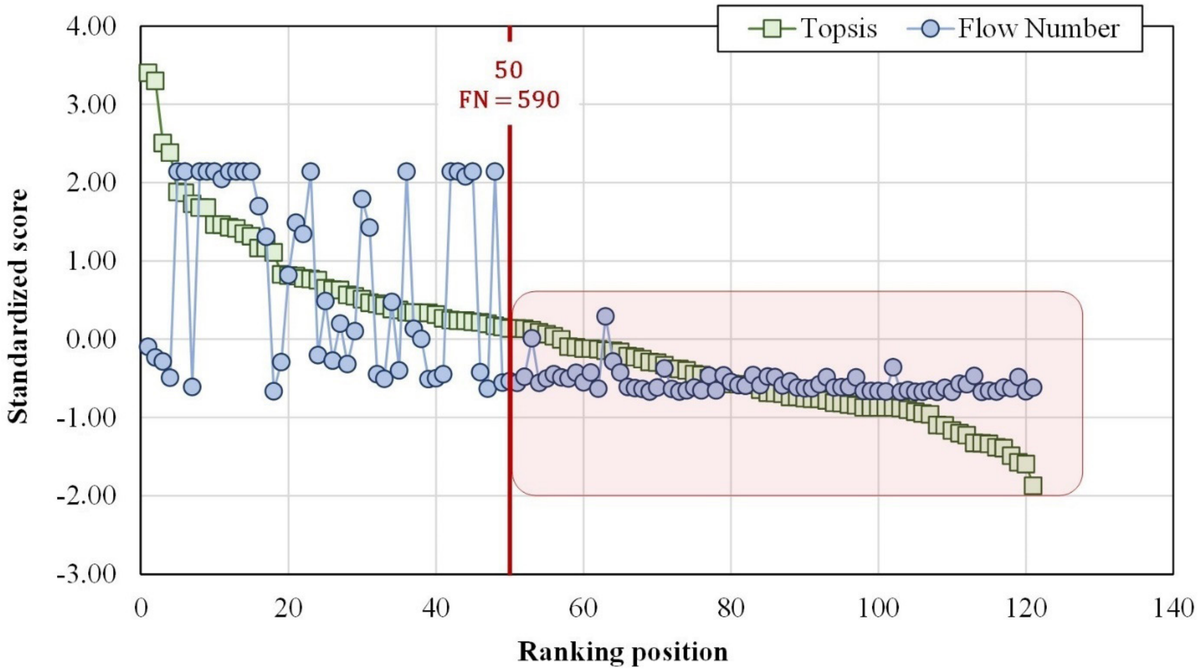


**Figure 1.** Standardized scores vs. positions in the TOPSIS ranking.

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.

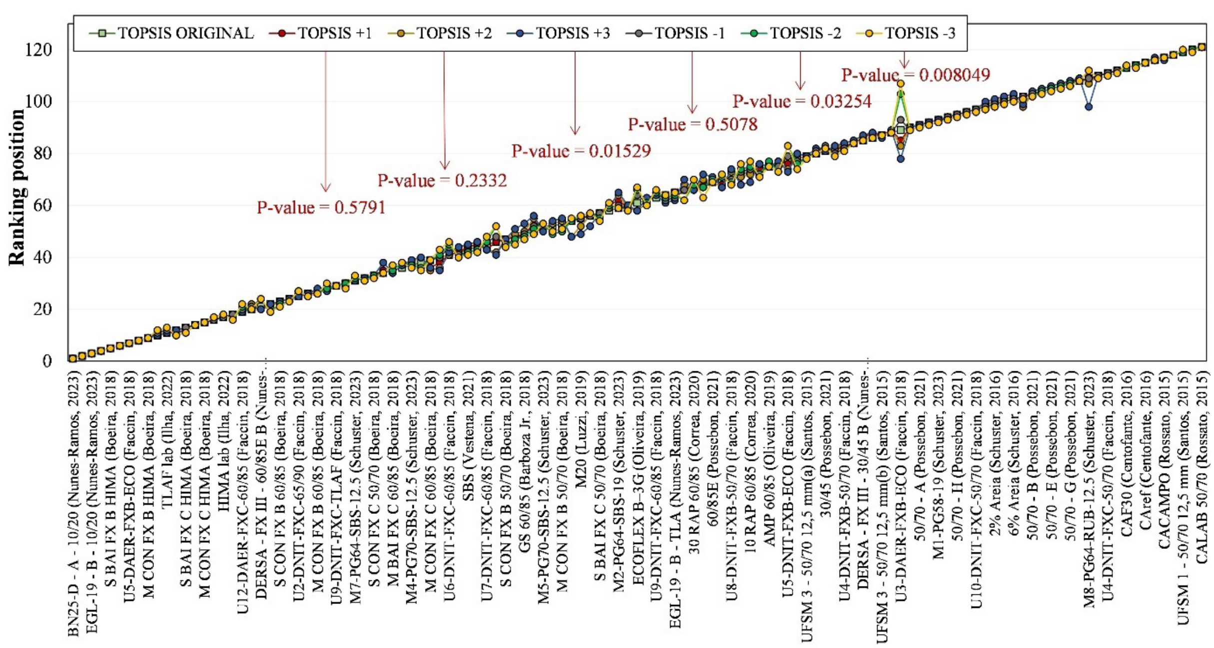


**Figure 2.** Rankings changes by sensitivity test.

## 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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