Considerations On The Analysis Of Permanent Deformation In The New Brazilian Asphalt Pavement Design Method

Considerações sobre a Análise da Deformação Permanente no Método de Dimensionamento Nacional (MeDiNa)

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ABSTRACT
The motivation for this study comes from the technical-scientific advance, which has increased the theoretical bases of the design of pavements over time and, mainly, because the new Brazilian pavement design method (MeDiNa) proposes the use of the Flow Number from uniaxial repeated load test to verify mechanical properties of the asphalt mixture as sufficient to eliminate other tests related to permanent deformation of the asphalt layer. This paper is a literature review with a collection of studies about the design of asphalt mixtures, results of large-scale paving tests, and the evolution of pavement design methods, regarding the understanding of permanent deformation in the asphalt layer. The information collected indicates that the Flow Number is a good ("it is necessary") parameter for evaluating the behavior of an asphalt mixture regarding permanent deformation, but, for a better evaluation in MeDiNa, it is necessary to carry out other tests ("it is not sufficient"), including large-scale and long-term evaluation tests.

RESUMO
A motivação para este estudo vem do avanço técnico-científico que ampliou as bases teóricas do dimensionamento de pavimentos ao longo do tempo e, principalmente, porque o Método de Dimensionamento Nacional (MeDiNa) propõe o uso do Flow Number do ensaio uniaxial de carga repetida na verificação de propriedades mecânicas da mistura asfáltica, como suficientes para eliminar outros ensaios relacionados à deformação permanente da camada asfáltica. Este artigo é uma revisão de literatura que aborda sobre métodos de dosagem de misturas asfálticas, resultados de ensaios de pavimentação em escala real e evolução dos métodos de dimensionamento de pavimentos, no que diz respeito ao entendimento da deformação permanente na camada asfáltica. As informações coletadas indicam que o Flow Number é um bom parâmetro ("é necessário") para avaliar o comportamento de uma mistura asfáltica quanto à deformação permanente, mas, para uma melhor avaliação no MeDiNa, é necessário realizar outros testes ("não é suficiente"), incluindo testes de avaliação em larga escala e de longo prazo.

1. INTRODUCTION

The increase in axle loads demanded by World War II was the turning point for the development of the first pavement design method. Since then, pavement design methods have evolved their

approaches from purely empirical to mechanistic-empirical (ME). The last approach aims to determine pavement structural responses in terms of stresses, strains, and displacements. That analytical treatment consists of modeling the pavement as a multilayer system, subjected to traffic load and environmental actions.

The ME approach is based on imputing proper characterization of materials, traffic load, and external actions into a model to determine pavement structural responses. Then, the relationship between these responses and the pavement performance is then made, according to the failure criteria adopted (fatigue cracking, permanent deformation, longitudinal irregularity, and others). The pavement performance prediction is made through transfer functions, which constitute the empirical part of ME methods (Thompson, 1996).

In Brazil, after more than sixty years of using the semi-empirical CBR method, which was adapted dorm the American version by the engineer Murillo Lopes de Souza, the National Department of Transport Infrastructure (DNIT) initiated the transition protocol to the new National Design Method (MeDiNa). As its failure criteria, MeDiNa adopts fatigue cracking and performs a secondary analysis on permanent deformation, even though permanent deformation is pointed out by several studies as one of the most frequent structural distresses of the Brazilian pavements (Moura, 2010; Bastos, 2017).

As highlighted by Soares (2019), a good research program allows itself to be constantly improving. Therefore, to contribute to MeDiNa's improvement, this paper aims to analyze how the permanent deformation is addressed in the flexible pavement design method, especially on the asphalt layer. To accomplish that, a literature review focusing on asphalt mixtures design, large-scale tests, and the evolution of flexible pavement design methods is done.

2. PERMANENT DEFORMATION IN PAVEMENT DESIGN METHODS

2.1. Design of asphalt mixtures

The permanent deformation is the result of either consolidation of the pavement by traffic, or by plastic flow of the asphalt binder. The latter can be minimized by optimizing the binder content, using angular aggregates, and rough micro-texture (Roberts et al., 1991). Thus, throughout history, understanding the design of asphalt mixtures is vital for understanding rutting and how it should be addressed in a ME pavement design method.

At the beginning of the 20th century, studies were carried out in the USA to measure the optimal amount of binder in the asphalt mixture, with emphasis on the Pat Test, presented in 1906, which performed a visual evaluation of mixtures with aggregates with a maximum size of 1 inch. In 1909, a method of designing mixtures with aggregates of greater size than could be dosed by the Pat Test was developed to be applied in the Bitulithic pavements. As early as the 1920s, the Hubbard-Field design method was developed, which determined the asphalt content based on mineral aggregate voids and stability (Roberts et al., 1991).

In 1927, the engineer Francis Hveem observed a relationship between the optimum binder content and the contact surface of the aggregate. In 1932, his observations and tests gave rise to the first and widely used asphalt mixture design method in the USA: the Hveem method. Such method determined that the asphalt content used had to satisfy the aggregate absorption and have a minimum thickness of aggregate surface coverage. In addition, the mixture behavior, in the presence of water, should be analyzed, as well as the resistance to plastic deformation that would be measured using a piece of equipment named the Hveem Stabilometer. Initially, the air voids in the mixture were not considered (Huber, 2013a).

Not only the asphalt layer but unbound layers also contribute to the total permanent deformation that occurs in the structure of pavement, so it is important to characterize and classify the behavior of these materials. In 1929, the test California Bearing Ratio (CBR), created by engineer O.J. Porter of the California Divisions of Highway, made it possible to assess the strength of the soil by comparing its mechanical properties to the properties of standard gravel (Waseem, 2013).

Years later, the search for improvements in the design of asphalt mixtures made it possible to consider the increase in wheel loads and tire pressure through the development of the Marshall method, in 1943. The Marshall asphalt mixture design method was derived from the Hubbart-Field method. It standardized the compaction energy impact and enabled the analysis of stability, creep, specific mass, void volume, and voids filled with bitumen. In 1962, the value of mineral aggregate voids was added as a design criterion. Standardized by the Asphalt Institute, AASHO, and ASTM, the Marshall method has become the most used method for designing asphalt mixtures worldwide (Huber, 2013a).

In 1987, the Federal Highway Administration (FHWA) found that the continuous growth in axle load and tire pressure caused permanent deformation to occur more frequently, especially in the states that used the Marshall methodology. In the 1980s, thirty-eight US states used the Marshall test, while eleven used the Hveem Stabilometer (Sousa et al., 1991).

Between 1987 and 1992, the Strategic Highway Research Program (SHRP) was developed. Its most significant result was the specification Superior Performing Asphalt Pavements (Superpave), which was divided into three levels (TRB, 2006): level 1- Design Method, level 2 Testing Based on Performance, and level 3 - Performance Prediction Models. As the SHRP research progressed, it became clear that the performance predictions analysis would be very complex, which meant that none of the US Departments of Transportation (DOT) would use them at that time. Such a conclusion led the research program to focus on level 1, related to the asphalt mixture design method (Huber, 2013b).

To develop the Superpave design method, two main steps were taken. First, it was implemented a consensual approach methodology called modified Delphi to define the properties that would be considered by the method. Secondly, the possible tests and trials were analyzed to define the most effective ones. As a result, seven aggregate properties and three mixture properties were considered: aggregate gradation control, aggregate angularity, plastic fines, Los Angeles abrasion resistance, sanity, deleterious materials, sand equivalent, void volume, mineral aggregate voids, and bitumen voids. According to Huber (2013b), the angularity of coarse and fine aggregates, the volume of voids, and voids filled with bitumen have a direct influence on controlling permanent deformation.

The Superpave design method resulted in many advances in paving technology. It not only refined the way to characterize aggregates and mixtures but also implemented the use of the gyratory compactor. Furthermore, it developed a new asphalt binder selection method: the Performance Grade (PG). The PG allowed mixture designers to take into account climatic conditions in the binder selection, which was a great advance since it became possible to consider the performance of materials in the field. However, it could not propose performance prediction models (Huber, 2013b).

While developing the AASHTO mechanistic-empirical pavement design method, it was noticed that, unlike Hveem's and Marshall's methods, the Superpave did not have simple mechanical tests. Thus, the NCHRP Report 465, in 2002, pursued to identify simple tests that

could be used to assess the main performance properties considered, which are permanent deformation, fatigue cracks, and thermal cracks. Regarding the evaluation of the permanent deformation of asphalt mixtures, the chosen parameters were the Dynamic Complex Module (E*), the Flow Time (FT), and the Flow Number (FN), which were obtained by dynamic triaxial, static triaxial, and triaxial repeated load, respectively (Witczak et al., 2002).

In 2005, the field validation and specification development program were completed with those chosen tests. The procedures recommended E* as the primary test to analyze the asphalt mixture's behavior regarding permanent deformation, and Flow Number as a second option, as a complementary procedure to assess resistance in the tertiary zone (TRB, 2006b).

In summary, as axle loads and tire pressure increased, the high occurrence of permanent deformation was noticed to be related to the asphalt mix design. Such findings led to the development of a new method, which was based on the material performance: the Superpave method, along with the Performance Grade binder selection method. Those methods represent a great advance, for they consider local climatic conditions that are known to influence pavement performance.

2.2. Full-scale accelerated pavement testing
2.2.1. WASHO Road Test

In 1952, the WASHO Road Test started, under the supervision of the HRB, to analyze the behavior of flexible pavements. The WASHO Road Test made it possible to broaden the understanding of the behavior of pavements, and the potential distresses that may arise in their structure. The information and results of this project were presented in two reports: Special Report 18 and Special Report 22 (HRB, 1954; HRB, 1955).

The WASHO Road's major findings regarding rutting enlightened the comprehension of pavement behavior. The test concluded that rutting occurs predominantly in the first 6 inches of the pavement structure. In addition, in its first stage, the rut is largely due to the consolidation of surface and base materials. Furthermore, it was also possible to conclude that the occurrence of rutting was not associated with the occurrence of cracks. Finally, it was verified that when increasing the asphalt layer thickness from 2 to 4 inches, there would be a significant improvement in the performance of the structure against rutting. As WASHO`s suggestions for future research, it was proposed the evaluation of the degree of compaction and the shear stress of materials on the occurrence of the rutting (HRB, 1955).

2.2.2. AASHO Road Test

The WASHO Road Test was historically significant, but subsequent research assumed greater relevance to the history of pavement design. In 1956, the construction of the AASHO Road Test section began in Illinois - USA. It analyzed Portland cement concrete pavement structures, asphalt concrete pavements, and bridges, both with steel beams and concrete beams. In total, the experiment and its results were presented in 7 reports produced by the HRB: Special Report 61A - Special Report 61G (HRB, 1962).

A relevant contribution of the AASHO Road Test was the definition of the terms serviceability and performance, which became important concepts for paving. It brought the focus of the pavement design research towards pavement performance, instead of designing based on bearing capacity (HRB, 1962). The AASHO Road Test determined empirical relationships between pavement performance, axle loads, and the number of load repetitions.

In addition, it analyzed skid resistance and tandem axle load equivalence to single axle (HRB, 1962).

The AASHO Road Test concluded that permanent deformation would mainly occur due to the decrease of sub-base and asphalt layer depths, respectively, so the material properties of the subgrade would be less significant. It also found that permanent deformation by traffic consolidation was relatively small, once most of this deformation was associated with shear stresses, which causes the material to move outwards from the center of the wheel (HRB, 1962).

2.2.3. WesTrack project

In 1994, the WesTrack Road Test was built to carry out Project 1-37, sponsored by the National Cooperative Highway Research Program (NCHRP), Federal Highway Administration (FHWA), and AASHTO, this test had as one of its main objectives to fill the gap left by the SHRP experiment on the performance analysis of asphalt pavements, considering not only the properties and characteristics of the asphalt layer but also considering the other pavement layers. The test took place in Nevada – the USA, where annual temperatures vary between -20°C and 40°C, it was also possible to carry out the initial field checks of the Superpave mixture design (TRB, 2002).

New issues such as road reconstruction and rehabilitation of pavements were addressed. In 2002, the final report on WesTrack project performance specification recommendations was released, called Recommended Performance-Related Specification for Hot-Mix Asphalt Construction: Results of the WesTrack Project. The mechanistic-empirical models developed, from that moment on, represented a major change in pavement design methods developed so far, making it possible to calculate the structural responses of the pavement (stresses, strains, and displacements) and use them to estimate the damage to the pavement over time (TRB, 2002).

Regarding permanent deformation, the results of the WesTrack experiment were subdivided into two levels: level 1 is based on regression and makes use of data obtained from rutting, number of load repetitions, and mixture characteristics; level 2 uses the same parameters to perform an analysis of mechanistic-empirical relationships and assumes that the pavement structure behaves like an elastic multilayer system (TRB, 2002).

3. EVOLUTION OF THE PAVEMENT DESIGN METHODS

From the first Roman roads until World War II, the pavement was built exclusively based on experience (O'flaherty and Hughes, 2015), but the context of the war made the development of a pavement design method urgent, given the performance of the United States at Allied.

Even though mathematical modeling of the pavement was developed in the early 1940s by Donald Burmister, the complexity of the calculations made the analytical approach unfeasible at that time (Ahlvin, 1991). On the other hand, the California Division of Highways (CDH) had already developed, from the CBR test, the curve B that empirically related the pavement thickness with the support index, becoming the first pavement design model (Balbo, 2007). For this reason, in 1942, the U.S. Army Corps of Engineering (USACE) started to adopt the CBR method, and like the CDH, carried out experiments to adapt curve B to airport pavements, given the discrepancy of the loads. As a result, USACE developed Curve A, which later had its results extrapolated giving rise to sizing abacuses, based on a standard 80 kN axles.

In the following years, the increase in loads and operating speeds generated the need for in-depth studies on the structure of the pavement, triggering full-scale tests all over the world.

The most notorious of the tests, the AASHO Road Test, had as its main product the AASHO Interim Guide for the Design of Rigid and Flexible Pavements, whose rupture criterion was functional, based on the concept of serviceability, defined as the pavement's capacity to provide comfort and bearing safety. The performance of the pavement was predicted depending on the serviceability, the thickness of the layers, the level of confidence, and the resilient modulus. The guide underwent revisions in 1972, 1986, and 1993, when it had its definitive version called AASHTO Guide for Design Pavements Structures.

The AASHTO method was based on statistical regression (Huang, 2004), which means that the performance equation is calibrated to conditions of the AASHTO Road Test, and, for this reason, it was not suitable for the entire American territory. However, the 1986 version of the guide already presented a window into the future, revealing that efforts were already being made to develop a rational method.

Between 1987 and 2002, the NCHRP coordinated numerous studies and tests for the development of AASHTO's mechanistic-empirical method. Therefore, in 2004 the Guide for Mechanistic-Empirical Design of new and rehabilitated pavement structures was launched, also known as Mechanical-Empirical Pavement Design Guide, or simply MEPDG. The new method adopted, as failure criteria, longitudinal irregularity, fatigue cracking, and permanent deformation of the pavement; the latter was obtained by adding the deformation of each pavement layer. The permanent deformation was determined by two different models, one for the asphalt layer and the other for the unbound layers (Witczak and El-Basyouny, 2004).

The model used for the unbound layers leaves permanent deformation as a function of the number of load applications, material properties, plastic deformation, vertical stress, layer thickness, and a local calibration coefficient. The model used for the asphalt layer, on the other hand, relates the plastic and elastic deformation of asphalt mixtures as a function of the number of load applications, temperature, and three field calibration factors (Equation 1). The local calibration coefficients were obtained in Project 1-37A using data in the Long-Term Pavement Performance (LTPP) program (Witczak and El-Basyouny, 2004).

$$\frac{\varepsilon_p}{\varepsilon_r} = k_1 \cdot 10^{-3.4488} \cdot T^{1.5606} \cdot N^{0.479244} \tag{1}$$

where: ε_p: Accumulated plastic strain at N repetitions of load (in./in.);

ε_r: Resilient strain of the asphalt material as a function of mix properties, temperature and time rate of loading (in./in.);

k_1: function to correct for the confining pressure at different depths;

T: Temperature (ºF);

N: Number of load repetitions.

In 2006, Project 1-40 revised and improved the results obtained in Project 1-37A, both supervised by the NCHRP. As a result, an updated design guide and the first version of the MEPDG Software for pavement design were obtained, considering the mechanistic-empirical method. In 2007, while the MEPDG has been submitted to NCHRP, FHWA, and AASHTO as interim software, a group of state agents was trained to share knowledge about the MEPDG and streamline its implementation. In 2008, the first edition of the practice manual for using the new method, entitled Mechanistic-Empirical Pavement Design Guide, was published. The transportation agencies started implementation activities, in terms of staff training, input data collection, acquisition of test equipment, and creation of test sections for local calibration (AASHTO, 2008).

The mechanistic-empirical method remains subject to modifications to represent the reality of pavements and their performance more accurately over time. The models implemented in the MEPDG Software were calibrated with a database of experimental tests allocated at various points in the U.S. territory. Therefore, it is necessary to calibrate the models with local data, and because of that, in 2010, AASHTO published the Guide for local calibration of the MEPDG (Waseem, 2013). In 2012, the NCHRP Project 9-30A aimed to recalibrate the asphalt layer rutting prediction model in MEPDG (Equation 2), for the previous calibration used standard values of material properties. At that time, the Dynamic Modulus and other fundamental tests were not part of the LTPP database, as they were further developed and validated by the NCHRP Project 9-19 (TRB, 2012). The rutting prediction model of the asphalt layer is represented below:

$$\frac{\varepsilon_p}{\varepsilon_r} = k_z \cdot \beta_{r_1} \cdot 10^{k_{r_1}} \cdot T^{k_{r_2} \cdot \beta_{r_2}} \cdot N^{k_{r_3} \cdot \beta_{r_3}} \tag{2}$$

where: ε_p: resilient strain calculated at the mid-depth of a thickness increment;

ε_r: incremental plastic strain at the mid-depth of a thickness increment;

k_z: depth function;

β_{r_1}, β_{r_2} e β_{r_3}: = local calibration coefficients; all equal to 1.0 for the global calibration effort completed in NCHRP Project 1-40D;

k_{r_1}: plastic deformation factor and equal to -3.35412 based on the global calibration effort;

k_{r_2}: plastic deformation factor related to the effect of temperature and equal to 1.5606 based on the global calibration effort;

k_{r_3}: plastic deformation factor related to the effect of wheel loads and equal to 0.4791 based on the global calibration effort;

T: Pavement temperature (ºF);

N: Number of load repetitions.

The second edition of the manual of practice for mechanistic-empirical design was published in 2015, using version 2.3.1 of the Pavement ME Design Software. In March 2020, the third version of the manual was released, which makes use of version 2.5.3 of the Pavement ME Design Software, commercially available on AASHTOWare. There is a new mechanistic-empirical model for concrete pavement overlays, new global calibration coefficients for flexible and semi-rigid pavements, and the inclusion of non-structural preventive maintenance treatment considerations for flexible and rigid pavements (AASHTO, 2020).

The prediction model made it possible to determine permanent deformation based on the variables that indeed affect the rut depth, such as temperature, load repetitions, environmental conditions, elastic deformation, etc. Besides, the MEPDG reinforces the asphalt layer contribution to rutting by having two prediction models for both asphalt and unbound aggregate layers.

4. ADVANCES IN BRAZILIAN ASPHALT PAVEMENT DESIGN METHOD

In Brazil, the National Highways Department (DNER) was created in 1937. It was responsible for the general planning of national highways, as well as their construction, inspection, and improvement. From the 1940s onwards, the technical-scientific advances that took place in

the world of paving, during and after World War II, were also reflected in the Brazilian paving because there was direct contact between Brazilian and U.S. engineers.

In the 1960s, DNER's engineer Murillo Lopes de Souza adapted the CBR design method, developed in the 1940s in the USA, to the reality of Brazilian pavements. This method was later modified to consider some conclusions obtained in the AASHTO Road Test experiment and its last update was made in 1981, which is still the official method in the country.

Despite the great advance that adaptation brought to the national paving scenario, it cannot be denied that important studies have been carried out in paving technology, since then. In addition to the outdated method, the maximum weight tolerance has gone through several modifications over time. These modifications affect the pavement performance, for they are designed considering the maximum legal load limits at the time of the project. As an example, Law No. 7408/85 established in 1985 a maximum 5% tolerance for the gross weight transferred by the axle (Brazil, 1985). However, Provisional Measure 1050/21, a more recent modification, changed this law and expands the tolerance to 12.5% (Brazil, 2021).

Intending to update the pavement design method in Brazil with a mechanistic-empirical approach, the National Department of Transportation (DNIT), formerly known as DNER, has been developing the National Method of Pavement Design (MeDiNa). In this scenario, it is important that MeDiNa is critically analyzed to seek its continuous improvement while keeping in mind all the progress it represents.

Regarding permanent deformation, the National Method considers the total rut depth equal to the sum of the deformations that occur in the granular layers, disregarding the asphalt layer contribution. To validate this, MeDiNa establishes limits for Flow Number (FN) values, which can be inputted into a table on the user manual, and as its output, the performance class can be obtained.

In contrast, in 1955, the WASHO Road Test made it possible to conclude that permanent deformation occurs predominantly from the top to 6 inches deep into the pavement structure, which makes the asphalt layer contribution very uncontestable (HRB, 1955). Later, in 2004, the first guide for ME design of pavements considered the total permanent deformation equal to the sum of the deformations that occur in the unbound and asphalt layers. This guide also stated that major research efforts should remain in place to ensure that this distress is considered both in the mix design phase and in the structural aspects of flexible pavement performance analysis (Witczak and El-Basyouny, 2004).

In Brazil, new considerations in the mixture design stage started to be implemented regarding the performance class of the asphalt mixtures. It was first proposed by Nascimento (2008) as an approach to the design of dense asphalt mixtures with a focus on preventing permanent deformation. In his work, the asphalt mixtures were subjected to permanent deformation tests in the French traffic simulator, uniaxial test, and flow number test. Among the conclusions, the study recommended FN values associated with levels of medium and heavy traffic, and it made recommendations of the minimum values that should be adopted in each case.

Another Brazilian research, carried out by Bastos (2017), investigated the permanent deformation in asphalt mixtures based on the laboratory results obtained in the Triaxial Stress Sweep (TSS) and uniaxial repeated load tests, also considering the rutting evolution on monitored test sections. Among the results, this research refined the flow number criteria in terms of medium, heavy, and extremely heavy traffic levels.

In the US, the NCHRP's AAT (2011) report (Report 673: A Manual for Design of Hot-Mix Asphalt with Commentary) presented a design manual for mixing hot asphalt (HMA) that incorporates the many advances in material characterization and dosing technology developed since the conclusion of the Strategic Road Survey (SHRP). This report presented the minimum values required for the flow number based on different traffic levels.

The criteria suggested by the works developed by Nascimento (2008), Bastos (2017), and AAT (2011) are presented in Table 1.

Table 1 - Minimum FN values for different traffic levels

	Medium $[3 \times 10^6; 1 \times 10^7]$	Heavy $[1\times 10^7; 3 \times 10^7]$	Extremely heavy $> 3 \times 10^7$
Nascimento (2008)	> 300	> 750	-
AAT (2011)	> 53	> 190	> 740
Bastos (2017)	> 100	> 300	> 1000

Source: Nascimento (2008), AAT (2011), and Bastos (2017)

The presented FN limiting values, established by different researchers, cannot be compared because their test conditions were different, as can be seen in Table 2.

Table 2 - Test conditions to obtain the minimum values of FN

	Air voids content (%)	Temperature (°C)	Strain (kPa)
Nascimento (2008)	6.5 – 7.5	60.0	204
AAT (2011)	4.7 – 8.2	31.3 – 54.3	600
Bastos (2017)	5.0 – 7.5	60.0	204

Source: Nascimento (2008), AAT (2011), and Bastos (2017)

Table 2 shows a similarity in the test conditions used in the studies developed by Nascimento (2008) and Bastos (2017). Despite that, the FN values recommended by Nascimento (2008) are almost 3 times higher than those suggested by Bastos (2017). This divergence is believed to be due to the consideration of field traffic in the research carried out by Bastos (2017). However, as the author herself suggested, it is necessary that several research groups, highway companies, and road concessionaires continue to collect data, so that these criteria are continually refined.

On the other hand, comparing the test conditions of the Brazilian and North American studies, it can be observed there is a difference in the strain values. The Brazilian standard adopts a value of approximately three times lower (204 kPa) than the value used by the AAT (2011) and by the North American standard AASHTO TP 79-15 (600 kPa). Even though the usual axle load and tire inflation pressure are higher in Brazil. Therefore, it is important to evaluate whether the Brazilian flow number test conditions represent the actual pavement loads.

Historically, the Flow Number, obtained in the triaxial repeated load test and presented in the NCHRP report 465, was one of the parameters chosen to analyze the permanent deformation in asphalt mixtures. The intention was to complement the Superpave design method, so it would be able to carry out a rigorous analysis of the potential of the mixtures (Witczak et al., 2002). In Brazil, the ABNT NBR 16505 standard was elaborated by the Organismo de Normalização Setorial de Petróleo (ABNT/ONS-034) and published in 2016 aiming to obtain the Flow Number performance class. In 2018, the DNIT 184 Standard was

created to present the procedure for determining permanent deformation and FN to be inputted on the new Brazilian pavement design method (Souza, 2021). In both standards, the FN is obtained through the uniaxial repeated load test. According to Bastos (2017), it is a test frequently used on ranking asphalt mixtures concerning permanent deformation, and it does not provide a prediction of the evolution of the damage.

Currently, MeDiNa considers only the Flow Number parameter for the evaluation of the permanent deformation in the asphalt layer, which represents the mixture design stage, but the structural aspects of the flexible pavement performance analysis were not yet incorporated. Based on studies developed in Brazil, the M-E method presents a relationship between the values of FN and the number of repetitions load (N), with limiting values for the performance classes of asphalt mixtures regarding permanent deformation, as shown in Table 3.

Table 3 - Limits of performance classes of asphalt mixtures

Classes	Flow Number (FN)	Recommended N: Normal conditions	Recommended N: Severe conditions
1	FN ≥ 100	$N < 1 \times 10^6$	Not recommended
2	$100 \leq FN < 300$	$1 \times 10^6 \leq N < 1 \times 10^7$	$N < 1 \times 10^6$
3	$300 \leq FN < 750$	$1 \times 10^7 \leq N < 1 \times 10^8$	$1 \times 10^6 \leq N < 1 \times 10^7$
4	$750 \leq FN < 2000$	$N \geq 1 \times 10^8$	$1 \times 10^7 \leq N < 1 \times 10^8$
5	FN ≥ 2000	-	$N \geq 1 \times 10^8$

Source: Franco and Motta (2020)

Load cycle number values are recommended for normal and severe conditions. In the first case, speeds are greater than 60 km/h, there are no intersections or the third lane, and/or the maximum temperature of the asphalt coat is moderate. In the second case, these are roads with slow traffic, with speeds below 60 km/h, where there are intersections, third lanes, toll plazas, channeled traffic, buses, and/or higher maximum temperature of asphalt layer (Franco and Motta, 2018).

The maximum temperature characterized as moderate occurs when the value is less than 64°C, otherwise, it is considered high. To define this temperature value, consider the moderate maximum temperature of the asphalt coating as the maximum temperature average of seven consecutive days, at a depth of 20 mm, determined according to the standard AASHTO M323 - Superpave Volumetric Mix Design. Therefore, after designing a new pavement structure, or evaluating an existing pavement, the MeDiNa's Software presents an FN value that must be required in the quality control during the work (Franco and Motta, 2018).

It is well known that temperature and speed are relevant factors for permanent deformation on the asphalt layer. Therefore, in Table 3, it is possible to observe the requirement for higher flow number values, considering the same N value, for the severe conditions where the traffic speed is lower and, consequently, the structure suffers the action of traffic for longer periods. However, the use of FN is still not fulfilling the need for developing a prediction model that should be incorporated into MeDiNa`s asphalt layer performance analysis, regarding rutting. Such a thing is done by the North American mechanistic method.

In the USA, TRB (2012), through the NCHRP report 719, calibrates the Asphalt Institute, Verstraeten, WesTrack, and MEPDG models to analyze the permanent deformation in the asphalt layer. At input level 1, calibration of the MEPDG model requires obtaining the Dynamic Modulus. For the other models, data from three tests can be used: the triaxial test with repeated load, the uniaxial with repeated load, or the shear with constant height. It was concluded that

there is no statistically significant difference in the evolution of permanent deformation in the asphalt layer when comparing the results obtained by the four models, which shows that the uniaxial repeated load test, used in Brazil to obtain the Flow Number, can be used for the calibration of the asphalt layer performance model regarding permanent deformation.

However, what MeDiNa does is disregard the permanent deformation in the asphalt layer by directly using the Flow Number value for that analysis, which is contrary to what is proposed by the mechanistic-empirical method and what is being used worldwide. This is because FN is used to evaluate asphalt mixtures for permanent deformation, but not to predict it in the asphalt layer.

Thus, it is possible to observe that the development of MeDiNa so far is limited to the considerations of the FN related to the mixture design stage, because at the time of its development there were no permanent deformation models calibrated for the Brazilian conditions of materials and climates or even results from large-scale testing. Therefore, to complement the new Brazilian asphalt pavement design method, this paper reinforces the need to carry out a broad survey covering the entire national territory, aiming at the development of empirical-mechanistic models through the association between the laboratory test results of asphalt mixtures and field performance in large-scale pavement tests.

5. FINAL CONSIDERATIONS

The conditions to which pavements are subject have changed significantly over time, as decisions about the road system generally depend on political, financial, and social factors. A significant example was the release of heavier traffic on U.S. highways in the 1940s, which affected the automobile and tire industry. Consequently, parameters such as applied load and tire inflation pressure suffered influence as well. In Brazil, there were also a series of changes in the axle load tolerance limits that impacted the conditions of the existing pavements, but that did not result in the same motivation for research development.

As for permanent deformation, in the 1950s, WASHO Road made it possible to understand that this distress occurs mainly on the surface of the pavement structure (first 6 inches), thus reaching the asphalt layer and the granular layers. The contribution of the asphalt layer to the total deformation was confirmed in latter works, such as the first mechanistic-empirical design guide. Thus, it is concluded that the disregard that MeDiNa does concerning the permanent deformation in the asphalt layer is not in agreement with the mechanistic-empirical precepts.

Regarding the asphalt layer, it is worth noting that the design method used may be associated with the occurrence of distresses. As found by the FHWA, permanent deformation often occurred in places that used the Marshall mixture design method, currently used in Brazil. Subsequently, the development of Superpave made it possible to consider properties that have a direct influence on permanent deformation, for it makes it possible to select the asphalt binders according to climatic peculiarities. Thus, the adoption of Superpave in Brazil can directly contribute to minimizing the occurrence of permanent deformation in the asphalt layer.

Finally, the information collected indicates that the Flow Number is a good ("it is necessary") parameter for evaluating the behavior of an asphalt mixture regarding permanent deformation, but, for a better evaluation in MeDiNa, it is necessary to carry out other tests ("it is not sufficient"). So, MeDiNa should avoid overestimating the Flow Number before rigorously evaluating its potential to characterize the behavior of the asphalt mixture

against permanent deformation, through large-scale tests and long-term surveys, which will contribute to adapting the mechanistic-empirical principles to the Brazilian reality.

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