EFFECTIVENESS OF DOMINANT AGGREGATE SIZE RANGE – INTERSTITIAL COMPONENT (DASR – IC) CRITERIA FOR EVALUATE RUTTING PERFORMANCE OF BRAZILIAN ASPHALT MIXTURES

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Resumo

Tradicionalmente, os métodos de dosagem de misturas asfálticas não consideram de maneira explícita o papel dos agregados em seu desempenho de campo. Sabe-se que um defeito típico das idades iniciais de um revestimento asfáltico é a deformação permanente, a qual é fortemente influenciada pelas características dos agregados, sobretudo a sua granulometria. O presente trabalho é focado em uma abordagem para avaliação e seleção granulométrica que visa auxiliar a composição de um esqueleto pétreo com intertravamento e estabilidade suficientes para resistir à deformação permanente, denominada *DASR – IC model* [denominada no Brasil como método de Faixa de Agregados Dominantes (FAD)]. Busca-se verificar a eficácia de determinados critérios propostos para 3 parâmetros do *DASR – IC model* em onze misturas asfálticas brasileiras. A resistência à deformação permanente foi expressa pelo *Flow Number* (*FN*), obtido no ensaio uniaxial de carga repetida. Pode-se concluir que a porosidade FAD (*DASR porosity*), relacionada à porção graúda dos agregados, consegue estimar satisfatoriamente a resistência à deformação permanente das misturas asfálticas, caracterizando-se como o principal parâmetro do método FAD. Os demais parâmetros avaliados, quais sejam, Fator de Ruptura [*Disruption Factor* (*DF*)] e Fração de Agregados Miúdos [*Fine Aggregate Ratio* (FAR)] caracterizaram-se como parâmetros secundários que complementam as análises e levam em consideração a porção miúda dos agregados. Todos os intervalos recomendados (critérios) para esses parâmetros mostraram-se adequados e podem levar a um projeto consciente de curvas granulométricas visando reduzir à suscetibilidade à deformação permanente na mistura asfáltica em campo.

Abstract

Traditionally, asphalt mixtures design methods do not explicitly consider the role of aggregates in field performance. A typical distress of early ages in asphalt layers is permanent deformation, which is remarkably influenced by the characteristics of the aggregates, especially gradation. This work is focused on an approach to evaluation and gradation selection that aims to help the composition of a mineral skeleton with proper interlocking and stability to resist to rutting, called DASR - IC model [denoted in Brazil as *Faixa de Agregados Dominantes* (FAD)]. The aim is to verify the effectiveness of criteria proposed to 3 DASR - IC model parameters in eleven Brazilian asphalt mixtures. The Flow Number (FN) from uniaxial repeated load test expresses the resistance to permanent deformation. It was concluded that the DASR porosity, related to the coarse aggregates, can satisfactorily estimate the resistance to permanent deformation of asphalt mixtures, being the main DASR – IC model parameter. Other parameters such as Disruption Factor (DF) and Fine Aggregate Ratio (FAR) were characterized as secondary parameters that complement the analysis and take into account the fine portion. All recommended ranges (criteria) for these parameters are suitable and could lead to a rational gradation selection to reduce the susceptibility to permanent deformation in asphalt mixtures in the field.

1. Introduction

The role of aggregate characteristics in the mechanical performance of asphalt mixtures is widely documented in the literature, especially the gradation (Ahlrich, 1996; Stakston and Bahia, 2003; Galalipour *et al.*, 2012.). A suitable

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particle size distribution produces stable asphalt mixtures with a proper interlocked mineral skeleton, resulting in increased resistance to permanent deformation, a typical early age defect in asphalt layers. Although this fact is well known, in Brazil, it is not used any parameter to evaluate the effect of gradation on the field performance of asphalt mixtures. Chun *et al*. (2012) emphasize that in the Superpave design method, although several parameters related to aggregate gradation have been studied in an attempt to identify its effect on the performance of the asphalt mix, there is still no consensus on the best alternative.

The first proposed method for evaluating the mineral skeleton of asphalt mixtures was the Bailey method, based on the theory of particle packing (Vavrik *et al*., 2002). Subsequently, Kim *et al*. (2006) and Guarin (2009) developed respectively, the DASR porosity and the Disruption Factor (DF), which also have the same theoretical basis of the Bailey method. In their results, both parameters proved to be important tools for assessing the potential performance of asphalt mixtures with respect to resistance to rutting. Complementing the work of these authors, Chun *et al.* (2012) proposed two additional parameters for gradation evaluation, the Effective Film Thickness (EFT) and the Fine Aggregate Ratio (FAR). These four parameters form the so-called Dominant Aggregate Size Range - Interstitial Component (DASR - IC) model. Chun and Kim (2016) recommend the incorporation of these parameters in the guidelines and specifications of Superpave design method for asphalt mixtures.

The present study aims to evaluate the resistance to permanent deformation of Brazilian asphalt mixtures based on the DASR - IC model by comparing their parameters with the results observed in the laboratory in order to identify and to verify whether the model is able to consistently explain the potential resistance to rutting of these mixtures.

2. Dominant Aggregate Size Range – Interstitial Components Model

The DASR - IC model was developed at the University of Florida and basically describes the asphalt mix from two main components: (i) Dominant Aggregate Size Range (DASR), related to coarse aggregates and (ii) Interstitial Component (IC), related to fine aggregates.

Kim *et al*. (2006) introduced the concept of DASR, which refers to the primary structure of coarse enough aggregates (larger than 1.18 mm) responsible for resisting to permanent deformation due to their interaction and interlocking features within the asphalt mixture. These features are observed when the relative ratio of the retained percentages between consecutive sieves is between 0.43 and 2.33, which ensures an adequate contact between particles (Kim *et al*., 2006). Thus, it is noted that not all coarse enough aggregates form, necessarily, the mineral skeleton of an asphalt mixture. The larger aggregates than the DASR are called floating aggregates, because there is no proper contact between such particles which remain dispersed in the aggregate matrix, and do not significantly contribute to the resistance to permanent deformation.

Interstitial aggregate (smaller than DASR), asphalt binder and air, called Interstitial Components (IC), fill the voids existing in the primary structure. The IC is responsible for adhesion and tensile strength of the asphalt mixtures. Guarin *et al*. (2013) concluded that IC properties also affect, significantly, the resistance to permanent deformation and fatigue cracking of asphalt mixtures. Figure 1 illustrates the components of the DASR - IC model.

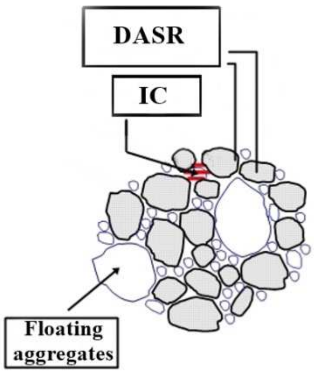

Figure 1. Schematic illustration of DASR – IC model (Adapted from Kim, 2006)

The DASR interlocking is evaluated from a parameter named DASR porosity, while the IC distribution inside the mineral skeleton of the asphalt mixture is evaluated by the Disruption Factor (DF). As previously mentioned, Chun *et al*. (2012) presented the Effective Film Thickness (EFT) and the Fine Aggregate Ratio (FAR). The first is a property of the IC and measures the thickness of the asphalt binder on the aggregate. As Kandhal and Chakraborty (1996), this thickness can be used as an indicator to characterize the durability and the resistance to fatigue cracking of the asphalt mixture. Since the focus of this article is permanent deformation, such parameter is not evaluated. On the other hand, the FAR is connected to the IC composition (particle sizes).

Roque *et al*. (2015), based on an extensive evaluation of field performance of asphalt mixtures from Superpave Monitoring Project II - Phase II in Florida, proposed acceptable ranges for each parameter of the DASR - IC model in order to obtain asphalt mixtures with good field performance, as shown in Table 1. In the referred research, two aggregate types were used, granite and limestone.

Table 1. Acceptable range for DASR – IC parameters (Roque *et al*., 2015)

Parameter	Range	Observation
DASR porosity (%)	38 - 52	between 48 and 52 are marginal porosities
DF	0.50 - 0.95	for cubical DASR structure
FAR	0.28 - 0.36	-
EFT (µm)	12.5 - 25.0	-

2.1. DASR Porosity

The term porosity is widely used in soil mechanics and defines the dimensionless relationship between void volume of a sample and its total volume. From the point of view of the DASR - IC model, the gradation voids are related to any material that does not act effectively in the formation of a resistant mineral skeleton, i.e., does not belong to the DASR: the asphalt binder, air void, and interstitial aggregates (smaller than DASR). The first two components form the Voids in Mineral Aggregate (VAM) of the asphalt mixture. Although the DASR indicate which particle sizes form the resistant structure of the asphalt mixture, the determination of porosity (Equation 1) is what indicates whether or not its structure resists satisfactorily.

$$\boldsymbol{\eta_{DASR}} = \frac{\boldsymbol{V_{v(DASR)}}}{\boldsymbol{V_{T(DASR)}}} = \frac{\boldsymbol{V_{IC,agg} + VMA}}{\boldsymbol{V_{TM} - V_{agg>DASR}}} \tag{1}$$

Where
$\boldsymbol{\eta_{DASR}}$: DASR porosity,
$\boldsymbol{V_{v(DASR)}}$: volume of voids within DASR,
$\boldsymbol{V_{T(DASR)}}$: total volume available for DASR particles,
$\boldsymbol{V_{IC,agg}}$: volume of IC aggregates,
$\boldsymbol{V_{agg>DASR}}$: volume of particles larger than DASR,
$\boldsymbol{V_{TM}}$: total volume of the asphalt mixture, and
$\boldsymbol{VMA}$: voids in mineral aggregate.

In the initial proposal of this parameter, Kim *et al*. (2006) established that the DASR porosity should be less than 50% so that the asphalt mix can present a suitable interlock between the aggregates in the mineral skeleton, and therefore good field performance. It was hypothesized that the lower the value of DASR porosity, the higher would be the resistance to rutting of asphalt mixtures. Recently, Roque *et al*. (2015) recommended the range of 38-52% for the DASR porosity. It should be noted the porosities range of 48-52%, called marginal porosities, are characterized by a very unstable interlocking and a performance difficult to estimate (Kim *et al*., 2006; Greene *et al*., 2014; Ferreira *et al*., 2016). The full development of this parameter can be found in Kim (2006) and Kim *et al*. (2006).

2.2 Disruption Factor

Guarin *et al*. (2013) emphasize that for calculating the DASR porosity (Equation 1), only the IC volume is considered. So, it does not take into account the influence of other characteristics of these components, which can affect the performance of asphalt mixtures, as rutting and fatigue cracking. The Disruption Factor (DF) was introduced to characterize the volumetric distribution of the components of the asphalt mixture that fill the voids of the DASR structure. Its main purpose is to determine the potential of this finer gradation fraction to disrupt the DASR structure, damaging the contact between the particles of the resistant structure, subsequently influencing the performance of asphalt mixture.

The DF is defined as the ratio of the volume of IC particles with potential to disrupt the DASR structure and the DASR volume void. Guarin *et al*. (2013) suggest the existence of an optimal DF range (Figure 2). In this regard, resistance to permanent deformation can be affected both by low and high DF values. According Roque *et al*. (2015), the DF should range between 0.50 and 0.95 for cubical DASR structures. For cubical arrangement, the resulting void will have eight spheres (aggregate particles) around it, which form the corners of a cubical void (Guarin, 2009).

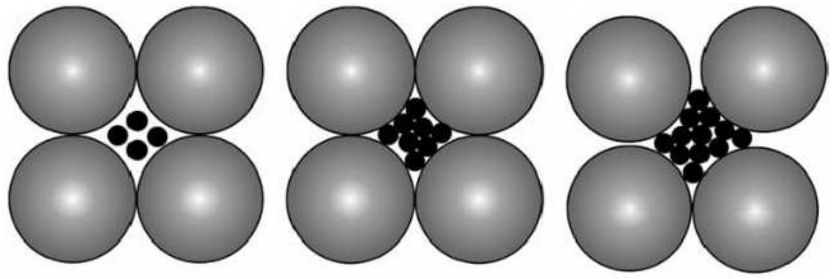

Figure 2. DF values: low, optimal and high (from left to right) (Adapted from Guarin *et al*., 2013)

Guarin (2009) shows that it is possible to infer the type of packing of the DASR particles from their porosities. For instance, a simple cubical packing is associated with DASR porosities of approximately 48%, while a hexagonal close packing is associated with DASR porosities of approximately 30%. In the first case, there may be a formation of only one type of void structure (cubical void). In the second case of packing, two types of void may occur: tetrahedral and octahedral. The calculation of DF for each type of void structure is required. As previously explained, the literature only recommends a suitable range for simple cubical packings. For the asphalt mixtures with low DASR porosity, this range is totally unknown.

In DF calculation, all those particles larger than the voids of DASR are considered particles with the potential to disrupt the DASR structure. Moreover, the size of these voids varies depending on the type of packing (Guarin *et al*., 2013).

2.3 Fine Aggregate Ratio

The Fine Aggregate Ratio (FAR) is defined as the ratio of Coarse Portion to Fine Portion of Fine Aggregate, and it represents the fineness of the IC, characterizing its composition (Chun *et al*., 2012). The Coarse Aggregate Fine Portion of (CFA) is represented by the largest particle size that composes the IC, while the Portion of Fine Aggregate Fine (FFA) is represented by all other particle sizes below the CFA. The FAR is related to time dependent response (creep response) of the asphalt mixture. The FAR as well as other parameters of the DASR - IC model discussed in this paper are shown in Figure 3.

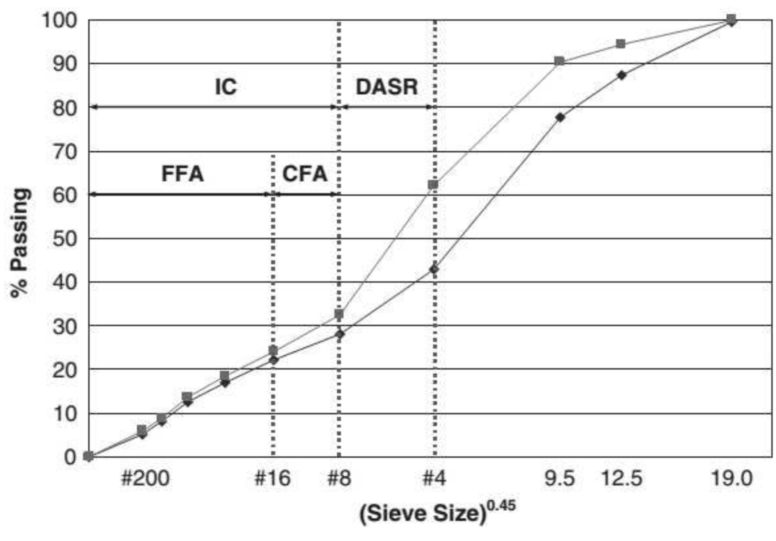

Figure 3. Illustration of DASR – IC parameters (Chun *et al*., 2012)

3. Materials and Methods

In this article, the gradation analysis of the DASR - IC model were performed in eleven Brazilian dense asphalt mixtures according to the requirements of Brazilian gradation specification ES 031 (2006) of DNIT (National Department of Transportation Infrastructure). All asphalt mixtures have the same type of asphalt binder (AC 50/70) and variable gradations. Their main characteristics are summarized in Table 2.

Table 2. Characteristics of the analyzed asphalt mixtures

Mixture	Design	Binder content (%)	Type of binder	NMAS (mm)	Voids (%)	Gsb	Gmm	Aggregate type
1	Marshall	5.8	50/70	12.5	4.0	2.326	2.423	Gneiss
2	Superpave	4.5		19.0		2.649	2.538	Gneiss
3		4.8		12.5		2.590	2.378	Gneiss
4	Marshall	4.2		25.0		2.679	2.568	Granite gneiss
5		4.9		19.0		2.672	2.534	Granite gneiss
6		4.6		12.5		2.673	2.541	Granite gneiss
7		4.9		9.5		2.667	2.523	Granite gneiss
8	Superpave	3.7		19.0		2.599	2.704	Diabase
9		3.7				2.608	2.718	Diabase
10		4.0				2.600	2.705	Diabase
11		4.0				2.595	2.701	Diabase

Mix 1 is an asphalt mixture of recognized poor field resistance to permanent deformation. Mix 2 was recently applied in experimental sections to be subjected to a Heavy Vehicle Simulator (HVS). All other mixtures were used in previous research, and their resistance to permanent deformation in the laboratory are known.

All asphalt mixtures investigated were subjected to uniaxial repeated load test according to the protocol proposed by Witczak *et al*. (2002), and their respective Flow Numbers (FNs) were determined. The FN is the parameter that soon should be part of the Brazilian specifications for asphalt mixtures to ensure adequate resistance to rutting.

With the results of FN, it was established correlations between the parameters of the DASR - IC model (DASR porosity, DF and FAR) and the resistance to permanent deformation of the analyzed mixtures. The validity of the criteria proposed by Roque *et al*. (2015) (Table 1) was checked for Brazilian asphalt mixtures. Basically, it was verified the ability of the DARS - IC model to explain the resistance to rutting of asphalt mixtures with different characteristics from those in which this approach was originally developed.

4. Results

4.1 Gradation Analysis Results

The parameters of the DASR - IC model were calculated for each of the asphalt mixtures and their values are shown in Table 3. Hereafter, we discuss these results comparing them to the ranges recommended by Roque *et al*. (2015) for each DASR – IC parameter.

Table 3. DASR – IC parameters for analyzed asphalt mixtures

Mixture	DASR (mm)	DASR porosity (%)	DF	FAR
1	2.36 - 1.18	83.6	2.96	0.42
2	12.5 - 4.75	48.6	0.19	0.08
3	4.75 - 1.18	46.3	0.72	0.41
4	19.0 - 2.36	31.3	2.10 (O) or 5.23 (T)	0.29
5	4.75 - 1.18	51.5	0.87	0.35
6	4.75 - 2.36	48.0	0.53	0.32
7	4.75 - 2.36	58.4	0.69	0.25
8	4.75 - 1.18	33.0	2.80 (O) or 7.79 (T)	0.28
9	4.75 - 1.18	35.7	2.98 (O) or 8.47 (T)	0.27
10	4.75 - 1.18	33.6	2.88 (O) or 7.94 (T)	0.28
11	12.5 - 1.18	27.0	2.91 (O) or 8.20 (T)	0.28

NOTE: O = Octahedral void type and T = Tetrahedral void type

For DASR porosity, Mix 1 and Mix 7 have values above 52%, which according to the DASR - IC model, indicates a mineral skeleton with low resistance to permanent deformation. It is observed that for both mixtures, their DASR structures are composed by only two sieve sizes. On the other hand, it is expected good performance of Mixes 3, 4, 8, 9, 10 and 11. Among these mixtures, there are continuous and well interlocked structures for DASR up to five consecutive sieve sizes (Mixes 11 and 4), which have the lowest values of DASR porosity. Mixes 2, 5 and 6 have marginal DASR porosities, meaning an unstable interlocking in the aggregates of the DASR structure.

As discussed above, the determination of DF depends on the existing void type in the DASR structure. The mixtures with DASR porosity close to 30% form two types of voids (octahedral and tetrahedral). In such cases, it is calculated the DF of each of these types (assuming all voids with octahedral shape, or all voids with tetrahedral shape, since the quantification of each type of existing void is a complex task). For the other cases, only a value of DF is determined. Roque *et al.* (2015) recommend a range for the cases of a single value of DF (cubical void). Mixes 3, 5, 6 and 7 follow this range. This indicates that their interstitial structure of aggregates help DASR resistance to shear stress; thus, they are more resistant to permanent deformation. Diversely, Mix 2 has a very low DF. As a result, its DASR structure does not receive significant aid from the interstitial aggregates in the resistance to permanent deformation, and may even have reduced the resistance. Mix 1 has a high DF, i.e., its resistance to rutting is greatly reduced by the disruption of the DASR structure by interstitial aggregates. For Mixes 4, 8, 9, 10 and 11 the acceptable ranges for DF are not defined.

It was hypothesized that the FAR is associated with the creep response of the asphalt mixture, so that higher FAR values correspond to higher creep rate. Therefore, this may result in increased susceptibility to rutting accumulation. As Mixes 4, 5, 6, 8, 10 and 11 obey to the range recommended by Roque *et al.* (2015), it is expected that such mixtures exhibit greater resistance to permanent deformation.

4.2 Evaluation of Uniaxial Repeated Load Test

The FN values of different Brazilian asphalt mixtures were confronted with DASR- IC parameters in order to verify the validity of the criteria proposed by Roque *et al.* (2015). Figure 4 shows the FN and DASR porosities of all asphalt mixtures.

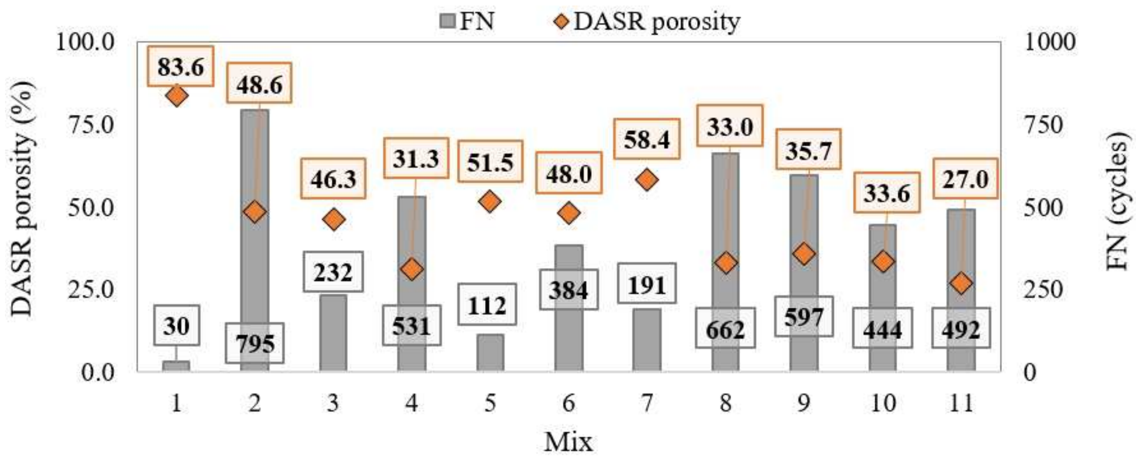

Figure 4. FN and DASR porosity values for analyzed asphalt mixtures

It is observed in Figure 4 that the Mix 1 has the highest DASR porosity and the lowest FN, which may explain its great susceptibility to permanent deformation accumulation, fact already identified in the field. Mixes 2, 5 and 6 have marginal DASR porosities, therefore supposedly an unstable mineral skeleton and a difficult prediction for field performance. It can be noted that Mix 2 has the highest FN among all mixtures analyzed, while Mix 5 shows the second worst FN. Finally, it is emphasized that all asphalt mixtures with DASR porosity less than 48% have the higher FN values, indicating a greater ability to resist permanent deformation.

Figure 5 shows the statistical correlation between FN (dependent variable) and DASR porosity (independent variable) of the investigated asphalt mixtures. In Figure 5a it is included all asphalt mixtures, whereas in Figure 5b asphalt mixtures with marginal DASR porosity were left out. The variability of the results of asphalt mixtures with marginal DASR porosity affect the correlation.

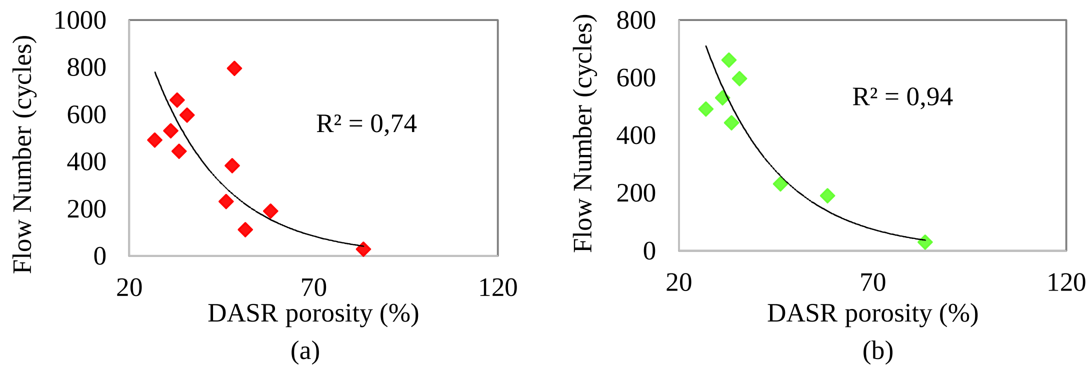

Figure 5. FN and DASR porosity correlation: (a) All mixtures and (b) Except mixtures with marginal DASR porosity

The results in Figure 5 provide evidence that the proposed criterion for DASR porosity is also valid for the analyzed Brazilian asphalt mixtures. Therefore, this parameter has the potential to be used as an indicator of resistance to permanent deformation.

Among the six asphalt mixtures with cubical DASR structure, only four of them meet the range recommended by Roque *et al*. (2015) (0.50 - 0.95). As seen in Figure 6, Mix 1 has a DF far above the recommended upper limit, thus, the interstitial aggregates disrupt the DASR structure, which combined with its high DASR porosity, can justify the low resistance to rutting. In Mix 2, the interstitial aggregates do not work with the DASR structure in the resistance to permanent deformation; nevertheless, it has the highest FN. It should be noted that Mix 1 has marginal DASR porosity, as well as Mixes 5 and 6, which have a DF within the recommended range, but some of the smallest FN values. All other mixtures shown in Figure 6 meet the criteria proposed for the DF and FN intermediary values (explained by the DASR porosity of each one). From these results, the DF is characterized as an additional parameter to DASR porosity, because its isolated consideration does not well explain the mechanical behavior of the analyzed asphalt mixtures.

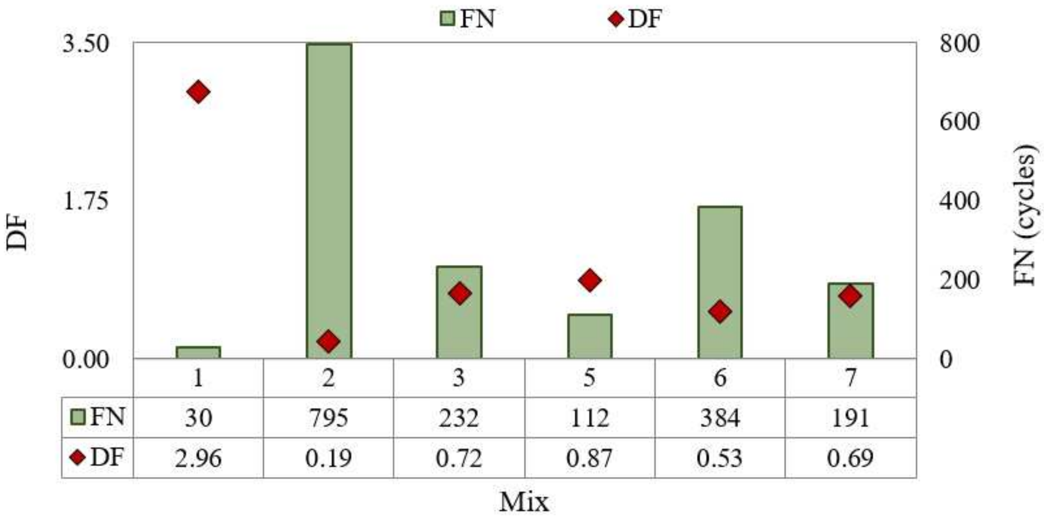

Figure 6. DF and FN values for analyzed asphalt mixtures

Guarin *et al*. (2013) relate DF with resistance to permanent deformation and suggest the existence of an optimal DF range. Figure 7 presents the resistance to permanent deformation (considering the FN) as a DF function for the same aggregate type [analogous procedure adopted by Guarin *et al*. (2013)]. The two types of DF for asphalt mixtures with hexagonal structure DASR are also considered.

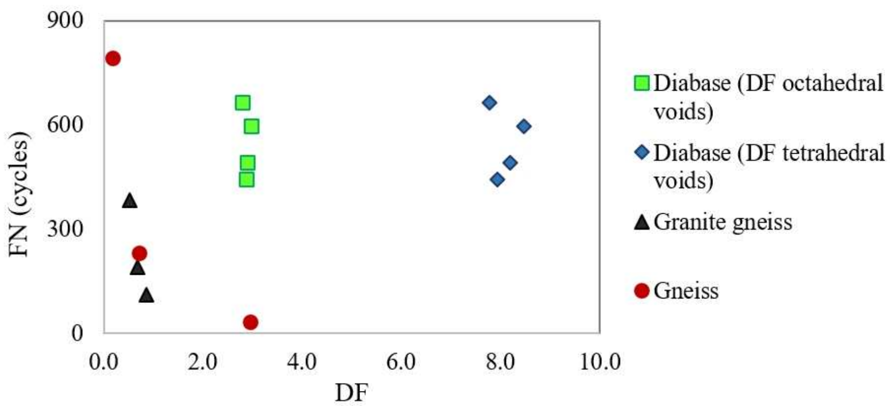

Figure 7. Relationship between FN and DF

Unlike Guarin *et al*. (2013), in Figure 7 it is not possible to identify any behavior that suggests the existence of an optimal DF range, i.e., a range that confers the best structure to rutting resistance. As it can be seen, the FN values are close enough for the same type of aggregate, and too dispersed if all asphalt mixtures are considered in the analysis.

Figure 8 shows how the FAR varies with the FN values. Mixes 4, 5, 6, 8, 10 and 11 were the only with FAR within the range recommended by Roque *et al*. (2015) (0.28 to 0.36). Concerning to asphalt mixtures of marginal

DASR porosity (Mix 5 and 6), which have a poorly understood behavior; the mixtures that meet the FAR criterion are those with the greatest resistance to permanent deformation. Mix 9 can also be included in this group. It is observed that its FAR is very close to the recommended lower limit and its FN is one of the highest. The smallest FN values are associated with asphalt mixtures that did not obey the FAR criterion. Thus, the criterion established by Roque *et al*. (2015) proved to be suitable for the mixtures analyzed in this article. It is important to point out that the FAR, beside DF, gives a better estimation of the potential resistance to rutting of asphalt mixtures, although it has little statistical correlation with the FN, as shown in Figure 9.

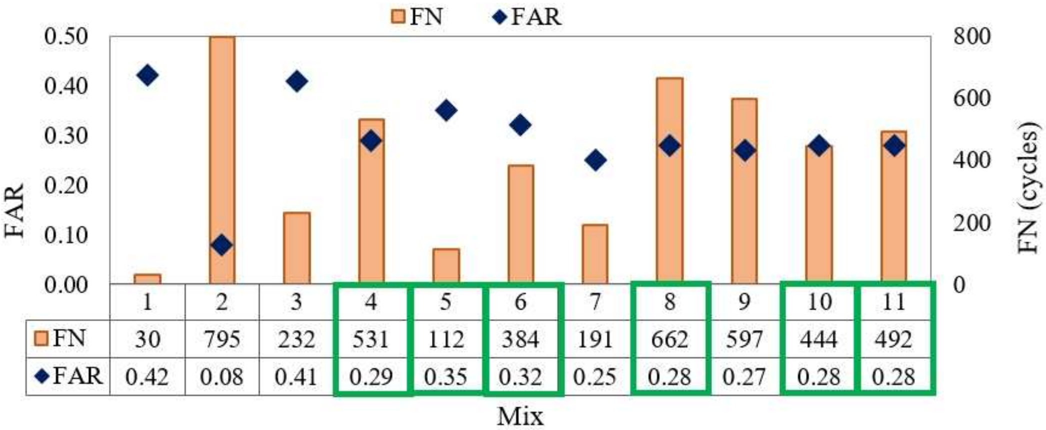

Figure 8. FAR and FN values for analyzed asphalt mixtures

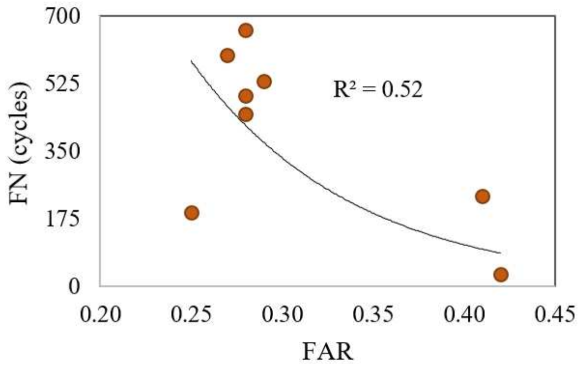

Figure 9. FAR and FN correlation (except mixtures with marginal DASR porosity)

5. Conclusions

The evaluation of the resistance to permanent deformation of Brazilian asphalt mixtures was conducted by repeated load uniaxial test (by means of the FN) to check the effectiveness of the criteria established for DASR - IC parameters as an aid tool in the mixture design phase. The objective was to have a simple method to identify asphalt mixtures with strong and stable mineral skeletons, minimizing the susceptibility to permanent deformation. The main conclusions and findings are as follows:

- The DASR porosity consistently characterizes the mineral skeleton interlocking and the resistance to permanent deformation of asphalt mixtures, making it a potential tool for practical application. Its main limitation is that the role of the fine aggregates on the mechanical behavior of asphalt mixtures is not directly considered.
- The DF is a secondary parameter that can refine the analysis of the DASR porosity, once it is directly related to the distribution of interstitial aggregates (fine portion) in the mineral skeleton. On the other hand, the DF is unable to estimate alone the rutting resistance of asphalt mixtures.
- The FAR is another secondary parameter, but with clear and direct relationship with resistance to permanent deformation of asphalt mixtures. It must be evaluated in addition to the DASR porosity.
- The criteria for the DASR – IC parameters recommended by Roque *et al*. (2015) proved to be valid for Brazilian asphalt mixtures, although a more thorough validation is recommended.
- The inclusion of these parameters and criteria in asphalt mixture design can greatly improve their performance in the field, reducing spending on rehabilitation and promoting the durability of asphalt

mixtures. In addition, the role of field compaction, binder content and type, granular layers characteristics, traffic and environmental conditions and other aggregates characteristics (shape, angularity, and texture) must be considered for a great asphalt pavement rutting performance.

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