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Probabilistic modeling of air void variability of asphalt mixtures in flexible pavements

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HIGHLIGHTS

- We present two methods to account for air void variability in HMA modeling.
- Both methods are probabilistic, use finite element and simulation techniques.
- One method considers the internal heterogeneity of air void distribution in HMA.
- The heterogeneous case better quantifies the reliability of pavement structures.

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ABSTRACT

This paper explores two methods for including air void variability in asphalt mixtures when analyzing the performance of flexible pavements. Both methods combine probabilistic theory, finite element modeling and simulation techniques. However, one approach considers the asphalt layer as a homogeneous material while the other captures the spatial variability of material properties within the layer. The main difference between both methods was observed in the dispersion of the mechanical response of the asphalt course. The results show that including the spatial variability of material properties is useful to obtain a better insight of the actual structural reliability of pavements.

1. Introduction

The topics of material variability and uncertainty quantification of the performance of construction materials have been increasingly studied in Civil Engineering. Works on this topic in geotechnical engineering and mechanics of materials include applications of stochastic finite elements [1], Bayesian inverse analyses [2] and random field theory [3,4]. In the specific area of pavement engineering, techniques such as probabilistic analyses [5–8], general stochastic analysis [9] and random fields [10–12] have been used to explore the impact of material variability and uncertainty quantification in pavement design and performance.

The importance of the uncertainty associated with the response of construction materials has been well recognized by governmental agencies, which have developed statistically-based quality control procedures to assess the construction quality of structures. In most cases, these procedures specify an acceptable range of variability of selected material properties within which the performance of the structures is not compromised. In pavement engineering, the existence of these regulations supports the fact that material variability is decisive to achieve high quality and durable road infrastructure projects. Within this context, this work aims to compare two different methodologies for including material variability—which constitutes one important source of uncertainty in the performance of road infrastructure—when modeling the mechanical response of Hot Mix Asphalt (HMA) in flexible pavements.

A HMA mixture is a composite material comprising asphalt binder, aggregates and air voids, and it is one of the most commonly used materials in road construction. It is well accepted that the long-term performance of HMA mixtures is significantly impacted by three main factors: (1) the characteristics and properties of its constitutive phases, (2) the material properties of the mixture itself, and (3) construction-related processes (e.g., actual properties of the material delivered at the project site, construction quality

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during compaction, etc.) [13]. Among other characteristics of the microstructure of HMA materials, the air void phase does not only determine relevant physical properties of the material that are associated with the durability of the mixture (such as moisture or oxygen diffusion coefficients), but it also impacts the mechanical response of the mixtures and several of their associated deterioration processes. However, most micro and macro mechanical models of pavements currently available in the literature do not include the influence of air voids on the predictability associated with the performance of the HMA when subjected to mechanical loading. Therefore, the development of more accurate mechanical models that can capture the variability of the air void phase of HMA materials constitutes a relevant topic of study in the area of pavement engineering.

To quantify the impact of the uncertainty of the air void structure on the mechanical response of asphalt mixtures, this work presents a comparative analysis of two numerical approaches that can be used to produce probable internal air void distributions within two-dimensional compacted asphalt courses. The first approach, herein named *homogeneous*, consists of applying simulation techniques to generate probable compacted asphalt layers characterized by a unique value of air void content. In other words, the mixture is assumed to be a homogeneous material characterized by a single randomly-generated value of air void content. The second approach also uses simulation techniques to generate probable values of air voids within compacted asphalt layers, but in this case the air voids are assumed to be heterogeneously distributed within the layer. This second approach has been named *random fields* because it uses a stochastic technique with the same name to produce such variable internal distributions. Note that although both approaches are probabilistic-based, the main difference between them is that the second includes not only the variability associated with the total air void content but also the spatial variability of this parameter within the asphalt layer. After generating probable air void content distributions, a finite element (FE) model is used to quantify the role of air void variability of HMA materials on the mechanical response of a pavement structure. In summary, the general methodology used for both approaches in this study has three main components:

1. Probabilistic-based techniques to capture the variability of the air void phase of HMA materials (with and without spatial variability).
2. finite element modeling.
3. simulation techniques.

The initial part of this work presents an introduction to the topic of air voids in asphalt mixtures. Then, the modeling methodology used in this study is explained, followed by a description of the two selected approaches. Finally, the results of the simulations are presented and analyzed.

2. Air voids in HMA mixtures

This section describes some of the main characteristics of the air void phase of HMA materials. This information was crucial to develop the selected probabilistic methodologies used to include the variability associated with this phase.

2.1. Internal distribution of air voids within HMA mixtures

Air voids (*AV*, usually expressed in percentage) are one of the three constitutive phases of HMA mixtures. The final distribution of air voids within an asphalt layer depends on several factors, including the compaction method, external temperature conditions, internal temperature distribution of the material at the moment of compaction, and aggregate gradation and morphological properties, among others [14,15]. Air voids constitute a complex non-uniform structure that offers a natural path for moisture and air to access the microstructure of the mixture. For this reason, this phase plays a main role in the development of environmentally related processes inside asphalt courses of flexible pavements, such as oxidation and moisture damage.

During the last decade, a significant progress in understanding the complexity of internal air void structures in HMA has been achieved. Among other reasons, this progress has been possible due to the application of non-destructive techniques such as X-ray Computed Tomography (CT) and image analysis methods [16–19]. Several works have used these techniques to compute the average vertical distribution of air voids within field cores obtained from asphalt courses of different depths [15,16,20,21], as observed in Fig. 1. From this figure, it is possible to conclude that the distribution of air voids in depth within compacted asphalt courses is not constant but it usually presents a shape characterized by larger values of air voids near the surface (e.g., around 11% *AV* in Fig. 1a), followed by lower values in the middle part of the layer (e.g., around 5% *AV* in Fig. 1a), and slightly larger values near the bottom of the layer (e.g., between 5 and 9% *AV* in Fig. 1a; high *AV* values at the bottom of Fig. 1d correspond to the interface with a subsequent asphalt layer). This variability comes as a contrast to the general practice of characterizing a HMA specimen only by its mean *AV* content value (e.g., close to 6.5% *AV* for the cores shown in Fig. 1a).

2.2. Influence of air voids on the mechanical properties of HMA

Air voids do not only affect environmentally related processes in asphalt mixtures but they also impact the mechanical properties of the material. Some studies conducted in this direction have found a fairly consistent correlation between *AV* and HMA viscoelastic material properties that, in general, yields lower values of modulus for higher *AV* values [22,23]. As explained later, data reported by [22] was selected in this study to account for a valid correlation between a given value of air voids of a HMA specimen and the linear viscoelastic material properties of a mixture at 20 °C (Fig. 2).

3. Modeling methodology

This study was developed following a 7-stage methodology:

1. Initially, the geometry representing a two-dimensional flexible pavement structure was defined. The top asphalt layer of this structure provides the area of interest in this work.
2. Probable *AV* content distributions within the asphalt course were generated using two different methodologies. A detailed explanation of these methodologies is presented in the following section.
3. The corresponding linear viscoelastic material properties of the asphalt layer were determined according to the *AV* contents generated in the previous stage. This was achieved by applying a relationship between *AV* values and the corresponding mechanical properties of HMA reported in a previous study [22].
4. The pavement structure was implemented in the FE software Abaqus® to analyze the mechanical response of the asphalt course after applying mechanical loading to the top of the structure. The load consisted of half of an 82 kN standard single axle load.
5. The mechanical response of the layer, represented by the magnitude of the horizontal strain (ε_h) at every point