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Practical lessons learnt from the application of X-ray computed tomography to evaluate the internal structure of asphalt mixtures

Allex Eduardo Alvarez-Lugo [a] & Juan Sebastián Carvajal-Muñoz [b]

[a] *University of Magdalena, Santa Marta, Colombia, allexalvarez@yahoo.com*
[b] *University of Magdalena, Santa Marta, Colombia, juancarvajal@tamu.edu*

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Abstract
X-ray Computed Tomography (X-ray CT) has allowed for the efficient non-destructive characterization of the internal structure of paving asphalt mixtures (AM), and has led to multiple practical lessons learnt based on the analysis of laboratory- and field-produced AM. This paper aims at summarizing these practical lessons, to facilitate their future application and further developments, in terms of: (*i*) fabrication of laboratory specimens, (*ii*) comparison of laboratory- and field-compacted mixtures, (*iii*) comparison of hot-mix asphalt and warm-mix asphalt mixtures, (*iv*) effects of additives, temperature, and compaction, (*v*) stone-on-stone contact, (*vi*) relationship between internal structure and performance, and (*vii*) modeling applications. These practical lessons are primarily gathered from the analysis of the air void distribution of laboratory-and field-produced AM, evaluated through X-ray CT, which has led to relevant inputs for the assessment of the response and performance of AM. X-ray CT enables computation of the AM internal structure with multiple practical applications and future opportunities to enhance the microstructure of AM and, consequently, optimize their performance.

Key words: X-ray computed tomography; internal structure; air voids; asphalt mixture; pavements engineering.

Lecciones prácticas aprendidas a partir de la aplicación de la tomografía computarizada de rayos-x para evaluar la estructura interna de mezclas asfálticas

Resumen
La Tomografía Computarizada de rayos-X (TC-rX) ha permitido una eficiente caracterización no destructiva de mezclas asfálticas (MA) de pavimentación y ha generado múltiples lecciones prácticas aprendidas a partir del análisis de MA producidas en campo y laboratorio. El presente artículo tiene como objetivo resumir las lecciones prácticas aprendidas, con el fin de facilitar su aplicación futura y desarrollos posteriores, en términos de: (*i*) fabricación de especímenes de laboratorio, (*ii*) comparación de mezclas compactadas en campo y laboratorio, (*iii*) comparación entre mezclas asfálticas en caliente y mezclas tibias, (*iv*) efectos de aditivos, temperatura y compactación, (*v*) contacto agregado-agregado, (*vi*) relación entre la estructura interna y el desempeño, y (*vii*) aplicaciones de modelación. Estas lecciones prácticas se recopilaron principalmente a partir del análisis de la distribución de vacíos en MA producidas en campo y laboratorio, evaluadas a través de TC-rX, el cual generó información relevante para evaluar la respuesta y el desempeño de MA. La TC-rX hizo expedito el cálculo de la estructura interna de MA con múltiples aplicaciones prácticas y posibilidades futuras para mejorar la microestructura de MA y, consecuentemente, optimizar su desempeño.

Palabras clave: tomografía computarizada de rayos-X; estructura interna; vacíos con aire; mezclas asfálticas; ingeniería de pavimentos.

1. Introduction

The paving industry has taken advantage of the research conducted in material characterization to produce high-quality asphalt mixes (AM) that allow for good performance, comfort, and safety for road users over time. One of those research topics concerns the use of X-ray Computed Tomography (X-ray CT) to determine the internal structure (or microstructure) of paving materials. Considering the relevance of X-ray CT in the research on AM [1,2], this paper aims at synthesizing some practical lessons learnt from the application of X-ray CT, mostly based on the computation of air void (AV) related characteristics, to facilitate their future application and future developments of AM.

The first section of the paper includes a brief description of X-ray CT and image analysis techniques. Next, seven

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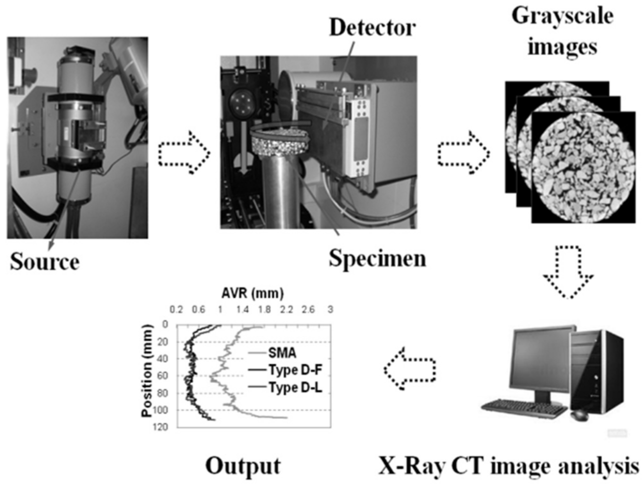


Figure 1. Evaluation of the internal structure of AM by means of X-ray CT
Source: The Authors..

sections introduce the main practical lessons documented with corresponding suggestions for future research. The paper is completed with a section on conclusions and recommendations.

2. X-ray CT and Image Analysis

Essentially, X-ray CT is a technology used to generate images of density distribution for the cross sectional area of a material specimen. The device is composed by an X-ray source with collimator, a rotating-specimen holder and a detector with a black filter (Fig. 1). The technology uses the ability of short wavelength radiation to pass through objects and measures the difference between X-ray intensities before and after passing through.

More specifically, when the initial radiation (I_0) passes through the object—material specimen—, some of it is absorbed and scattered while the other portion (I) gets through and, it is consequently, detected. The amount of penetration and absorption are a function of the: a) linear attenuation coefficient, which depends on the material density, b) X-ray's energy, c) atomic number, d) density, and e) object thickness [3]. The generation of X-ray CT images involves mathematical processes for converting the different intensities' measurements into two dimensional slice images (2D) in grayscale (i.e., consisting of 256 ranges of gray intensities, from 0-black to 255-white). Consequently, the resulting image is a depiction of the varying spatial densities within the object planes, which subsequently allows for identifying its internal structure [3].

Although this technology was originally developed for medical purposes, paving engineering discovered its potential applications for materials research and adapted it. Therefore, in the last decade and a half, X-ray CT has been frequently used to assess the internal structure of AM produced under varying conditions in both the laboratory and field.

The image acquisition and analysis for AM can be performed in three basic steps (Fig. 1):

1. A source of X-ray energy emits pulses to irradiate the AM specimen and the detector receives the remaining energy that got through the specimen and sends the data to a processing unit.
2. The processing unit transforms the data into 2D-grayscale images (raw images) with a specific resolution *N_mm/pixel* that depends on the equipment configuration and characteristics.
3. The raw 2D images are analyzed by means of specialized software (e.g., Image J [4], Image-Pro® Plus [5], and iPas [6]) based on mathematical algorithms to compute the internal structure's characteristics. Further analyses can be performed based on the internal structure's characteristics; for instance, subsequent studies can be developed to assess the internal structure's influence on the AM performance by means of predictive mathematical models (Section 9).

By means of image analysis, the internal structure of AM can be quantified in terms of both the AV characteristics and aggregate characteristics. The AV evaluation include, for example, computation of the total air void (TAV) content, air void size (AVR), connected air void (CAV) content, and ratio of total to connected AV content (TAV/CAV). The assessment of aggregate characteristics can include computation of its size distribution, contacts (stone-on-stone contact), and orientation.

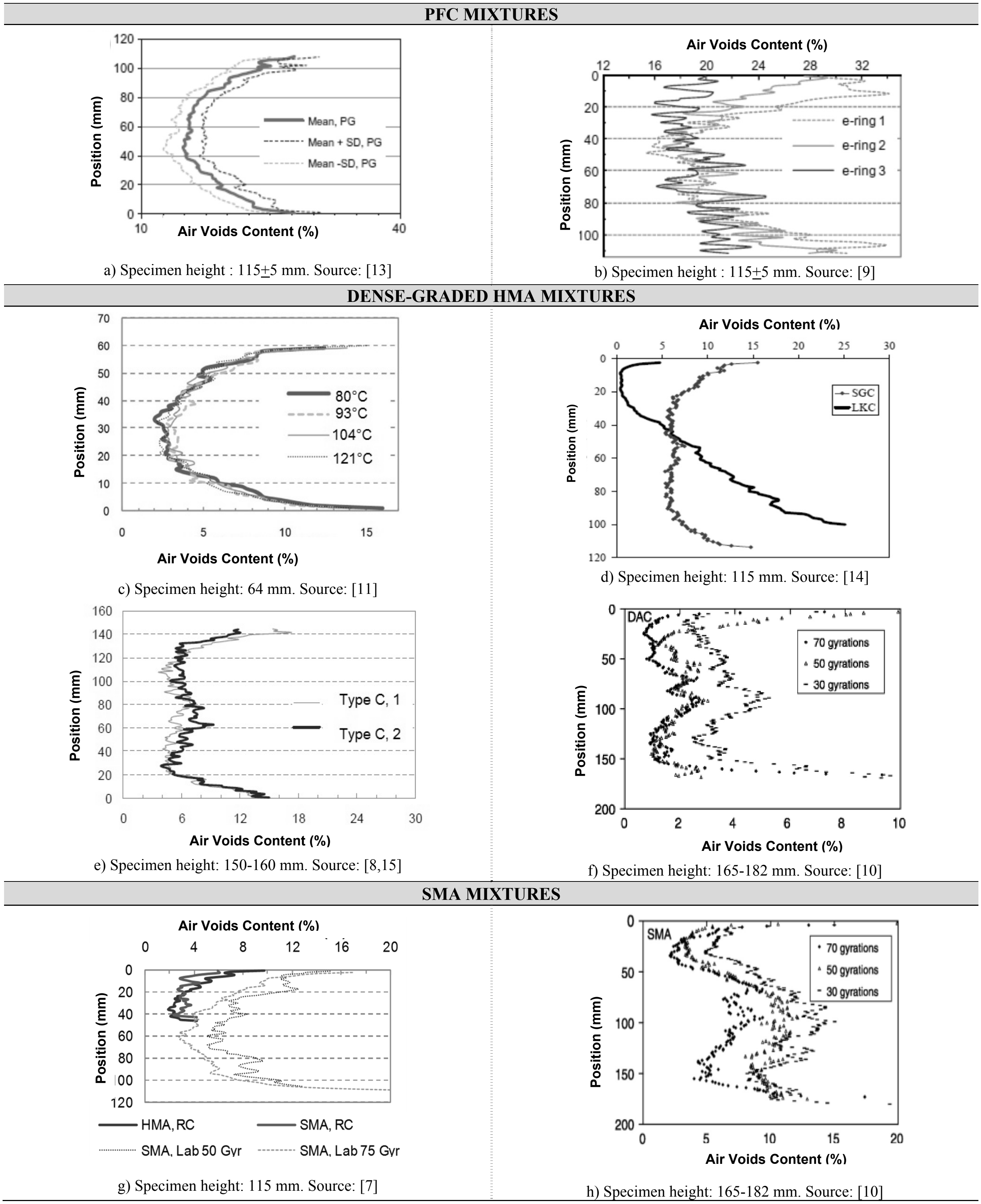
Based on the aforementioned indexes, the following sections summarize practical lessons learnt from the application of X-ray CT and image analysis to evaluate the internal structure of AM.

3. Fabrication of Laboratory Specimens

Recent studies [7-12] have systematically concluded that fabrication of laboratory-compacted specimens using the Superpave gyratory compactor (SGC) should be modified in order to reduce the high vertical- and horizontal-heterogeneity in the internal structure [7-11,13-16] (e.g., vertical and horizontal distributions of the: a) TAV content, b) AVR, and c) CAV content).

Fig. 2 summarizes the typical vertical distribution of TAV content values previously reported for SGC specimens compacted at different heights for three types of AM. These heterogeneous distributions show that the top- and bottom-portions of the specimens have the highest TAV content values as compared to the more homogeneous central portions. In addition, the "shape" of the vertical distribution of TAV content in the SGC specimens is related to the specimen height as supported by Fig. 2c, d, e, and f. The mixture characteristics can also be related to the vertical distribution of AV content [17].

Corresponding specific recommendations for improvement of the vertical homogeneity of SGC specimens include cutting 10 to 20 mm from the top- and bottom-portions of the specimens—with proper consideration of the nominal-maximum aggregate size coverage requirements and the aspect ratio of the specimen—. These recommendations were suggested for improvement of SGC specimens of: a) permeable friction course (PFC) (or open-graded friction course, OGFC) mixtures [9,10], b) dense-graded hot mix asphalt (HMA) mixtures [8,10,18,19], and c) dense-graded warm mix asphalt (WMA) mixtures [11,12]. Similarly, Muraya [10] proposed the reduction of the height of SGC specimens from 150 to 121 mm to enhance the homogeneity of stone matrix asphalt- (SMA), dense graded-, and porous-mixtures.



a) Specimen height : 115±5 mm. Source: [13]

b) Specimen height : 115±5 mm. Source: [9]

c) Specimen height: 64 mm. Source: [11]

d) Specimen height: 115 mm. Source: [14]

e) Specimen height: 150-160 mm. Source: [8,15]

f) Specimen height: 165-182 mm. Source: [10]

g) Specimen height: 115 mm. Source: [7]

h) Specimen height: 165-182 mm. Source: [10]

Figure 2. Typical vertical distributions of TAV content in different types of AM produced using the SGC.

In terms of reducing the horizontal heterogeneity of SGC compacted specimens, Muraya [10] and Dubois et al. [17] suggested coring the outside part of the specimens (i.e., dense-graded HMA and PFC mixtures). This suggestion is consistent with the recommendations reported for PFC mixtures [9] of coring from 152 to 102 mm, which was supported in data similar to that shown in Fig. 2b. This figure compares the typical heterogeneous distribution of TAV content for three concentric cores in a PFC specimen, where the e-ring 1 corresponds to the innermost core of the specimen. Similarly, differences between the AV content in the core and the outer portions of Marshall specimens were previously reported [16].

Nevertheless, the coring and sawing processes may induce variations due to the enlargement or filling of AV with fine-aggregate particles and asphalt mastic. As a result, future research was suggested [9] to fully validate the effects of coring PFC mixtures given the possibility of rearranging the internal structure during this process.

The aforementioned modifications in the specimen fabrication process—leading to a more homogeneous internal structure—would allow for more representative results in the laboratory tests performed for mixture design and evaluation. In fact, some authors [20-23] emphasized the need to produce specimens with uniform AV distributions to enhance testing repeatability based on avoiding high variations of stress and strain in a particular specimen.

4. Laboratory- and Field-Compacted Mixtures

The studies available [7,9,14,19,24-28] on the comparison of laboratory-compacted and field-compacted AM—assessed through analysis of road cores—systematically concluded that minimum or sometimes even no similarities can be found between their microstructure. This conclusion was substantiated based on the analysis of road cores and SGC compacted specimens of HMA mixtures (i.e., dense-graded [7,14,24-26,28], PFC [9], and SMA [27]) and WMA mixtures (i.e., dense-graded [7]). The data in Fig. 2g exemplify this aspect including the comparison of both SGC compacted specimens and road cores, identified as "Lab" and "RC", respectively. In fact, the vertical AV distributions showed dissimilar tendencies that do not allow for further macroscopic comparisons. Additional information on the distribution of TAV in road cores was reported by Masad et al. [29].

Recently, Dubois et al. [17] reported homogeneous internal structures (i.e., TAV content and AVR in dense-, open- and gap-graded HMA mixtures) and improved comparability with field-compacted specimens using a laboratory roller compactor. Similarly, the use of double static compression permitted homogeneity in longitudinal—vertical—AV contents, although they exhibited larger transverse scattering as compared to gyratory compaction [17].

On the other hand, Masad and Button [14] concluded that a relationship between field- and laboratory-compaction is available for determining the required field compaction effort based on the slope of a laboratory compaction curve determined using either the SGC or the linear kneading compactor (LKC). However, additional research is needed to comprehensively relate the laboratory- and field-compaction methods and, hence, ensure more homogeneity in the AM microstructure.

As a result of the previous conclusions, it is crucial that further research focus on developing compaction methodologies that allow for better comparisons between the internal structures of laboratory- and field-compacted AM to: a) improve their compatibility, b) allow for a more homogeneous internal structure, and c) eventually, ensure similar or superior performance.

5. Microstructure of HMA- and WMA-Mixtures

The limited information available at this time [7,11,12,30] on the comparison of the microstructure of laboratory-compacted (i.e., SGC specimens) HMA- and WMA-mixtures leads to conclude that they are comparable in terms of the vertical distribution of: TAV content, CAV content, and AVR. More specifically, some of the WMA additives evaluated (i.e., Asphamin®, Evotherm®, Rediset®, and Sasobit®) [7,11,12,30], and corresponding fabrication processes of WMA mixtures, induced limited differences in the mixture internal structure as compared to those obtained with the conventional—control—HMA mixtures.

In addition, Masad et al. [31] concluded that the use of Evotherm® allowed for a more uniform distribution of TAV and AVR as compared to that obtained in HMA mixtures fabricated using unmodified binders. Estakhri et al. [30] concluded that the use Evotherm® and Aspha-min® induced changes in the compactability and thus, influenced a particular internal structure that could be equivalent to that of HMA mixtures depending on the materials used for its production. However, this conclusion is not warranted due to the limited research conducted on the WMA's internal structure.

At this point, more research is required to further assess the influence of different aggregate gradations, specimen height and diameter, and the use of additional WMA additives and compaction methods on the microstructure of WMA-mixtures.

6. Effects of Additives, Temperature, and Compaction

6.1. Additive effects

Currently, a wide range of additives are available in the global market for the production of modified asphalts, and more recently of WMA mixtures. In addition, the effects of using additives on the internal structure of AM need to be accounted for, since they may differ from one mix to another as a result of factors including the: a) type of mix, b) type of additive, c) additive-asphalt-aggregate compatibility, and d) mixture fabrication protocol.

As a result, in terms of AM microstructure, the main practical lesson concerns the careful selection of the additive for the production of AM in accordance with the materials involved in its production and the specific mixture design. For instance, according to Wegan and Nielsen [32] the effect of using polymer modified asphalt on the microstructure of AM depends on the type of neat binder, the mixture gradation, as well as the temperature and mode of compaction.

In addition, the comparison of PFC mixtures produced with polymer modified asphalt and asphalt rubber [13], led to conclude that these mixtures are different materials with particular internal structures that require the use of different fabrication protocols (i.e., specifications for mix design), as well as specific handling and control techniques.

Consequently, additives play a specific and relevant role on the AM production and its internal structure, which should be further studied in order to better define the most appropriate additives doses, types, and conditions for a homogeneous internal structure, and high-quality performance in the field.

6.2. Temperature effects

The mixture temperature during compaction in both the field and laboratory has to be carefully controlled to minimize the temperature gradients, which can lead to diverse heterogeneous microstructures in AM. However, additional information is still required to clearly assess the effect of the temperature gradients, especially in field compaction conditions.

In the laboratory, based on the compaction of SGC specimens, Masad et al. [31] concluded that more homogeneous temperature profiles can lead to more homogeneity in the internal structure (i.e., vertical distribution of TAV content). However, the relationship was reported as weak and does not warrant improved homogeneity. In addition, the authors concluded that the heterogeneity is not only the result of the temperature profile, but it is also due to the friction against the metallic-mold boundaries.

Research on WMA mixtures [11] concluded that different compaction temperatures generated internal structures—TAV content and AVR—with insignificant statistical differences (see Fig. 2c; specimens fabricated using Evotherm®). On the contrary, Estakhri et al. [30] stated that different laboratory compaction temperatures induced changes in the TAV content of both HMA- and WMA-mixtures (i.e., fabricated using Evotherm DAT®, Sasobit®, and Advera®), which is due to the differences among the physico-chemical properties of the additives used.

Future research should look for improved comparisons between different types of AM to determine the most suitable conditions of temperature control to promote homogeneity in the internal structure of both field- and laboratory-compacted AM.

6.3. Compaction effects

Compaction is one of the most critical variables to be considered in the design and construction of AM, since both the density and microstructure acquired by AM is related to their performance. Therefore, adequate compaction control in both the field and laboratory has to be conducted to produce AM with proper performance [33].

Previous research [14,17,19,34] concluded that the compactor type and its mode of energy application, as well as the compaction energy influence to a great extent the internal structure of AM. Regarding the type of compactor, Harvey and Monismith [35] reported dissimilar mechanical responses when using different compaction methods (i.e., rolling wheel, kneading compaction, and gyratory compaction), since they induced different internal structures. In general, the strongest conclusion of their study regards the disability to interchange different compaction methods in the laboratory due to their strong influence on AM performance.

More recently, Jonsson et al. [36] compared the rolling wheel, Marshall, and gyratory compaction using X-ray CT and concluded that none of these methods produced homogeneous distributions of TAV content. The Marshall compaction led to the most homogenous horizontal and vertical distributions of TAV [36]. In terms of the gyratory compaction, numerous studies [8-10,13,14,17] have reported the production of heterogeneous distributions of TAV content —as shown in Fig. 2 and previously discussed—and CAV content [9].

According to Verdi et al. [37], the AM final density depends principally on the number of gyrations and less on the vertical pressure applied by the gyratory compactor. In addition, recent research [10,17] suggested that the number of gyrations cannot be used as a control parameter for compaction due to the scattered AV distributions.

In this regard, although "theoretically" higher compaction efforts are used to get homogeneous distributions of AV, this case does not often occur, because of external factors affecting the aggregates packing in the AM [31]. Fig. 2f and 2h and Fig. 3 show data supporting the effect of the compaction energy—number of gyrations—for specimens fabricated with different mixture types and at two heights. Similar results were reported for PFC mixtures [9].

Future studies should be able to determine which types of compaction—equipment and methods—are more efficient for obtaining homogeneous AM specimens in both the laboratory and field.

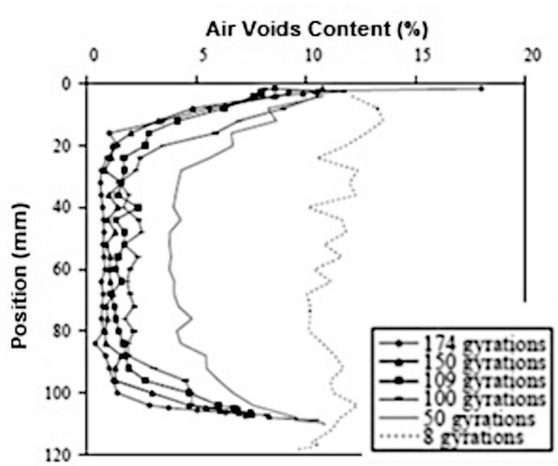


Figure 3. Vertical distribution of TAV content under varying compaction energies in the SGC.
Source: [14].

7. Stone-on-Stone Contact

The arrangement—microstructure—of the structural skeleton formed by the aggregates in the compacted AM determines to a vast extent its mechanical response. This aspect is particularly critical to ensure the proper performance of PFC- and SMA-mixtures based on a fully developed condition of stone-on-stone contact in the coarse aggregate. This contact condition is mostly evaluated conducting macroscopic evaluations according to the VCA—voids in the coarse aggregate—method [38,39]. Additional research [40], based on the application of X-ray CT and image analysis, further validated the VCA method. However, the authors [40] highlighted the advantage of image analysis over the VCA method, since it can allow the quantification of the number of contact points as well as optimizing the aggregate gradation.

As in the case of the TAV- and CAV-content, a homogeneous vertical distribution of the number of contact points is desirable. However, a recent study based on X-ray CT and image analysis showed the existence of heterogeneous distributions of contact points (as an index of stone-on-stone contact) in SGC compacted specimens of PFC mixtures [41]. Thus, the need for a homogeneous microstructure still includes both the AV- and aggregates-arrangement.

Recent research [42-45] also determined the influence of stone-on-stone contact and aggregates characteristics on the internal structure and corresponding mechanical response of the dense-graded and SMA mixtures. In particular, the main practical lesson derived from these studies [42-45] concerns maximizing the number of contact points for a stiff structural skeleton capable of providing a good mixture performance. The ways of obtaining these may include use of adequate compaction: a) vertical pressures and b) angles—gyratory compactor—to get an appropriate orientation of the aggregates and enhance the mechanical response.

Future research should focus on determining the relationship between the aggregate geometric characteristics (e.g., evaluated using nondestructive technology) and the internal structure of AM to obtain conclusive results that can be used as inputs for mix design, modeling, and field applications.

8. Relationship between Internal Structure and Performance

The AM field performance largely depends on the mixture microstructure [8,14]. Previous research [31] stated that gyratory-compacted specimens exhibited the poorest mechanical response, evaluated by means of the shear permanent deformation (PD) test, while linear kneading-compacted specimens had the highest resistance to PD, and the rolling wheel-compacted specimens reported intermediate results. The differences in the internal structure of the specimens—exemplified in Fig. 2d—can partially explain their diverse mechanical response.

In addition, Masad et al. [31] concluded that similar TAV contents can lead to comparable rut depth between field- and laboratory-specimens, and the Hamburg PD test results were more affected by the AV content rather than by the microstructure. However, specimens with a uniform distribution of TAV content had less variation in the Overlay test (i.e., cracking resistance) than those with a heterogeneous microstructure.

Studies on PFC mixtures [9,46] concluded that their particular responses to mechanical tests, used to assess the mixture performance as a result of their specific gradations, type of binders, and mix design, are highly dependent on the internal structure and exhibited different responses to those typically identified for dense-graded HMA.

In years to come, research on assessing performance of AM should further account for the microstructure to determine their relationship. This will lead to a better understanding on the best scenarios for obtaining the performance pursued when designing different types of AM.

9. Modeling Applications

The X-ray CT outputs constitute a vast amount of relevant information for the development of mathematical models used to determine the possible scenarios at which the pavement materials could fail, be susceptible to damage or develop inappropriate performance in the field. Therefore, the integration of X-ray CT and mathematical models turn out to be critical and essential to have a deeper understanding on the AM characteristics and account for new approaches in their design, production, and placement in the field.

In response to this need of understanding the relation between the mixture's internal structure and the distresses affecting the AM, numerous mathematical-modeling applications have been accomplished by means of the information available from X-ray CT. Ultimately, the main objective of these studies has to do with finding accurate simulations of field response, based on inputs from the laboratory, and get valid information for improving the design, construction, and forensic evaluation of AM [14].

In particular, based on X-ray CT images, Caro [47] proposed a coupled micromechanical model to evaluate moisture damage induced in AM. This research, along with similar studies [48-50] led to a more comprehensive analysis of the microstructure effects on the performance and damage phenomena of AM as compared to the conventional phenomenological approaches applied for their study. One of the strongest recommendations offered by the authors concerns the advance in innovative probabilistic models and enhancement of the existing ones to have more accurate predictions of moisture induced damage and have improved predictions of the AM field performance.

Mathematical models have also been proposed to predict the fatigue life, aging process, influence of chemical substances [51], and permeability of dense-graded HMA [29] and PFC mixtures [52]. Additional information on similar studies related to modeling and simulation on AM can be found in work by Liu et al. [51].

All the efforts and innovation conducted in the modeling of AM damage by means of non-destructive techniques constitute a highly valuable element of research that allows for future pavement structures with enhanced durability, better functionality, and performance. Therefore, there is a long way to go in this regard for future research.

10. Conclusions and Recommendations

This paper summarized the main practical lessons learnt from the use of X-ray CT and image analysis for the evaluation of the internal structure of AM (mainly based on the analysis of the distributions of AV content). Based on the information presented, the following conclusions and recommendations are offered:

- X-ray CT and image analysis enable the computation of the internal structure for AM, which have allowed a better understanding of AM characteristics and response including, for example, the nondestructive analysis of the AV characteristics and the computation of aggregates distribution, orientation, and contact.
- This feasible quantification of the AM microstructure, based at present primarily on the analysis of AV characteristics, supported extensive analysis of both laboratory- and field-compacted AM leading to multiple practical applications as previously documented.
- The control of the variables affecting the AM internal structure (e.g., asphalt-, aggregate-, and additive-properties, mixture type, production methods, temperature, and compaction) is to be further studied to define the conditions to ensure an optimum microstructure and, consequently, an optimum AM performance.
- In the coming years, the advancement of non-destructive material characterization techniques should allow for a more comprehensive evaluation of the AM microstructure that lead to better mixture designs and higher durability over time in the field. For this purpose, more detailed studies of internal structure of different AM need to be performed as well as development of new devices and equipment with higher accuracy and representativeness.

11. Disclaimer

This paper does not constitute a standard, specification, nor is it intended for design, construction, bidding, contracting, or permit purposes. Trade names were used solely for information and not for product endorsement.

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A.E. Alvarez-Lugo, received a Bs. Eng. in Civil Engineering in 1998 from the Universidad Nacional de Colombia. He got his MSc. degree in Civil Engineering in 2001 from the Universidad de los Andes, and his Ph.D. (Materials-Pavements) in 2009 from Texas A&M University. From 1998 to 2000 and 2001 to 2002, he worked in consulting engineering in the pavements engineering sector, and since 2002 he has been working as a professor in civil engineering and researcher. Currently, he is an Associate Professor and Head of the Civil Engineering Department at the University of Magdalena, Santa Marta, Colombia. His research interests include: bituminous materials, nanotechnologies, development of new materials for the pavement industry, non-destructive analysis of pavements, and design and implementation of permeable friction courses (PFC) mixtures.
ORCID: 0000-0001-9010-7642

J.S. Carvajal-Muñoz, received a Bs. Eng. in Environmental and Sanitary Engineering in 2012 and a Bs. Eng. in Civil Engineering in 2013 from the University of Magdalena. He has research experience since 2008 working as research assistant for the GIRPSU- and GIIC-research groups at the same institution. In 2013 he worked as Occasional Professor for the Civil Engineering program at the University of Magdalena. He is currently a M.Sc. student (Materials) at Texas A&M University. His research interests include both environmental sciences and civil engineering. In the first he is interested in biological fertilization of soils, recycling of materials, photocatalysis and advanced treatment of waste waters. In the civil area he is interested in Materials science and characterization, use of recycled materials in pavements and soils, bituminous materials, and non-destructive characterization of asphalt mixes.
ORCID: 0000-0003-3977-5076