INTERNAL STRUCTURE OF LABORATORY COMPACTED WARM-MIX ASPHALT

ESTRUCTURA INTERNA DE MEZCLAS ASFÁLTICAS TIBIAS COMPACTADAS EN LABORATORIO

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ABSTRACT: Warm-mix asphalt (WMA) mixtures are asphalt mixtures fabricated at lower temperatures (i.e., 20–50 °C) than conventional hot-mix asphalt (HMA). Therefore, compared to HMA, WMA offer several engineering, economical, and environmental advantages. However, research is still required to identify the response, properties, and performance of WMA, since it is still a relatively new technology. This paper focuses on the analysis of the internal structure of WMA specimens compacted using both the Superpave Gyratory Compactor (SGC) and the Texas Gyratory Compactor (TxGC). This analysis was conducted in terms of the air voids (AV) characteristics assessed by applying X-ray computed tomography and image analysis techniques. The results obtained suggest that the addition of WMA additives and corresponding reduction of the compaction temperature for SGC specimens did not lead to significant changes in the vertical distribution of total AV content, as compared to that of the control-HMA. However, some differences were reported in terms of the AV size, which suggests the existence of discrepancies in the aggregate packing condition. Therefore, additional research is suggested to fully validate the equivalence of the internal structure of both WMA and HMA.

KEYWORDS: Warm-mix asphalt (WMA), hot-mix asphalt (HMA), mixture internal structure, air voids (AV), X-ray computed tomography (X-ray CT), pavement structure.

RESUMEN: Las mezclas asfálticas tibias (MAT) son mezclas asfálticas fabricadas a menores temperaturas (i.e., 30–50 °C) que las mezclas asfálticas en caliente (MAC) convencionales. Por tanto, en comparación con las MAC, las MAT ofrecen diferentes ventajas ambientales, económicas y de ingeniería. Sin embargo, aún se requiere investigación para identificar las propiedades, el desempeño y la respuesta de las MAT, dado que estas mezclas constituyen una tecnología relativamente nueva. Este artículo se centra en el análisis de la estructura interna de especímenes de MAT compactados usando el Compactador Giratorio Superpave (CGS) y el Compactador Giratorio de Texas (CGTx). Este análisis fue realizado en términos de las características de los vacíos evaluadas mediante la aplicación de tomografía computarizada con Rayos-X y técnicas de análisis de imágenes. Los resultados obtenidos sugieren que la adición de aditivos tipo MAT y la correspondiente reducción de la temperatura de compactación de especímenes compactados en el CGS no generaron cambios significativos en la distribución vertical del contenido total de vacíos comparado con la distribución de la MAC de control. Sin embargo, algunas diferencias fueron reportadas en términos del tamaño de los vacíos, lo cual sugiere la existencia de discrepancias en la condición de empaquetamiento del agregado. Por lo tanto, se sugirió investigación adicional para validar completamente la equivalencia de la estructura interna de las MAT y las MAC.

PALABRAS CLAVE: Mezcla asfáltica tibia, mezcla asfáltica en caliente, estructura interna de la mezcla, vacíos, Tomografía Computarizada con rayos-X, estructura de pavimento.

1. INTRODUCTION

Warm-mix asphalt (WMA) is the term used to describe the collection of technologies engineered to allow reducing the plant production and road placement temperature of asphalt mixtures as compared to traditional hot-mix asphalt (HMA). At present, the use of WMA technologies (or WMA) allow mixture production at temperatures 20–50°C lower than those used for the HMA [1,2]. In addition, several advantages are already identified for WMA, as compared to HMA, which include: (*i*) reduction of fuel consumption for the

mixture fabrication, (*ii*) reduced emission of pollutants (e.g., blue fumes), (*iii*) improved compaction, and (*iv*) the possibility of having a longer paving season [3].

The rigorous environmental regulations applied to the construction industry as well as the sustained high cost of fuel in recent years led to an accelerated growth in the application of these WMA technologies during the last decade [2]. For example, the state of Texas (USA) placed 1000 tons of WMA between 2006 and 2007, whereas in 2009, Texas had placed more than one million tons of WMA [3]. In addition, this rapid growth is reported in Europe [2] and other places like China [1]. However, research is still required to completely identify the response, properties, and performance of WMA, since WMA is still a relatively new technology.

In this context, characterization of the internal structure of civil materials, including asphalt mixtures, can lead to a better understanding of the macroscopic response and performance of these materials. In this regard, recent research has focused on characterizing the internal structure of dense-grade HMA [4-7]. In addition, previous research included the characterization of the internal structure of open-graded HMA (i.e., permeable friction course mixtures [8] and European porous asphalt [9]). Based on similar principles, the analysis of the internal structure of WMA has been hardly explored (e.g., [10]) and it can offer additional information to better understand the effect of using different WMA technologies instead of the traditional HMA.

Consequently, the objective of this paper focuses on characterizing the internal structure of different WMA laboratory-compacted specimens to identify differences with respect to an HMA used as a control (or reference) mixture. In addition, the internal structure of different WMA specimens, compacted at diverse temperatures and fabricated using two different laboratory compaction devices, is compared.

The mixtures analyzed were fabricated with three WMA additives, namely Asphamin®, Sasobit®, and Evotherm®. The analysis of mixture internal structure was conducted in terms of the air void (AV) characteristics, which were determined by applying X-ray computed tomography (X-ray CT) and subsequent image analysis techniques.

In the paper, after presenting the methods and materials used, a section on the analysis of mixture internal structure is included. Next, results are presented and discussed. The paper is completed by a section of conclusions and recommendations.

2. METHODS AND MATERIALS

This study includes the characterization of laboratory-compacted dense-graded WMA and the corresponding control-HMA. The control-HMA was used to comparatively assess the effect of the WMA additives on the internal structure of the compacted asphalt mixtures. Table 1 summarizes the main characteristics of the WMA as well as the control-HMA evaluated. These mixtures were designed in accordance with the Texas Department of Transportation (TxDOT) mix design procedure for dense-graded HMA [11] and corresponding specifications of materials [12].

Table 1. Characteristics of the mixtures evaluated

Mixture type	Type D dense graded
Asphalt type	PG 64-22
Aggregate type	91% Limestone; 9% field sand
OAC	4.6% for the control-HMA and all WMA
Additives (in addition to WMA)	1% lime for control-HMA and all WMA

Note: OAC = optimum asphalt content

The WMA additives used were: Asphamin®, Sasobit®, and Evotherm®. Asphamin® is a hydro-thermally crystallized synthetic zeolite [2]. At high temperatures (above 100 °C) the zeolite releases water and foams the asphalt to increase the workability and improve aggregate coating at reduced temperature. Sasobit® is an asphalt modifier engineered to reduce the asphalt viscosity, and Evotherm® is an emulsion-type product (it has a high asphalt residue) that also includes additives to improve aggregate coating and adhesion promoters [13]. Detailed information on these WMA additives is reported elsewhere [2,3,14].

The WMA and control-HMA specimens were compacted in the laboratory using a Texas Gyratory Compactor (TxGC) and a Servopac Superpave Gyratory Compactor (SGC), in accordance with the test methods Tex-206-F and Tex-241-F [11], respectively. The TxGC and SGC are used in Texas for the fabrication of specimens (of both HMA and WMA) that are subsequently used for mix design and performance evaluation, respectively. The SGC produced 152.4 mm-diameter specimens (at variable heights). For this study, SGC specimens of two heights, namely 115±5 mm and 62±2 mm were analyzed. The TxGC compacted 101.6

mm-diameter specimens. The corresponding target specimen height was 50.8±1.5 mm [11].

The control-HMA was compacted at 121°C and the WMA (Asphamin®, Sasobit®, and Evotherm®) at 104°C. Analysis of the effect of compaction temperature on the internal structure of WMA specimens (i.e., Evotherm® WMA), was conducted on SGC specimens compacted at temperatures of 80°C (field-compaction cessation temperature for the control-HMA), 93°C, 104°C, and 121°C (compaction temperature specified for the control-HMA). The two intermediate temperatures did correspond to potential temperatures for WMA field compaction. Both the SGC and TxGC specimens were compacted, tested for computation of total AV content [11], and scanned using the X-ray CT equipment. Table 2 presents the total AV content values computed for the scanned specimens.

Table 2. Total AV content of scanned specimens

Specimen	CT (°C)	TAVC (%)
SGC Control-HMA, 115 mm	121	2.91
SGC Asphamin®, 115 mm	104	2.90
SGC Sasobit®, 115 mm	104	2.84
SGC Evotherm®, 115 mm	104	3.21
TxGC Control-HMA	121	1.96
TxGC Sasobit®	104	2.20
TxGC Evotherm®	104	2.36
SGC Evotherm®, 115 mm-2	121	2.8
SGC Evotherm®, 62 mm	80	5.1
SGC Evotherm®, 62 mm	93	5.2
SGC Evotherm®, 62 mm	104	5.2
SGC Evotherm®, 62 mm	121	5.1

Note: CT = compaction temperature; TAVC = total air voids content

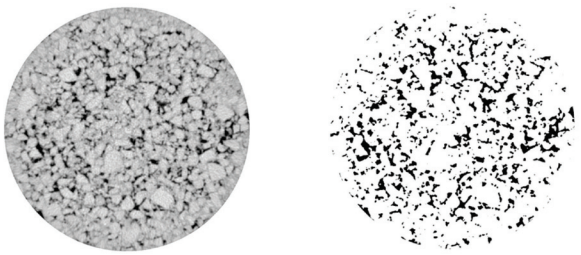
The next section describes the analysis of mixture internal structure and the computation of corresponding parameters in detail.

2.1. Analysis of mixture internal structure

As summarized by Alvarez et al. [8], the internal structure of HMA can be computed based on both the AV characteristics and aggregate structure. The former can include the distribution of total AV content, the distribution of AV size, and AV connectivity (associated AV forming flow paths), while the aggregate can be assessed in terms of its distribution, contact, and orientation. In the past, the lack of available techniques to properly identify the HMA internal structure limited corresponding characterization [15]. However, during the last decade, the X-ray CT and application of subsequent image analysis have permitted proper nondestructive quantification of the internal structure of HMA and other construction materials.

In this particular study, the internal structure of WMA and a control-HMA was characterized in terms of both the distribution of total AV content and distribution of AV size (i.e., mean radius of AV). These indexes were calculated based on computer images captured using the X-ray CT, and the subsequent analysis of these images. The fundamentals and operation principle of the X-ray CT are discussed elsewhere [16,17].

Parallel gray-scale images (horizontal transversal bidimensional sections) were acquired with a 1 mm vertical gap using the X-ray CT equipment at Texas A&M University. Figure 1(a) presents a typical gray-scale image obtained for a WMA. These images have a 0.17 mm/pixel resolution. The image analysis included two main steps: (*i*) thresholding and (*ii*) calculation of the AV characteristics (content and size). The first process was performed on the grayscale images that were scanned, and it allowed for the generation of corresponding black and white images (Fig. 1b). The solid phases (aggregate and mastic) were converted to white zones, while the AV became black pixels (the black zones in Fig. 1b). The second analysis stage, conducted on the black and white images, allowed for the computation of both total AV content and AV size, as subsequently discussed. These image analyses were performed by using an application for image analysis, previously developed [18], based on the Image-Pro® Plus software [19]. Additional details on this analysis of images can be found in previous work [18,20].



(a) (b)

Figure 1. Grayscale image (a) and corresponding black and white image (b) of a dense-graded WMA

Computation of the total AV content for an individual black and white image (AV_i) was conducted as follows:

$$AV_i = \frac{A_{vi}}{A_T} \quad (1)$$

where A_{vi} is the area of AV in image *i* and A_T corresponds to the cross-sectional area (circle area) of image *i*. Based

on these individual computations (AV_i), the total AV content for a particular specimen (AV_s)—represented by n black and white images—is computed as

$$AV_s = \frac{\sum_{i=1}^{n} AV_i}{n} \quad (2)$$

The calculation of the mean radius of AV ($\bar{r}_i$) in image i was based on Eq. 3, where M_i corresponds to the number of AV in image i.

$$\bar{r}_i = \sqrt{\frac{A_{\dot{v}}}{\pi M_i}} \quad (3)$$

Since the parameters referred to are computed for each image (spaced 1 mm apart) representing a specimen, corresponding computations led to the vertical distribution of both total AV content and mean radius of AV (or AV size).

3. RESULTS AND DISCUSSION

This section summarizes the results of the internal structure analysis conducted on the mixtures. The results include: (*i*) a comparison of SGC and TxGC compacted specimens and (*ii*) the analysis of the effect of temperature on the internal structure of the Evotherm® WMA compacted specimens.

3.1 Analysis of SGC and TxGC compacted specimens

This section presents results of the mixture internal structure for both SGC- and TxGC- compacted specimens. Figure 2 shows the vertical distribution of total AV content for both the control-HMA and WMA specimens fabricated using the SGC.

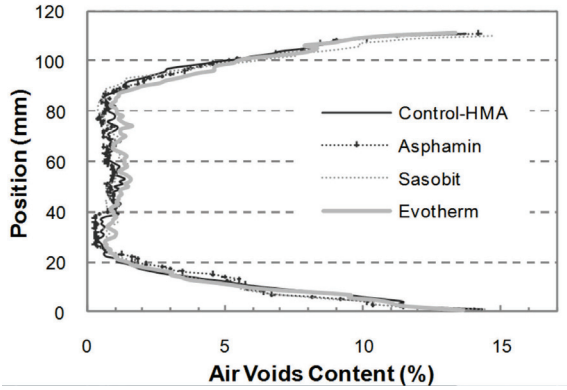


Figure 2. Vertical distribution of total AV content for SGC specimens (control-HMA and WMA)

These results suggest that the use of WMA additives and corresponding reduction in the compaction temperature of the asphalt mixtures did not lead to changes in the internal structure of the SGC-compacted specimens, as evaluated in terms of the distribution of the total AV content. The maximum differences in the total AV content between the control-HMA and the WMA specimens was approximately one percentage point, and it was registered in the central portion of the SGC specimens. Based on the typical variability of HMA laboratory production, the difference at one percentage point in the total AV content can be accepted as part of the variability associated with typical replicate HMA specimens.

The heterogeneous vertical distribution of total AV content obtained for these SGC specimens suggests the need of cutting the top and bottom portions of both the WMA and control-HMA specimens. Cutting approximately 20 mm at the top and bottom of the SGC specimens would lead to a more homogeneous distribution of AV. As identified in previous research [5], this new distribution would permit an improved assessment of performance (e.g., permeability measurement, fatigue life, etc.) as compared to that obtained with the originally compacted SGC specimens. In addition, this recommendation is coincident with previous research suggestions on PFC [21] and dense-graded HMA mixtures [22].

The vertical distribution of total AV content of both the control-HMA and WMA specimens fabricated using the TxGC (for mix design purposes) is shown in Fig. 3.

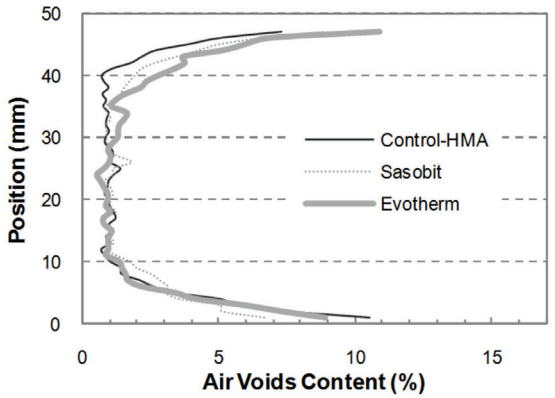


Figure 3. Vertical distribution of total AV content for TxGC specimens (control-HMA and WMA)

Although the total height of these specimens corresponds to 51 mm, the X-ray CT scanned height and corresponding results shown in Fig. 3 were reduced to approximately 47 mm due to technical difficulties

to scan the top and bottom sections of the specimens.

The vertical distribution of total AV content for both the control-HMA and WMA specimens fabricated using the TxGC are similar. The maximum differences registered in the distribution of the total AV content are around two percentage points. Therefore, and as indicated for the SGC specimens, the incorporation of WMA additives and corresponding reduction of the compaction temperature did not generate major changes in the internal structure of TxGC specimens.

Figure 4 presents a comparison of the vertical distribution of total AV content for the specimens used for mix design (TxGC) and performance evaluation (SGC) of WMA. The central portion of both types of specimen registered similar values of total AV content. However, the top and bottom portions of the SGC specimens have higher values of total AV content as compared to those computed for the TxGC specimens. As a conclusion, both types of specimen will benefit from cutting the top and bottom portions to obtain a more uniform distribution of AV, although the portion to cut in the TxGC specimens may include only 5 to 10 mm in height.

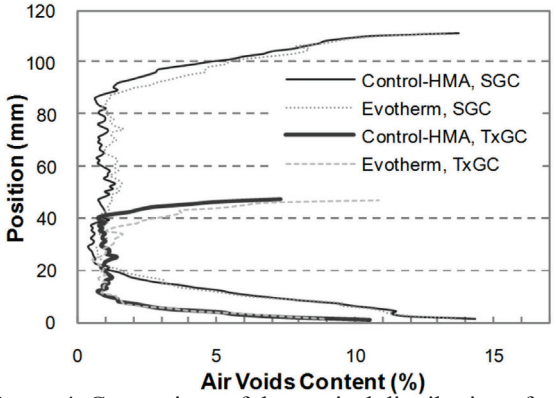


Figure 4. Comparison of the vertical distribution of total AV content for both SGC and TxGC specimens

Figure 5 shows the comparison of the vertical distribution of AV size (i.e., AV radius) for specimens compacted using the SGC as well as the TxGC. As compared to the control-HMA, the WMA specimens exhibited approximately parallel distributions of AV radius. However, the WMA specimens showed higher values of AV radius along the entire specimen height.

These differences can be related to discrepancies in the aggregate particles packing as suggested in previous research by Watson et al. [23] and discussed by Alvarez et al. [24]. As aggregate packing increases, and consequently the number of particle contacts increases (i.e., stone-on-stone contact condition), the AV are separated into smaller AV. Additional research is, however, recommended to further assess the aggregate structure in both the WMA and the corresponding control-HMA, based on image analysis of the aggregate phase.

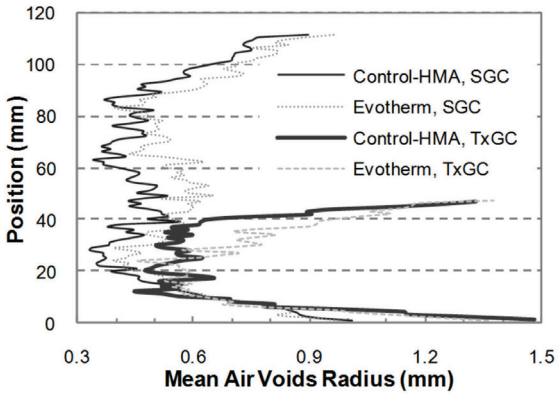


Figure 5. Comparison of vertical distribution of AV size for SGC and TxGC specimens

3.2 Analysis of the effect of temperature on the internal structure of the Evotherm® WMA compacted specimens

The effect of compaction temperature on the internal structure of WMA was evaluated by comparing the distribution of both the total AV content (Fig. 6) and AV size (Fig. 7) of laboratory compacted (SGC) short specimens (62 mm in height). These specimens were fabricated using Evotherm® WMA.

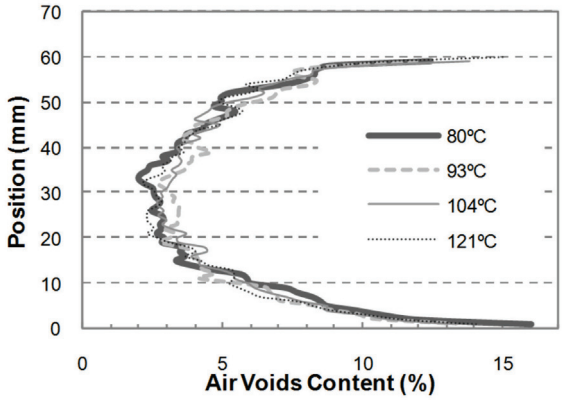


Figure 6. Vertical distribution of total AV content for SGC specimens produced using Evotherm®-WMA and

compacted at different temperatures.

Data presented in Fig. 6 suggest that the reduction of the WMA compaction temperature from the temperature specified for compaction (121 °C) to the cessation temperature (80 °C) of the control-HMA, did not modify the heterogeneous distribution trend of the total AV content of short SGC specimens. Similar conclusions can be stated based on the differences of the AV size reported in Fig. 7.

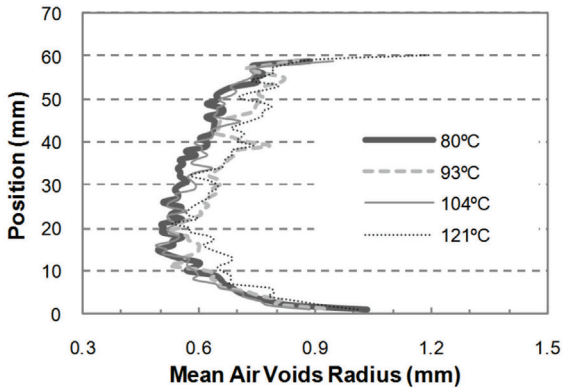


Figure 7. Vertical distribution of AV size for SGC specimens (62 mm in height) produced using Evotherm®-WMA and compacted at different temperatures

A comparison of the AV size distributions computed for both the tall (115 mm in height) and short (62 mm in height) SGC specimens (reported in Figs. 5 and 7, respectively) suggests higher AV size values in the short specimens. These discrepancies provide preliminary evidence of differences in the aggregate particle packing for these two types of SGC specimens. A better coincidence is observed for the distribution of AV size computed for the short SGC specimens—used for performance evaluation in the Hamburg Wheel Tracking test (Tex-242-F [25])—and the TxGC specimens, which are used for mix design purposes as specified by TxDOT [11] (Figs. 5 and 7).

Figure 8 compares the vertical distribution of total AV content for SGC specimens (fabricated using Evotherm®-WMA) compacted at two different heights. The mean total AV content for the 62 and 115 mm–in-height specimens was, respectively, 5.15% and 3.21% (Table 2). At similar total AV content values at the top and bottom portions for both specimen types (i.e., heights), the short specimens exhibited higher AV content in their central portion. This is coincident with their higher total AV content values. However, the data shown in Fig. 8 provide evidence of a more heterogeneous distribution for the total AV content of the short specimens.

In addition, these short specimens—produced to meet the specimen height for subsequent performance testing—cannot be cut to improve the heterogeneity of the total AV content distribution. Therefore, based on the available data, the production of SGC specimens for testing WMA in the Hamburg Wheel Tracking test should be conducted by compacting the specimens to 115 mm in height and subsequent cutting (for the top and bottom portions) to ensure the specified height (62±2 mm) [25].

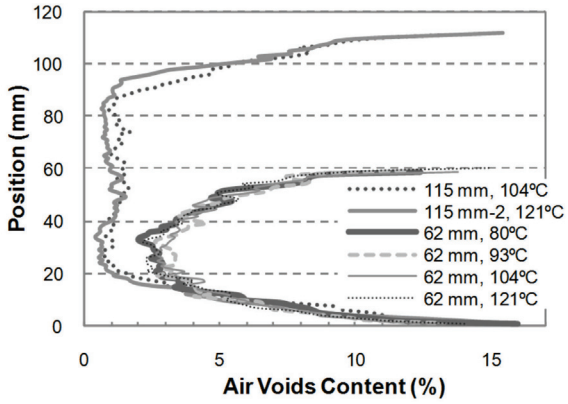


Figure 8. Comparison of the vertical distribution of total AV content of SGC specimens (Evotherm®-WMA) of different heights

Previous research [26] evaluated the macroscopic response of WMA in terms of laboratory compactability, and concluded that the they exhibited better compactability compared to that of corresponding control-HMA mixtures. Despite these previous results, the evaluation of the mixture internal structure conducted in this study did not suggest major differences between the control-HMA and the WMA related to possible changes in the mixture compactability. However, additional research is still needed in order to assess the characteristics of the aggregate phase in WMA.

6. CONCLUSIONS AND RECOMMENDATIONS

This paper presents an analysis of the internal structure

of warm-mix asphalt (WMA) fabricated using three different additives, which include Asphamin®, Sasobit®, and Evotherm®. The mixtures analyzed were compacted in the laboratory using the Superpave gyratory compactor (SGC) as well as the Texas gyratory compactor (TxGC). The analysis of internal structure was conducted in terms of the characteristics of AV, including the distribution of both total AV content and AV size (i.e., the radius of AV).

Based on the analysis conducted for the mixtures studied, the following conclusions can be offered:

- Analysis of both the control-HMA and WMA suggested that the addition of WMA additives and corresponding reduction of the compaction temperature did not lead to significant changes in the vertical distribution of total AV content of SGC- and TxGC-compacted specimens.

- However, some differences were reported for the AV size (i.e., the AV radius) of the control-HMA and WMA. These differences can be related to discrepancies in the packing (stone-on-stone contact condition) and orientation of the aggregate particles. Therefore, in addition to the parameters of mixture internal structure evaluated in this study, future research is recommended, which would characterize the aggregate particles structure in the WMA, and thus fully validate the possible equivalence of the internal structure of WMA and HMA.

- Production of 62 mm-in-height specimens for the performance evaluation of WMA using the Hamburg Wheel Tracking test should be conducted by compacting 115 mm-in-height specimens and then by cutting the top and bottom portions to ensure the height specified for the Hamburg test specimens. This procedure is recommended as an alternative to direct compaction of 62 mm-in-height SGC specimens for subsequent performance evaluation.

- Mixture internal structure assessment of field-compacted WMA is required to further validate the findings reported in this study. This proposed evaluation can also permit the comparison of the mixture internal structure of field- and laboratory-compacted WMA.

The analysis of the mixture internal structure performed offers additional information on the mixture microstructure, which can be used to better explain the performance of WMA. Additional research is recommended in order to link the performance evaluation of WMA and the characterization of its internal structure.

7. DISCLAIMER

The contents of this paper reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein and do not necessarily reflect the official views or policies of any agency or institute. 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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