Distribution of air voids in compacted Hot-Mix Asphalt samples – laboratory vs field

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***Synopsis*—The research work presented in this paper investigated the spatial distribution of air voids in compacted Hot-Mix Asphalt (HMA) core samples under different compaction levels and layer/briquette thicknesses. A medium-graded HMA mix was used to investigate the vertical and radial or diametrical distribution of air voids in asphalt samples compacted using the Superpave Gyratory Compactor (SGC). The spatial distribution of air voids in asphalt cores extracted from two road sections constructed using the standard South African Bituminous Treated Base (BTB) and High Modulus Asphalt (HiMA) mixes were also investigated to supplement the study. Findings of the study indicate that the vertical distribution of air voids of the compacted HMA samples differs, with the top and bottom parts exhibiting relatively high air voids content (i.e., low density). The middle part of the HMA samples appears to possess fairly uniform air voids distribution, which confirms the current procedure of coring samples for HMA performance testing from the middle part of the compacted HMA specimens. On the other hand, the radial distribution of air voids was uniform for both the gyratory compacted samples and the field cores. The study has demonstrated that the spatial distribution of air voids may serve as a potential indicator of problems such as aggregate segregation, and temperature variation with depth during compaction, which influence compaction efficiency, as well as the future performance of the asphalt mix layer.**

Keywords*— HMA compaction, density, air voids, aggregate segregation, temperature variation.

I. INTRODUCTION

The volumetric and mechanical properties of Hot-Mix Asphalt (HMA) are highly affected by its internal structure. During compaction, HMA undergoes internal structural changes in response to the compaction effort, whereby the distance between aggregate particles reduces, resulting in decreased air voids [1-2]. The aggregate packing characteristics (orientation, contact and distribution), binder volume and air voids characteristics (distribution, size and interconnectivity) define the internal structure of HMA, which in turn, plays a significant role in the mechanical and volumetric properties of HMA [2-7]. As such, monitoring of air voids during construction of asphalt pavement layers is not only a means of Quality Control (QC) and Quality Assurance (QA), but also a primary indicator of the internal structure of the compacted HMA layer and its future performance.

The objective of the study presented in this paper was to investigate the spatial distribution of air voids in asphalt samples compacted using the Superpave Gyratory Compactor (SGC) and field compacted HMA core samples under different compaction levels and layer/briquette thicknesses. In the laboratory study, a medium-graded HMA mix was used to investigate the vertical and radial distribution of air voids of gyratory compacted samples at two target air voids contents (i.e., representing typical design and field construction air voids) and two sample heights (170 and 120 mm). The spatial distribution of air voids in asphalt cores extracted from two road sections constructed using the standard South African Bituminous Treated Base (BTB) and High Modulus Asphalt (HiMA) mixes were also investigated. The distribution of the air voids could serve as a potential indicator of aggregate segregation, as well as temperature variation with depth during HMA compaction, which may influence compaction efficiency and HMA performance. Furthermore, the understanding of the distribution of the air voids could assist in identifying those parameters which need to be considered and controlled when developing models for simulating the arrangement of the internal structure of the asphalt mix during the compaction process and subsequent performance of the HMA layer.

The paper is organized and structured as follows; this introduction section is followed by an overview of the approaches for the determination of the density of compacted HMA specimens. The experimental plan is then described, followed by an analysis and discussion of the test results. Conclusions and recommendations are presented at the end of the paper.

II. DETERMINATION OF DENSITY OF COMPACTED HMA

The Saturated Surface-Dry (SSD) method is a widely used approach for the determination of the Bulk Density (BD) of compacted HMA specimens. The South African standard procedure for the determination of the BD using the SSD method is described in SANS 3001-AS10 [8]. Using the SANS 3001-AS10 standard test method, the dry mass (M_1) of the HMA specimen is first determined, following which, the specimen is immersed in a water bath set at room temperature (typically 25 °C) for approximately 3 to 5 minutes. The specimen is then weighed again (M_2) while suspended in water such that it is fully immersed as illustrated in Figure 1a. The HMA specimen is then removed from the water bath and dried by a cloth to obtain a saturated surface-dry condition, following which, the mass of the specimen is determined in the air (M_3). With the three determined masses, the BD of the HMA specimen is calculated using Equation 1 [8].

$$BD = \frac{(M_1)}{M_3 - M_2} \times \rho_w \qquad \text{Equation 1}$$

where, BD is the bulk density of the specimen in kg/m^3, M_1 is dry mass of the specimen in gram (g), M_2 is the mass of the specimen in water in gram (g), M_3 is the saturated surface-dry mass of the specimen in gram (g), and ρ_w is the density of water at the test temperature in kg/m^3.

The calculated BD is used in combination with the Maximum Void-less Density (MVD) of the loose HMA material to determine the air voids content of the HMA specimen using Equation 2. The air voids content is widely used as a measure of HMA compaction.

$$Air\ Voids\ (\%) = 100 \times \frac{(MVD - BD)}{MVD} \qquad \text{Equation 2}$$

Although the SSD is the widely used method for the determination of the BD of the compacted HMA specimens, the method is inaccurate in the determination of the density of porous asphalt or HMA specimens with interconnected voids. As an alternative to the SSD method, the vacuum sealing approach is preferred for the determination of the density of porous asphalt or HMA specimens containing interconnected voids [9-10]. The method involves vacuum sealing of the HMA specimen in a plastic bag as illustrated in Figure 1b. The detailed procedure for the determination of BD using the vacuum sealing method is described in ASTM D 6752 standard test method [11]. In this study, the SSD method was used to determine the BD of the asphalt specimens as the HMA mixes investigated were dense-graded, and were not considered to be porous material.

a) Typical SSD set-up

b) Vacuum sealed specimen

Fig. 1. Typical SSD and vacuum saling device set-up

Advanced technologies such as X-ray Computed Tomography (X-ray CT) scanning in combination with image analysis techniques are also increasingly being used for the direct measurement of air voids in compacted HMA specimens [1,2,12]. The X-ray CT scanning technology not only allows for the direct measurement of air voids but also the air voids size and distribution, as well as the determination of aggregate particle arrangement, which enables a more detailed description of the internal structure of the compacted HMA specimens. It should, however, be mentioned that the advanced techniques may not necessarily be practical for routine testing of HMA specimens. Hence, their current application may be limited to research purposes and during the forensic investigation of asphalt pavements failures.

III. EXPERIMENTAL PLAN

A. *Materials and HMA Mix Design*

A typical medium dense-graded 10 mm Nominal Maximum Aggregate Size (NMAS) mix, with Andesite aggregates and penetration-grade (50/70) asphalt-binder was used in the laboratory study. The asphalt-binder conforms to the South African specification for penetration bitumen [13] and is equivalent to PG 58-22 as per the draft South African Performance Grade (PG) bitumen specification. HMA mix design and aggregates used in the study were sourced from a commercial asphalt plant in the South African Gauteng province, and are used routinely in the production of wearing courses of known good performance. Figure 2 plots the HMA mix design gradation curve, which falls within the specified envelopes according to the South African standard specifications for road and bridge works [14].

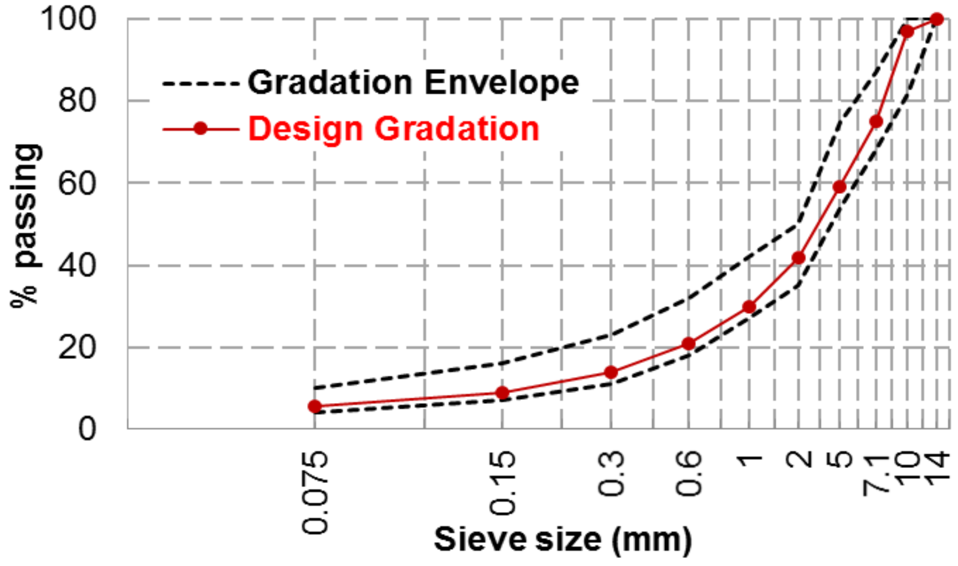


Fig. 2. Design gradation

B. *HMA Mixing and Compcation*

Calculated masses of aggregate and asphalt-binder were pre-heated to the required mixing temperature (150 °C) separately. The pre-heated aggregate and asphalt-binder were then mixed using a heated mechanical mixer until a uniform mixture was obtained (approximately 15 minutes). After mixing, the loose HMA material was placed into an oven set at compaction temperature (135 °C) for four hours to simulate short-term ageing [15].

After short-term ageing, HMA samples were compacted using the SERVOPAC gyratory compactor to a typical design and field construction air voids content of approximately 4.0±0.5% and 7.0 ±0.5%, respectively. A 150 mm diameter mould was used, and HMA samples were compacted to 170 mm and 120 mm target heights for both design and field target compaction levels. The 170 mm was selected as typical height used for compacting specimens for HMA performance tests such as dynamic modulus and repeated axial permanent deformation tests. Typically, 120 mm high samples are used during HMA design to evaluate the mix volumetric properties as described in the South African HMA design manual [16]. Three replicates HMA samples were compacted for each combination target air voids and sample height as illustrated in Table I. The compaction matrix presented in Table I allowed for the investigation of both, the influence of the target air voids and the sample thickness on the distribution of air voids of the compacted HMA samples.

TABLE I. HMA SAMPLE COMPACTION MATRIX

Targeted Air Voids (%)	Sample Height	Number of HMA Samples
4.0±0.5%	170 mm	3
	120 mm	3
7.0 ±0.5%	170 mm	3
	120 mm	3

C. *Maximum Void-less Density (MVD) Determination*

The MVD of the HMA mix was determined on loose asphalt material according to SANS 3001-AS11 [17], which implies that the air voids calculations were based on average MVD values for the mix as a whole. Due to mix segregation, the MVD would specifically vary within the individual HMA specimens, thereby, introducing a limited error in the air voids determination.

D. *Specimen Preparation and Bulk Density (BD) Determination*

From the 170 mm high HMA samples, 100 mm diameter specimens were cored from the centre and the top and bottom were trimmed to produce 150 mm high specimens [15]. The coring and trimming is usually done to remove surface roughness which influences the uniformity of the density of laboratory compacted HMA samples [15,18]. The 150 mm high specimens were used to prepare specimens for vertical and radial air voids investigation as illustrated in Figure 3.

In order to investigate vertical distribution of air voids, the BD of the 150 mm high specimens was determined, following which, the specimens were sliced/cut into three specimens of 50 mm height (top, middle and bottom) and the BD of each individual specimen was according to SANS 3001-AS10 [8]. After the determination of the BD, the 50 mm high specimens were sliced into two 25 mm high specimens (resulting in six specimens) and their bulk densities were determined again.

Similar approach was used for the 120 mm high samples, whereby 100 mm diameter specimens were cored from the centre and the top and bottom were trimmed to produce 100 mm high specimens. The BD of the 100 mm high specimens was determined, following which, the specimens were sliced/cut into three specimens of approximately 33.3 mm height (top, middle and bottom) and the BD of each individual specimen was determined.

On the other hand, for the investigation of the radial distribution of air voids, the density of the 100 mm diameter specimen was determined, following which, the specimen was cored to 78 mm diameter and the BD was determined. The 78 mm diameter specimen was cored to 54 mm and the bulk density was determined again. The 100, 78, and 54 diameters were as a result of the standard coring bits commercially available in South Africa.

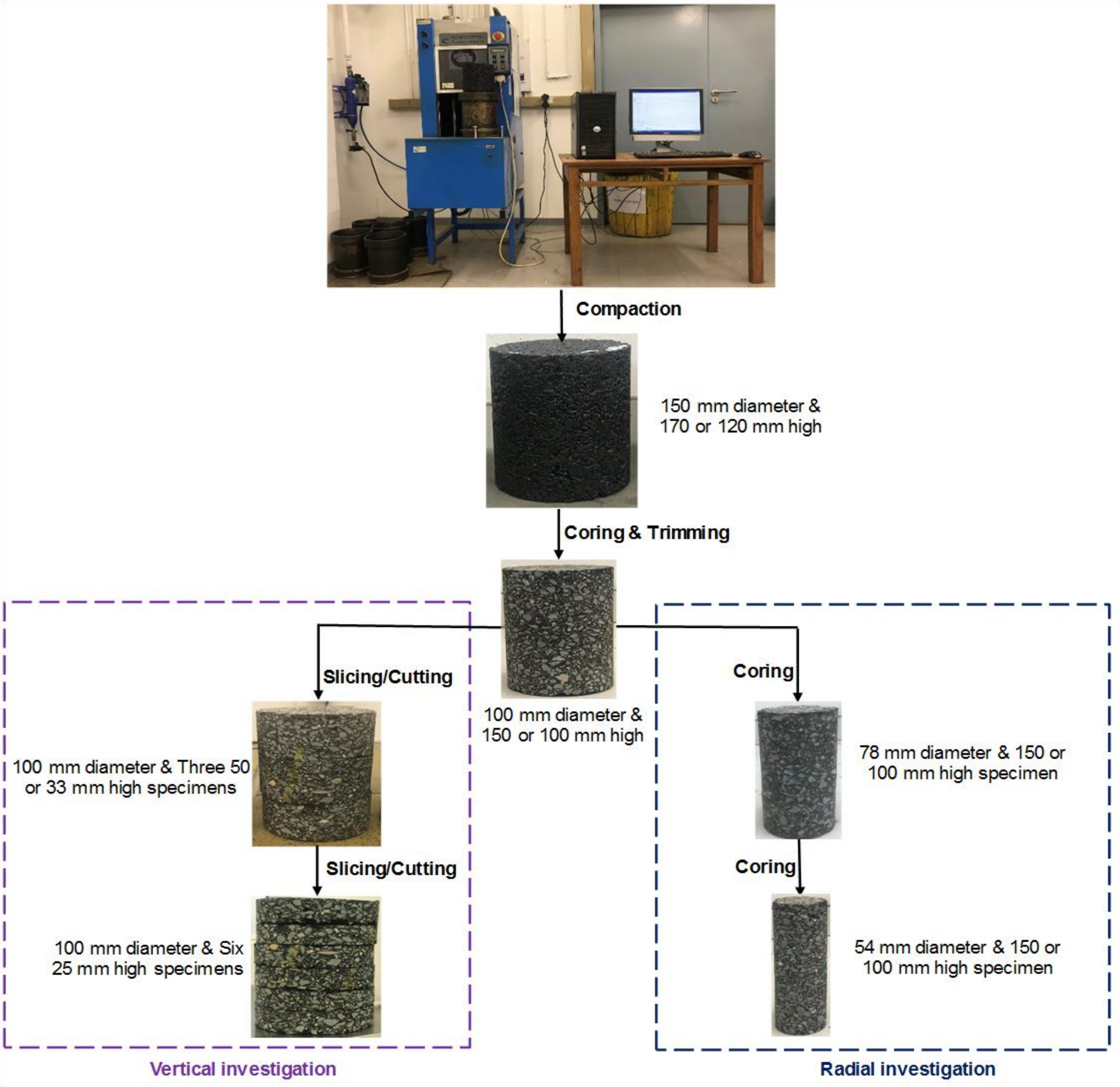


Fig. 3. HMA Compaction and specimen preparation procedure

E. *Field Core Sampling*

To supplement the laboratory study, field asphalt cores were extracted from the SANRAL experimental section on R104 road near Pretoria. The cores were extracted from the sections constructed with BTB and HiMA mixes. These sections were selected because the thickness of the asphalt base layer for each mix was adequate for the investigation of the vertical air voids distribution. The NMAS of the BTB and the HiMA mixes were 14 and 20 mm, respectively, and their design gradations are presented in Figure 4.

The design pavement structures for the BTB and HiMA section were similar, consisting of a G7 subgrade layer, 150 mm C3 subbase layer, 150 mm BTB/HiMA base layer and 40 mm asphalt wearing course. However, field core samples indicated that the thicknesses of the BTB and HiMA layers were each approximately 130 mm. The field cores were extracted from the lane of the experimental section that has been closed to the normal traffic in order to eliminate long-term densification of the asphalt layers. A total of three cores were extracted for each of the BTB and HiMA sections, two cores for the investigation into vertical and one core for the investigation into radial air voids distribution. Core sample preparation procedure was as described for the laboratory prepared samples, except that the field cores were sliced to a maximum of four specimens, as opposed to six specimens, due to insufficient sample thickness.

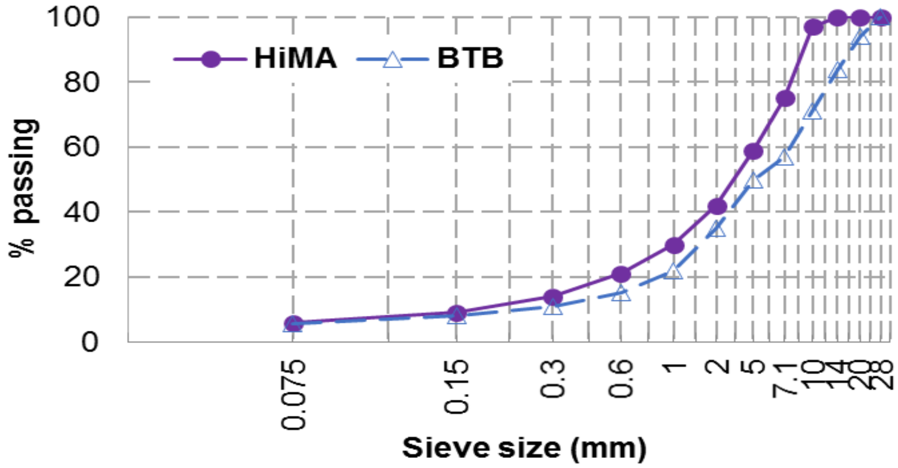


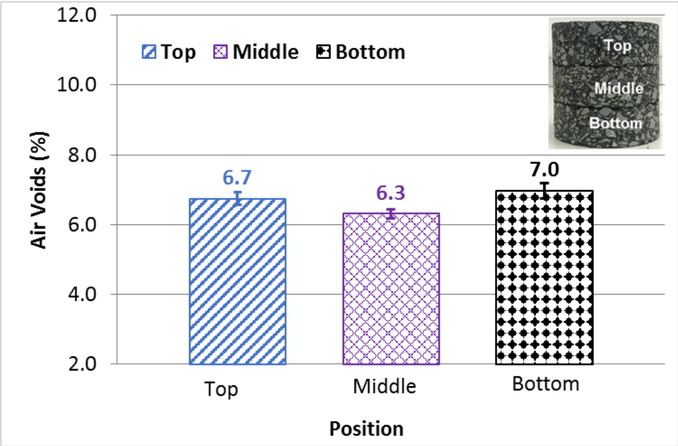
Fig. 4. BTB and HiMA design gradation

IV. Results and Discussions

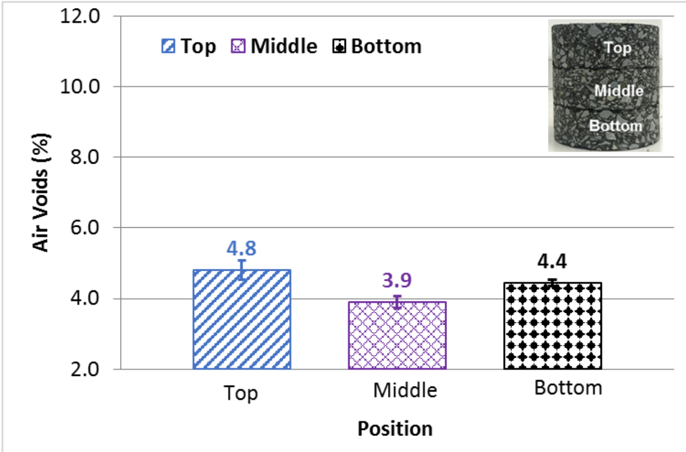
A. *Vertical Distribution of Air Voids*

Figure 5 shows the average air void results of the top, middle and bottom parts of the laboratory compacted HMA specimens for the various targeted compaction heights and air voids content. The results indicate that the top and bottom parts of the HMA specimens exhibit low compaction (i.e., higher air voids content). It can be seen that the variation in compaction becomes more pronounced at a higher targeted compaction level (i.e., targeted air voids of 4.0±0.5%) and lower sample thickness (i.e., 120 mm), as seen in Figure 5. The average air voids content presented in Figure 5 were determined using three replicates HMA specimens. Standard error bar is also plotted in Figure 5, and do not overlap, indicating that the air voids of the top, middle and the bottom parts of the HMA specimens differ.

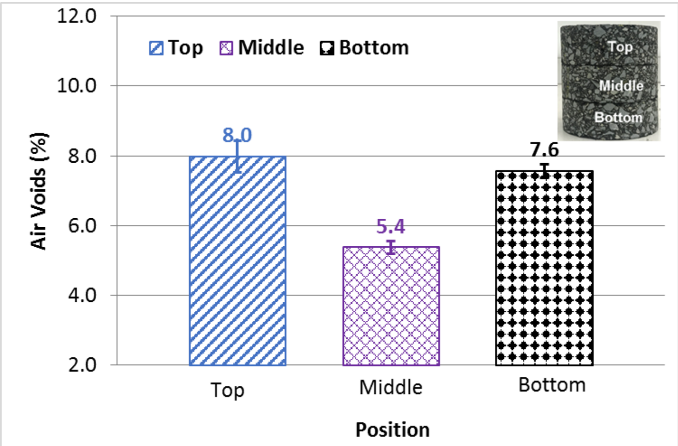
As the distribution of the air voids define the internal structure of HMA, the trends presented in Figure 5 points to the conclusion that the top, middle and bottom parts of the HMA specimens are more likely to possess different internal structures. Consequently, the performance of the top, middle and bottom parts with respect to the HMA properties such as permeability, resistance to permanent deformation, fatigue cracking and moisture damage may also differ.



a) 170 mm high & 7.0 ±0.5% targeted air voids



b) 170 mm high & 4.0±0.5% targeted air voids



c) 120 mm high & 7.0 ±0.5% targeted air voids

d) 120 mm high & 4.0±0.5% targeted air voids

Fig. 5. Average air voids content of the top, middle and bottom parts

Where the top, middle and bottom part were further subdivided into 6 sections, the results are presented in Figure 6, plotting the average air voids as a function of sample height for the laboratory specimens prepared from the HMA samples compacted to 170 mm high for both 4.0±0.5% and 7.0 ±0.5% targeted air voids content. Each data point in Figure 6 represents the average of three replicates HMA specimens. The average air voids content determined using the entire HMA specimens before slicing is also plotted in Figure 6. It can clearly be seen that the top and bottom parts of the HMA specimens exhibit low compaction. Hence, the current practice of trimming 10 mm on top and bottom ends of the HMA specimens prior to density measurement and performance testing may not necessarily ensure uniform specimen air voids. Furthermore, the trimming of the specimens results in a decrease in the overall average voids of the sample. This has implications for sample preparation to specific target voids.

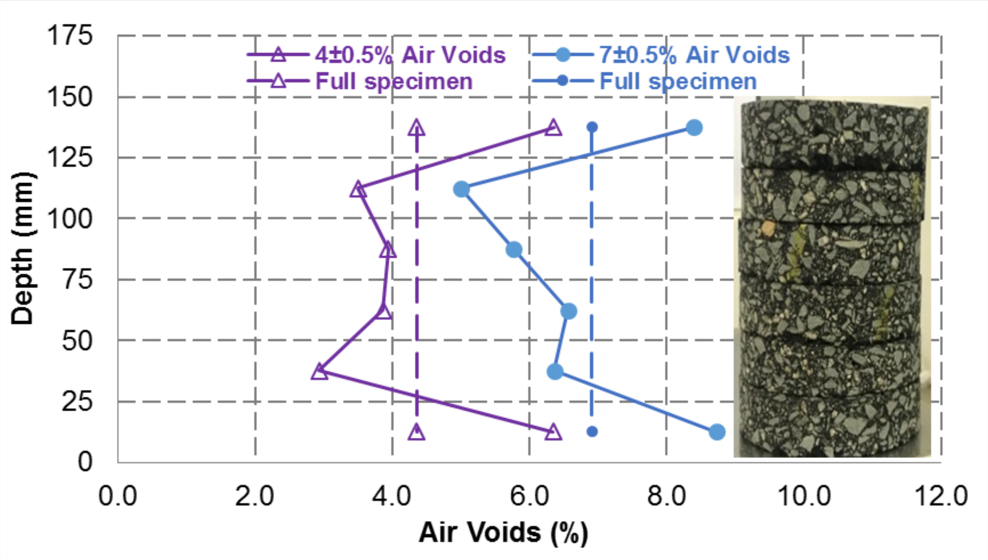


Fig. 6. Vertical distribution of air voids – laboratory compacted samples

The vertical distribution of the air voids for the field cores are presented in Figure 7, alongside the average air voids content determined using the entire HMA specimens before slicing. Due to insufficient specimen height, the field cores were sliced into four specimens only, as opposed to six specimens obtained from the laboratory compacted samples. Nevertheless, with the HiMA cores the result follows the same trend as the laboratory compacted samples, whereby the top and bottom ends exhibits high air voids. For the BTB cores, only the bottom part exhibits higher air voids. However, the difference in compaction levels is significantly higher than that of the HiMA cores. Factors such as aggregate segregation and temperature variation with depth during HMA compaction may have contributed to the observed trend, and should further be investigated in future studies.

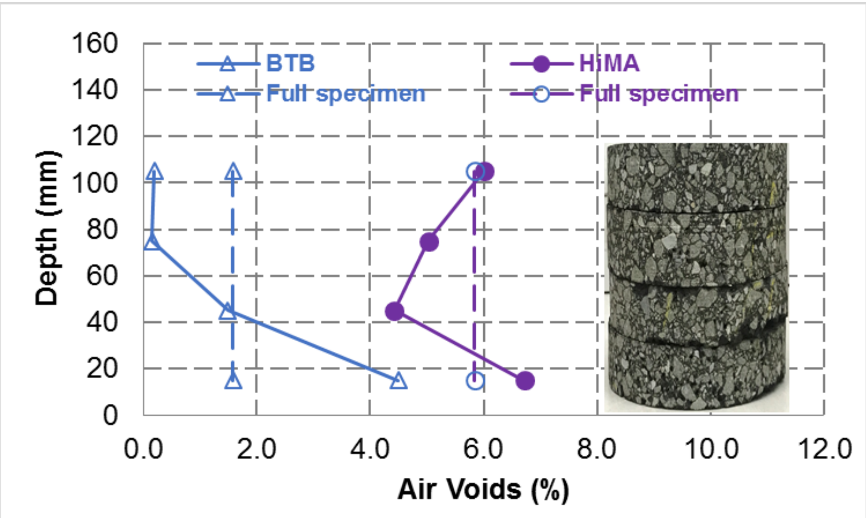
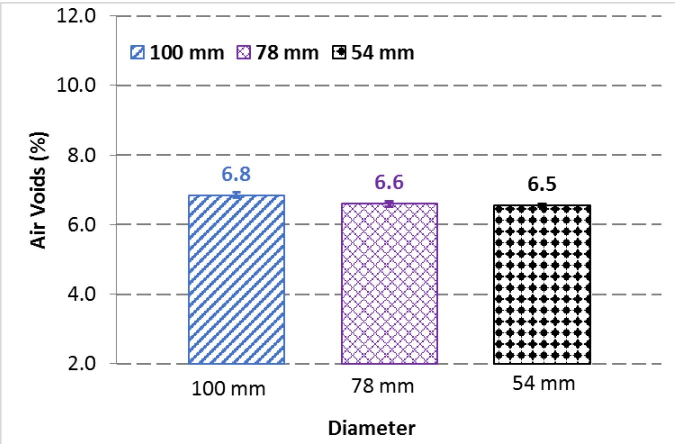


Fig. 7. Vertical distribution of air voids – field cores

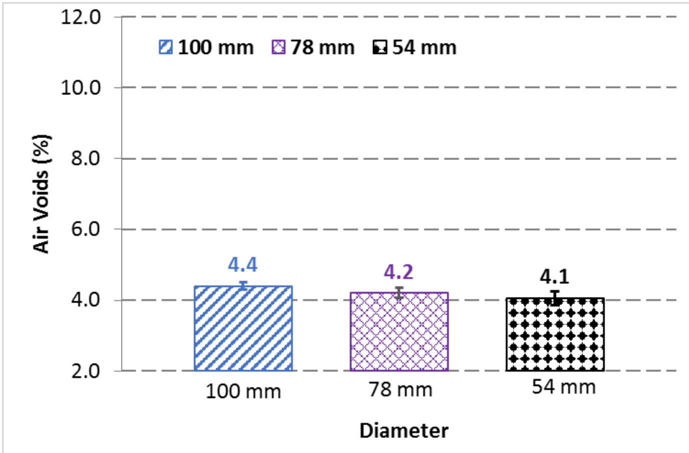
B. *Radial Distribution of Air Voids*

Figure 8 presents air voids determined on the 100, 78, 54 mm diameter specimens cored from the laboratory compacted samples. The results indicate insignificant difference in the air voids radially, regardless of the differences in target compaction level (i.e., 4.0±0.5% versus 7.0 ±0.5 %,) and height (i.e., 170 mm versus 120 mm). For each set of the results, the standard error bars are comparable indicating that statistically, the air voids of the 100, 78 and 54 mm core specimens do not differ significantly.

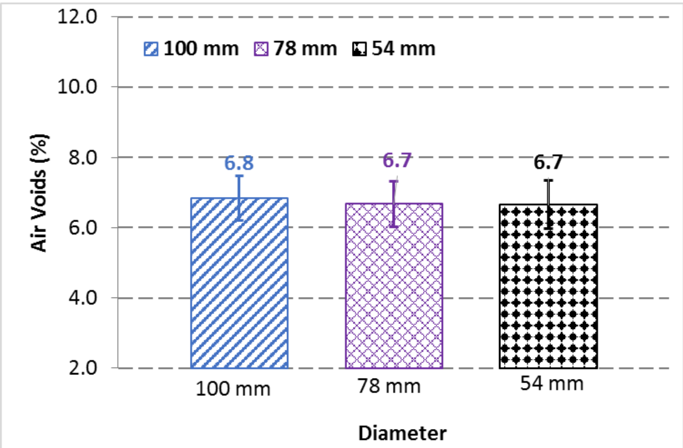
Figure 9 shows the radial air voids distribution results of the field core specimens for both, HiMA and BTB mixes. Similar to the laboratory compacted samples, the results of the field core samples show insignificant differences of the air voids for the 100, 78, and 54 mm diameter specimens.



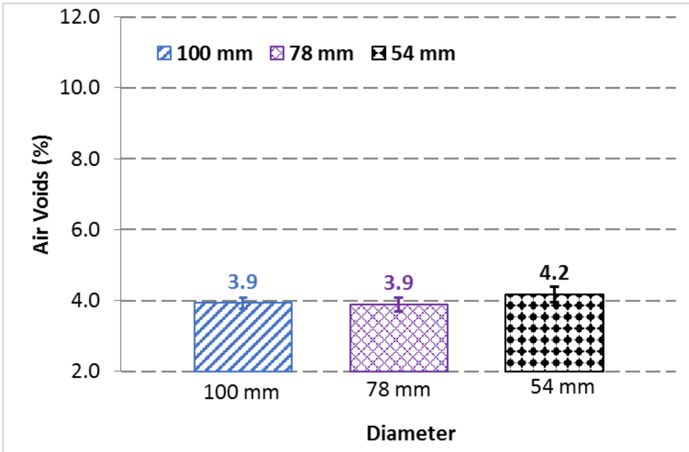
a) *170 mm high & 7.0 ±0.5% targeted air voids*



b) *170 mm high & 4.0±0.5% targeted air voids*



c) *120 mm high & 7.0 ±0.5% targeted air voids*



d) *120 mm high & 4.0±0.5% targeted air voids*

Fig. 8. Radial distribution of air voids – field cores

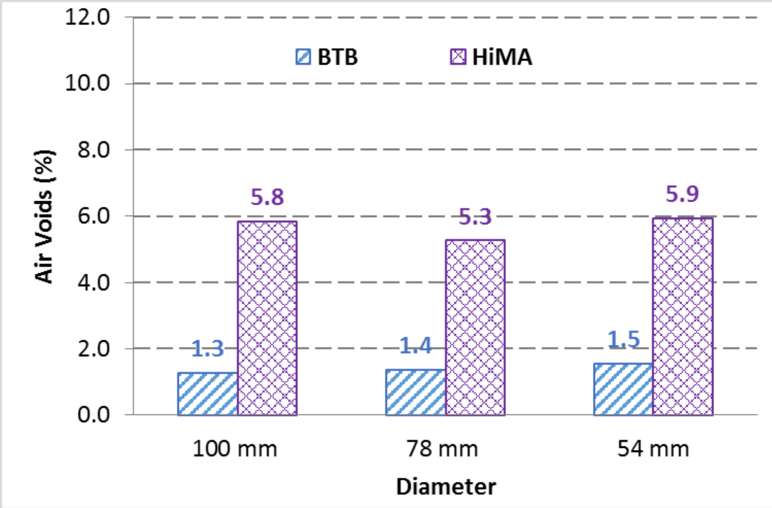


Fig. 9. Radial distribution of air voids – field cores

V. Conclusions and Recommendations

The paper investigated the spatial distribution of air voids in gyratory compacted and field compacted HMA samples under different compaction levels and sample thickness. Based on the results and discussions contained in this paper, the following conclusions are drawn and recommendations made.

- The trend indicated by the vertical distribution of the air voids of the gyratory compacted samples show that the top and bottom parts exhibit relatively high air voids content (i.e., low density), with the differences being more pronounced on the samples compacted to higher target compaction level (i.e., 4.0±0.5%) and lower sample thickness (i.e., 120 mm). Hence, the current practice of cutting 10 mm from each end of the gyratory samples may not necessary ensure uniform specimen air voids;
- A similar vertical air voids distribution trend was observed on the field cores. However, the bottom part of the BTB layer exhibited significantly higher air voids (i.e., as high as 4.0% air voids difference between the top and the bottom). Aggregate segregation and temperature variation with depth during compaction could be among the factors contributing to the observed trend, and should further be investigated in future studies, and
- The radial distribution of air voids was found to be uniform for both the gyratory compacted and field compacted samples.

Overall, the study has demonstrated that the understanding of the distribution of the air voids in the compacted HMA may provide useful information on the HMA internal structure, and its influence the volumetric and mechanical properties of the HMA. As this study investigated limited HMA mix types, it is recommended that future studies should include other HMA mix types to validate the findings. Furthermore, the effect of variation of the MVD within the sample on the calculation of air voids, as well as the effect of support conditions, and temperature variation with depth during field and laboratory compaction should be investigated in the future studies.

ACKNOWLEDGEMENT

The authors would like to acknowledge the South African Council for Scientific and Industrial Research (CSIR) for funding and supporting this study. The laboratory support received from Mr Nnditsheni Mpofu and Mr Ngwako Maake of the CSIR road pavement materials laboratory is acknowledged.

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