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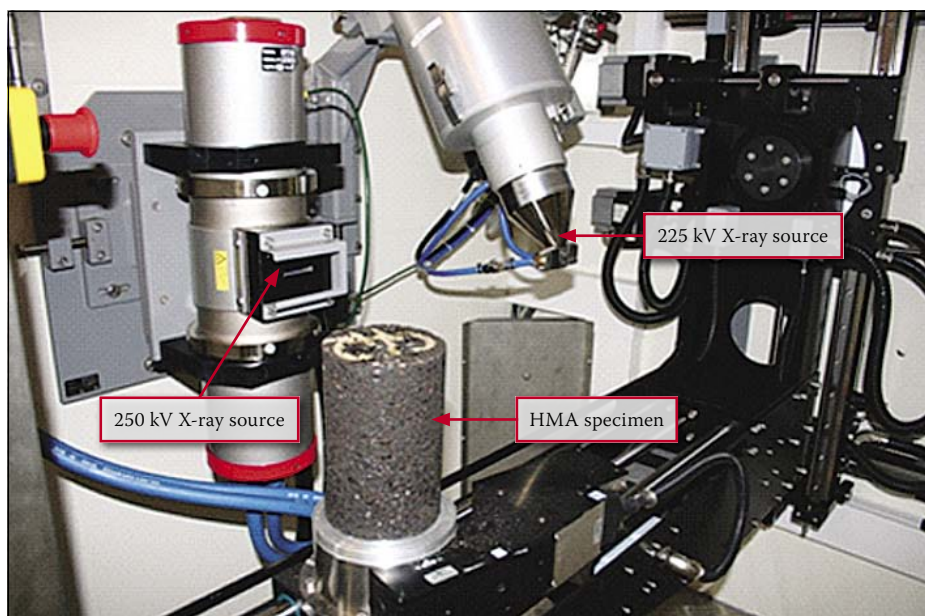China
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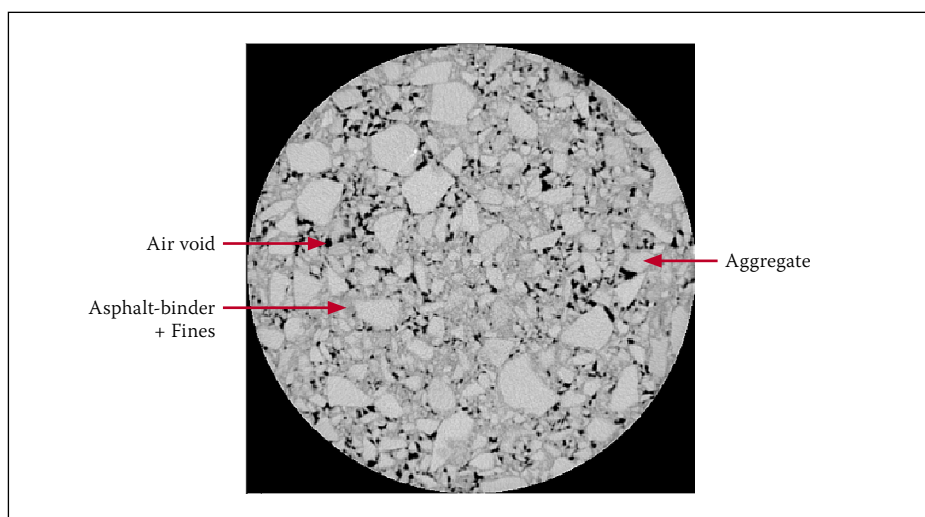
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Air void characterisation of HMA gyratory laboratory-moulded samples and field cores using X-ray computed tomography (X-ray CT)

L F Walubita, B Jamison, A E Alvarez, X Hu, C Mushota

The research work presented in this paper deals with the characterisation of the internal structure of hot-mix asphalt (HMA), incorporating both gyratory compacted samples produced in the laboratory and field cores. The primary objective was to determine the optimum trim depth on either end of laboratory-moulded HMA cylindrical samples that would optimise the air void (AV) uniformity in the test specimens. The analysis was based on the X-ray Computed Tomography (X-ray CT) scanning tests and subsequent image analyses. Two Texas HMA mixes, namely a coarse-graded (Type B) and a fine-graded (Type D) mix, with gyratory samples compacted in the laboratory to two different heights (110 and 164 mm) were evaluated for their internal structure in terms of the distribution of both the AV content and AV size. Analysis of the results indicated that the coarse-graded HMA mix (Type B) and the taller (164 mm in height) gyratory-moulded samples would be more likely associated with a more heterogeneous distribution of the AV content and AV size, respectively. Supplemented with field cores, the X-ray CT results indicated significantly poor AV content distribution (i.e. higher AV content and weakest area) at the ends, particularly in the top and bottom 20 mm zone of the samples. Thus, for 150 mm diameter samples of height equal to or greater than 110 mm, trimming a minimum of 20 mm on either side of the gyratory compacted samples should be given due consideration without compromising the specimen aspect ratio and NMAS coverage requirements (NMAS – nominal maximum aggregate size). In general, test specimens should always be cut from the middle zone of the SGC moulded samples where the AV is less heterogeneously distributed.

Figure 1 Pictorial setup of the X-ray CT scanner

Figure 2 Example of a grey scale X-ray CT image (Kassem *et al* 2008)

INTRODUCTION

The internal structure of a hot-mix asphalt (HMA) can be analysed in terms of the air voids (AV) characteristics (e.g. distribution, size, and connectivity), and the aggregate orientation, contact, and distribution (Alvarez *et al* 2010a). This HMA characteristic (internal structure) is one of the key factors that greatly influences the performance of HMA, including variability in the test results of not only the gyratory laboratory-moulded samples, but also of field cores. This is particularly critical for HMA tensile loading tests such as the direct-tension (DT) test. Thus, it is important to characterise the mix internal structure, for example via the distribution of the total AV content (or AV content) as a function of the HMA sample height, to ensure uniform mix internal structure (e.g. AV uniformity) and reduce variability in the laboratory test results (Walubita *et al* 2010a).

In this study, the X-ray Computed Tomography (X-ray CT) scanner and subsequent image analysis techniques were used to characterise the AV distribution (i.e. AV content and AV size) as a function of HMA sample height (or depth). The primary objective was to determine the optimum trim depth on either end of laboratory-moulded HMA cylindrical samples that would optimise the AV uniformity in the test specimens. X-ray CT scanning tests were conducted on cylindrical HMA samples (150 mm diameter) that were gyratory laboratory-moulded to two different heights of 110 and 164 mm. Two Texas HMA mixes, namely a coarse-graded (Type B) and a fine-graded (Type D) mix, were used for the study. To relate to *in situ* field conditions, the results of these two laboratory mixes were supplemented with X-ray CT results of field cores from in-service perpetual pavement (PP) sections.

In the paper, the X-ray CT scanner and the concepts of image analysis are described first, followed by the experimental design plan and the laboratory test results including the effects of the AV distribution on the DT

test failure mode. A summary of key findings and recommendations is then presented to wrap up the paper.

X-RAY COMPUTED TOMOGRAPHY (X-RAY CT)

The X-ray CT is a non-destructive test used to capture the internal structure of materials. Various applications of this method have been discussed by Masad (2004) and others (Braz *et al* 1999; Shashidhar 1999). In HMA mixes, X-ray CT has been used successfully for characterising the influence of compaction on HMA internal structure (Masad *et al* 2009), assessing internal structure of open-graded mixes (Alvarez *et al* 2010a; Muraya 2007), analysing water transport characteristics (Kassem *et al* 2008; Masad *et al* 2007), and stone-on-stone contact assessment (Alvarez *et al* 2010b; Watson *et al* 2004). The X-ray CT setup at Texas A&M University, used to perform the HMA scanning for this study, is shown pictorially in Figure 1.

The setup shown in Figure 1 includes two separate systems placed in the same shielding cabinet. The mini-focus system has a 350 kV X-ray source and a linear detector, whereas the micro-focus system has a 225 kV X-ray source and an area detector. The mini-focus source can penetrate thicker and denser samples than the micro-focus source. The micro-focus system, however, provides better resolution than the mini-focus system. All the experimental measurements in this study were conducted using the mini-focus 350 kV X-ray source system. This system has the necessary power and resolution to penetrate the HMA samples and provide good quality grey scale images for subsequent analysis of AV characteristics (Kassem *et al* 2008).

In the X-ray CT, a test specimen is placed between an X-ray source (Figure 1) and a detector. The intensity of X-rays change from I_0 before entering the specimen to I after penetrating the specimen due to the absorption and scattering of radiation. The relationship between I_0 and I is related to the linear attenuation coefficients of the materials that constitute the specimen, which are related to the densities of these materials. As such, determining the attenuation coefficients allows calculating the density distribution within a specimen section. These different densities are represented in a grey scale image of the section that consists of 256 grey intensity levels with a lower density material represented by a darker colour (e.g. AV are shown as black pixels) – see Figure 2.

In this study, images were captured every 1 mm in the vertical direction of the specimen and with a horizontal resolution equal to approximately 0.17 mm/pixel. Images were

Table 1 HMA Mix-Design Characteristics

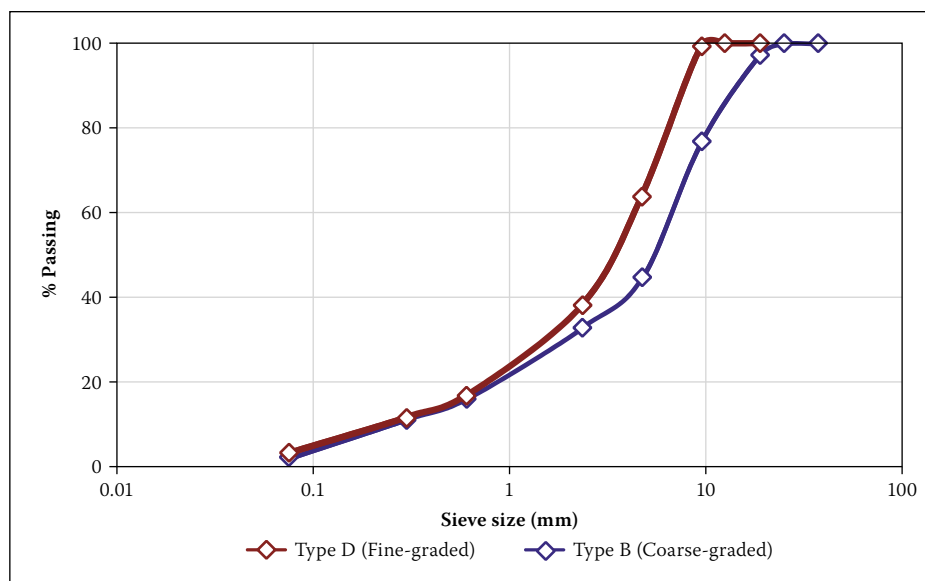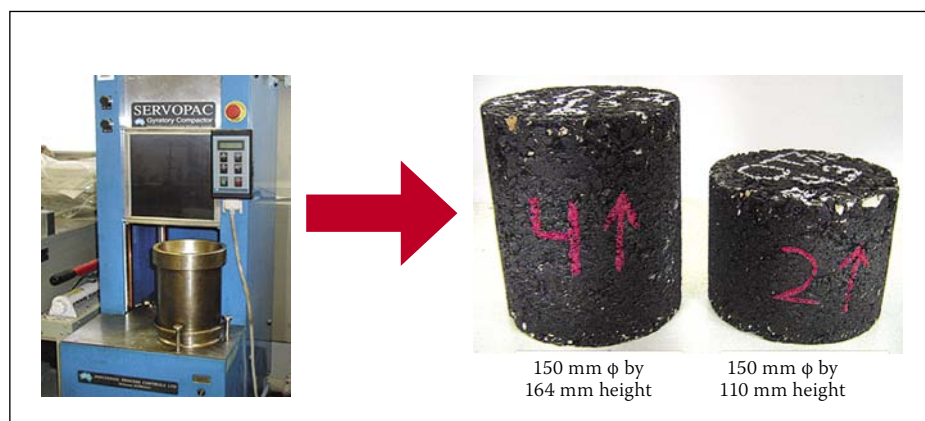| HMA Mix	Aggregate Gradation	Mix-Design	Sample Diameter	Sample Height	Replicates Scanned
Type B	Coarse (22 mm NMAS)	4.3% PG 64-22 + Limestone	150 mm	110 and 164 mm	≥ 2
Type D	Fine (9.5 mm NMAS)	5.0% PG 70-22 + Limestone	150 mm	110 and 164 mm	≥ 2
Legend: NMAS = nominal maximum aggregate size; PG = performance-graded asphalt-binder						

analysed using macros that were developed (Masad *et al* 2007) in Image-Pro® Plus software (Media Cybernetics 1999). Using a suitable grey intensity threshold value, AV can be separated from other HMA mix constituents (aggregate and asphalt-binder). The threshold level represents a boundary value below which pixels in the analysed image are considered as part of the AV, whereas pixels that have intensity values above the threshold value are considered to belong to the remaining phases. The analysis is capable of quantifying the vertical and horizontal distributions of AV, size distribution of AV, and connectivity of the AV. Additional details on the image analysis and computation of these parameters are documented elsewhere (Alvarez *et al* 2009). Readers are referred to Masad (2004) and Masad *et al* (2009) for more details on the different X-ray CT configurations, operational features and other capabilities.

However, it must be stated herein that the accuracy of the image analysis is also considered to be a function of the maximum scanning resolution of a specific X-ray CT device that is used. To attain more accurate results, some researchers proposed to apply a correction scheme such as a Weibull distribution (Luo & Lytton 2011). In this study, the mini-focus 350 kV X-ray source that was used was considered to have sufficient resolution and to be accurate enough not to warrant the need for data correction adjustments.

EXPERIMENTAL DESIGN

Two Texas HMA mixes were evaluated in the laboratory; a coarse-graded Type B and a fine-graded Type D mix. The HMA mix-design characteristics are summarised in Table 1 and the aggregate gradations are shown in Figure 3. As shown in Table 1, two moulded cylindrical sample heights of 110 and 164 mm respectively were investigated, all with a diameter of 150 mm. These two heights were evaluated, because they represent the mould height that is typically used for fabricating test specimens for various laboratory tests such as the Overlay Tester (OT), dynamic modulus, repeated load permanent deformation, and DT (Walubita *et al* 2010c). A minimum of two cylindrical replicate specimens were scanned with the X-ray CT per sample height per mix type.

Figure 3 Aggregate gradations of the Type B and D mixes

150 mm φ by 164 mm height 150 mm φ by 110 mm height

Figure 4 The Servopac SGC and some moulded samples

Table 2 Typical as-built *in situ* HMA mix-design characteristics for the PP field cores

HMA mix designation	Typical as-built *in situ* mix-design characteristics	Aggregate gradation
PFC	6.0% PG 76-22S + 1.0% lime + 0.3% cellulose fibres + igneous/limestone aggregates	Open-graded (19 mm NMAS)
SMA	6.0% PG 76-22S + 8.0% mineral filler + 1.5% lime + 0.3% cellulose fibres + 4.5% fly ash + igneous/limestone aggregates	Gap-graded (12.5 mm NMAS)
¾" SFHMA	4.4% PG 76-22 + 1.5% lime + 1.0% anti-strip + limestone aggregates	Moderately coarse-graded (19 mm NMAS)
1" SFHMA	4.2% PG 70-22 + 1.5% lime + 0.5% anti-strip + limestone	Coarse-graded (25 mm NMAS)
RBL	5.4% PG 64-22 + 1.5% lime + 0.5% anti-strip + limestone aggregates	Dense- to fine-graded (12.5 mm NMAS)
Legend: PFC = permeable friction course; SMA = stone mastic (matrix) asphalt; SFHMA = stone-filled hot mix asphalt; RBL = rich-bottom layer; PG = performance-graded asphalt-binder; S = styrene-butadiene-styrene polymer (added as 5% by weight of asphalt-binder)		

Sample moulding was accomplished using a Servopac Superpave gyratory compactor (SGC) to a final target total AV content of 7±1%. This is the AV content that is typically specified for laboratory performance testing in Texas (TxDOT 2004; TxDOT 2011; Walubita *et al* 2010c). The SGC and some examples of the moulded samples are shown in Figure 4. Standard SGC moulding parameters were used, namely 600 kPa vertical pressure and 1.25° compaction angle at a rate of 30 gyrations per minute (Walubita 2006). Moulding and compaction temperatures were consistent with the asphalt-binder PG grade (Table 1) (TxDOT 2004; TxDOT 2011). Note that the SGC mould shown in Figure 4 can handle sample heights of up 172.5 mm

As stated in the introductory section, field cores were used to supplement and relate the total AV distribution of the laboratory-moulded samples to *in situ* field conditions. To achieve this, cores from PP sections that represent thick multi-layered HMA pavement structures with numerous layer-lift thicknesses and constructed with both fine- and coarse-graded HMA mixes were used (Walubita *et al* 2010a). The typical as-built *in situ* HMA mix-design characteristics of these PP cores are summarised in Table 2.

Table 2 shows that the PP core consists of a wide spectrum of aggregate gradations ranging from open- (PFC) to coarse- through to fine-graded (RBL) HMA mixes. Therefore, these PP cores were deemed satisfactory to provide a field correlation to the total AV distribution structure of the laboratory-moulded samples for the mixes listed in Table 1. Accordingly, the laboratory X-ray CT results of these PP field cores are also presented and discussed in the subsequent sections of this paper. More details about PP structures are published elsewhere (Walubita *et al* 2010a).

RESULTS, ANALYSES AND DISCUSSION

This section presents the results of the AV characteristics analysis for both laboratory-moulded samples and field cores. The results are presented in terms of the following: distribution of AV content and AV size for laboratory-moulded samples, distribution of AV content for field cores, and effects of AV distribution on the tensile failure mode of laboratory-moulded samples.

Distribution of air voids (AV) content: laboratory-moulded samples

The vertical distribution of the total AV content as a function of the SGC sample height (or depth) is shown in Figures 5 and 6 for the
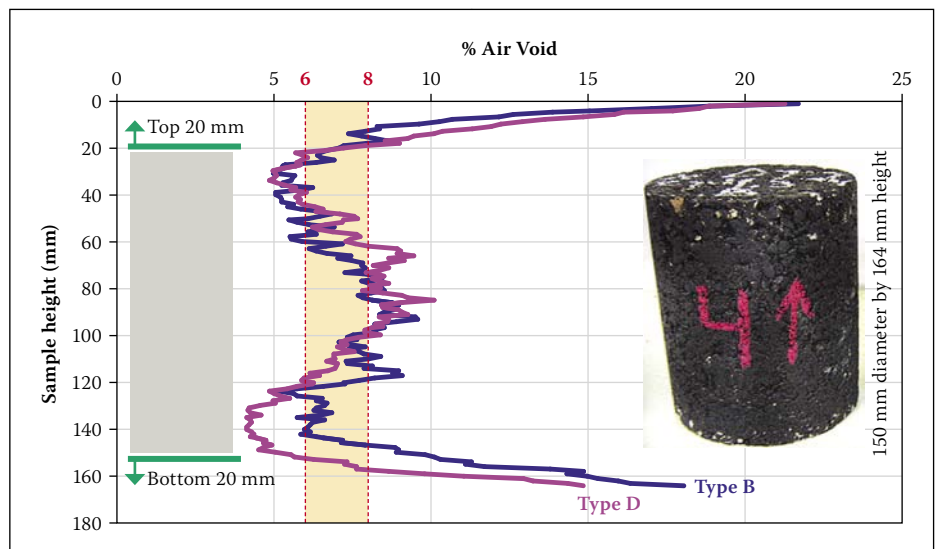

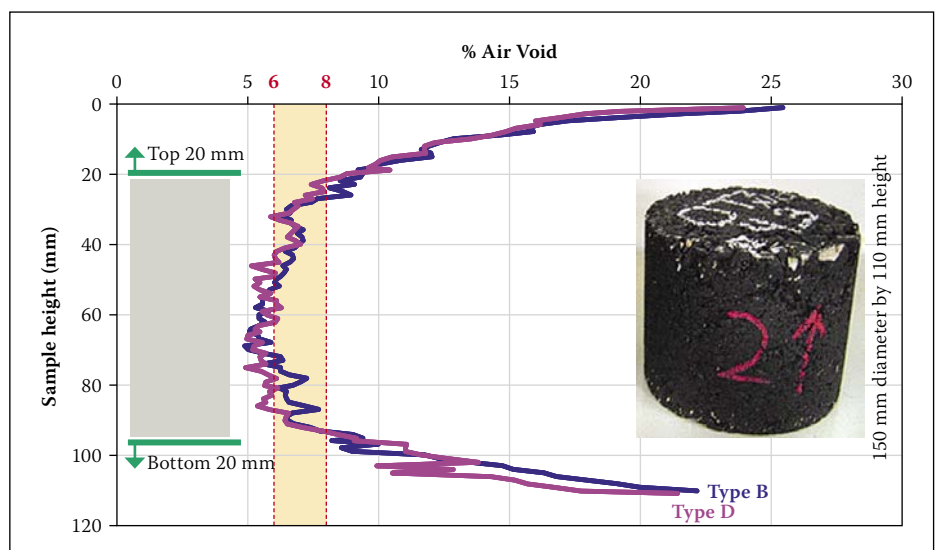**Figure 5** Vertical distribution of AV content for 164 mm high samples

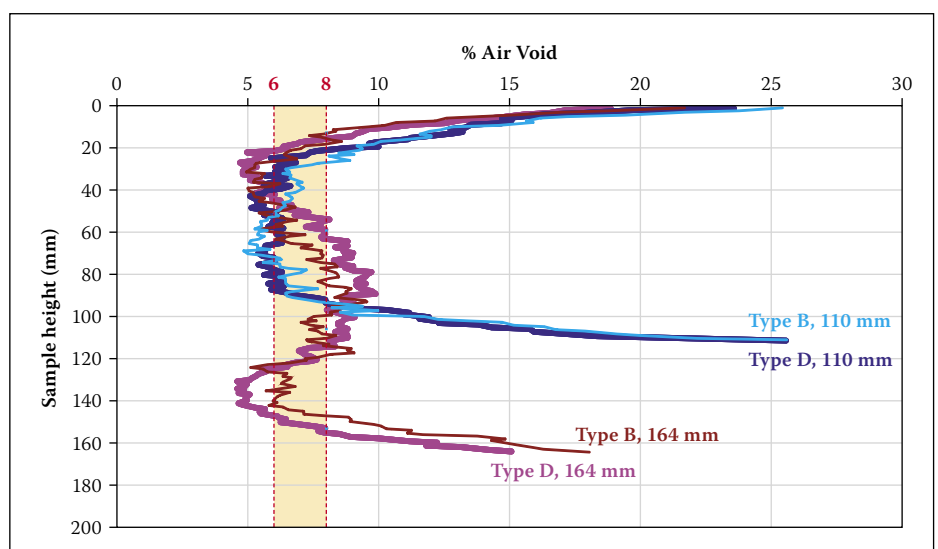**Figure 6** Vertical distribution of AV content for 110 mm high samples

Figure 7 Vertical distribution of AV content versus samples height

164 and 110 mm high samples respectively. These vertical distributions of AV content are hardly uniform and exhibit considerably high values (i.e. low density) at the top and bottom ends of the SGC samples, particularly in the top and bottom 20 mm zone, where

the range of the AV content is from 8% to as high as 25%. For a final target AV content of 7±1% for the laboratory samples, both Figures 5 and 6 suggest staying away from these end zones. Based on this data, trimming a minimum of 20 mm off the top and

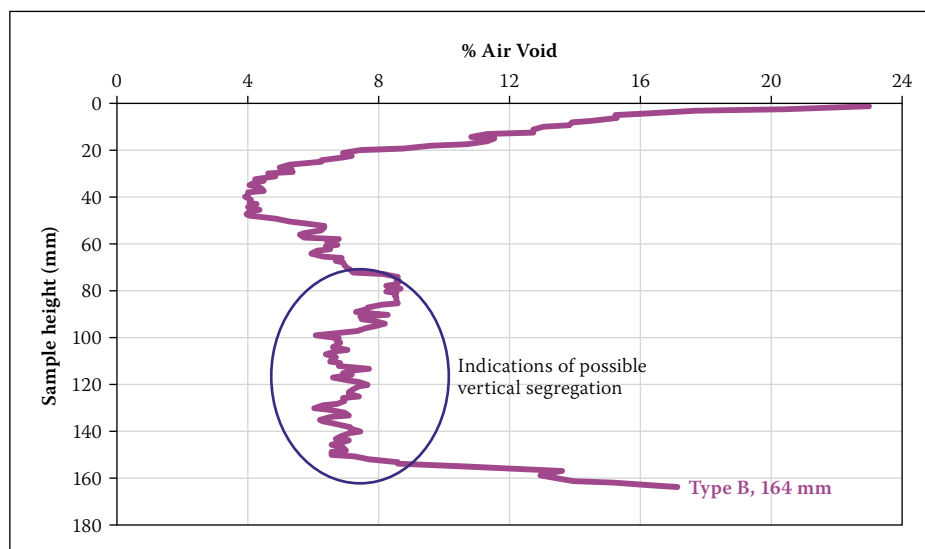bottom ends of the SGC laboratory-moulded samples may thus be warranted.

Additionally, the taller 164 mm SGC sample (Figure 5) also exhibited much higher AV content values in the middle zone, and their AV content distribution is generally more heterogeneous than that of the shorter 110 mm high samples. Although lower than the 7±1% target in the central portion of the specimen, the AV content distribution for the 110 mm high samples (Figure 6) appears to be less heterogeneous, particularly in the middle zone and does not exhibit any significant difference between the coarse-graded Type B and the fine-graded Type D mix (Walubita *et al* 2010a).

Overall, these results (particularly Figure 6) indicate that test specimens should generally be cut from the middle zone of the SGC-moulded samples where the AV content is less heterogeneously distributed, i.e. avoid the edges. For example, a single test specimen of 38 mm thickness for the overlay tester would easily be cut from the middle zone of the SGC-moulded sample shown in Figure 6 with reasonable uniformity in terms of AV content distribution.
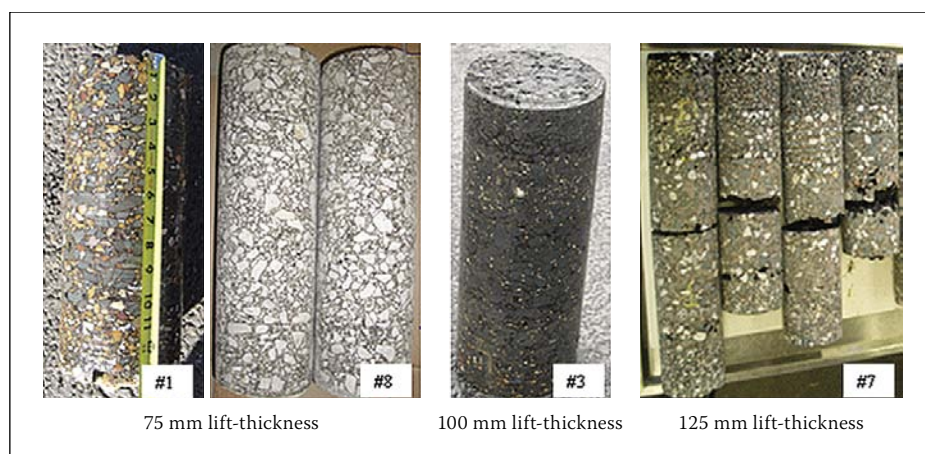
As indicated in Figure 7, taller moulding heights would be more prone to heterogeneous AV content distribution and variability than shorter moulding heights (having better AV content uniformity in the middle zone of the SGC samples). Thus, wherever possible and under the current compaction SGC parameters, shorter compaction moulding heights should always be given preference to promote the AV content uniformity in the test specimens.

In general, higher sample-mould heights are also comparatively more susceptible to aggregate segregation, particularly for the coarse-graded HMA mixes. In fact, it is normal practice for the HMA mix to be scooped and poured into the SGC mould in more than one lift when the moulding height is greater than 110 mm just to minimise vertical segregation. Figure 8 illustrates an example of a possible vertical segregation of the aggregates within the SGC sample of a coarse-graded Type B mix (22 mm NMAS).
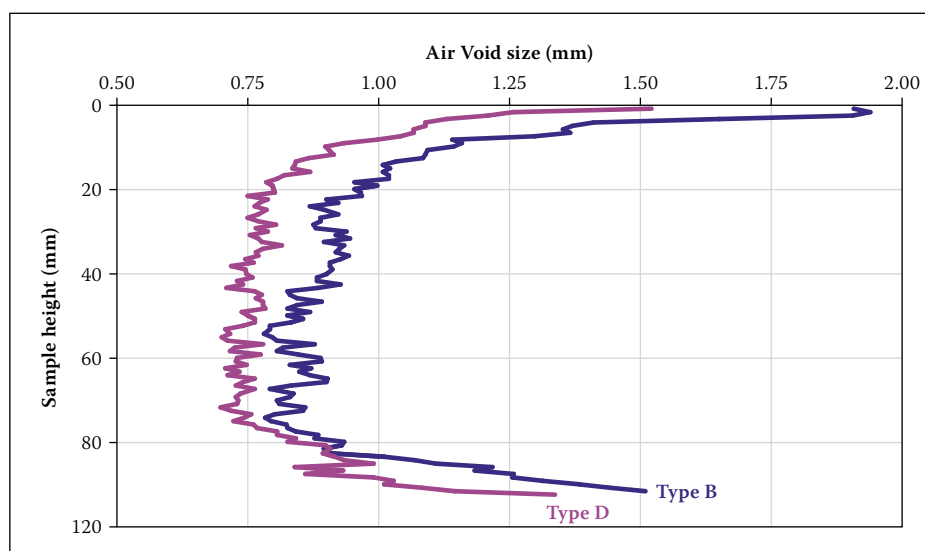
Clearly, the AV content between the sample heights of 20 mm and 70 mm is relatively lower in magnitude than that below 70 mm. One possible explanation for the higher AV content above 80 mm height is that the larger aggregate particles may have vertically segregated to the sample bottom, thereby creating the higher AV content seen in Figure 8. By contrast, this AV content distribution pattern (Figure 8) was not observed with the fine-graded Type D mix or with the shorter mould height of 110 mm (Walubita *et al* 2010a). In summary, taller mould heights can

Figure 8 Possible vertical segregation in the coarse-graded Type B mix

75 mm lift-thickness   100 mm lift-thickness   125 mm lift-thickness

Figure 9 Effects of the compacted lift thickness for the SFHMA layer
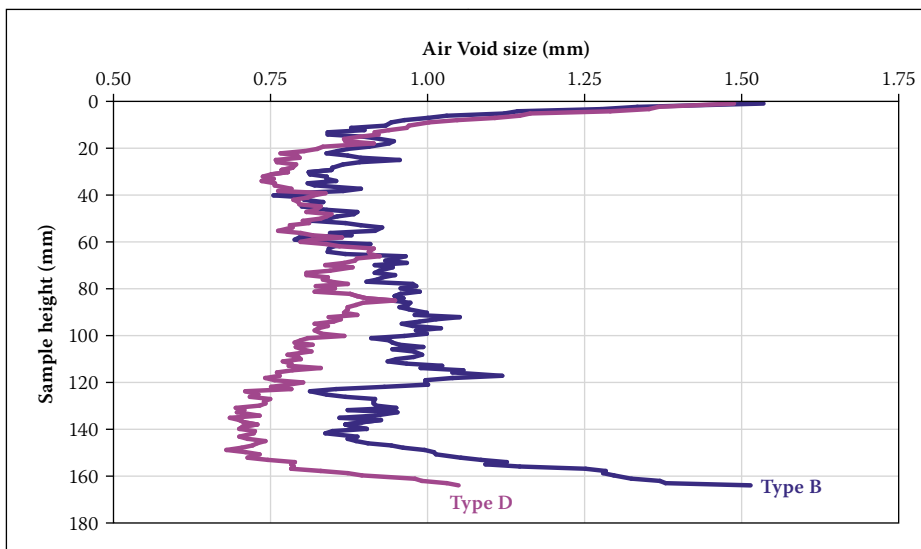

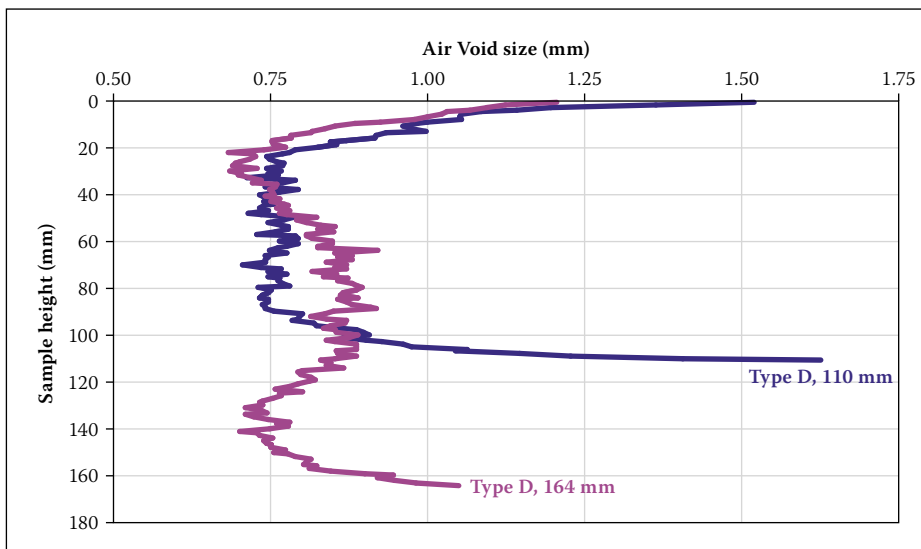**Figure 10** AV size comparisons – 110 mm high samples

have a higher tendency to promote vertical aggregate segregation, particularly in coarse-graded mixes. Additional research should be conducted to determine if this phenomenon exists in other HMA mix types.

In addition, the results shown in Figures 7 and 8 are consistent with field experience, where compaction and density (i.e. AV content uniformity) problems have also been
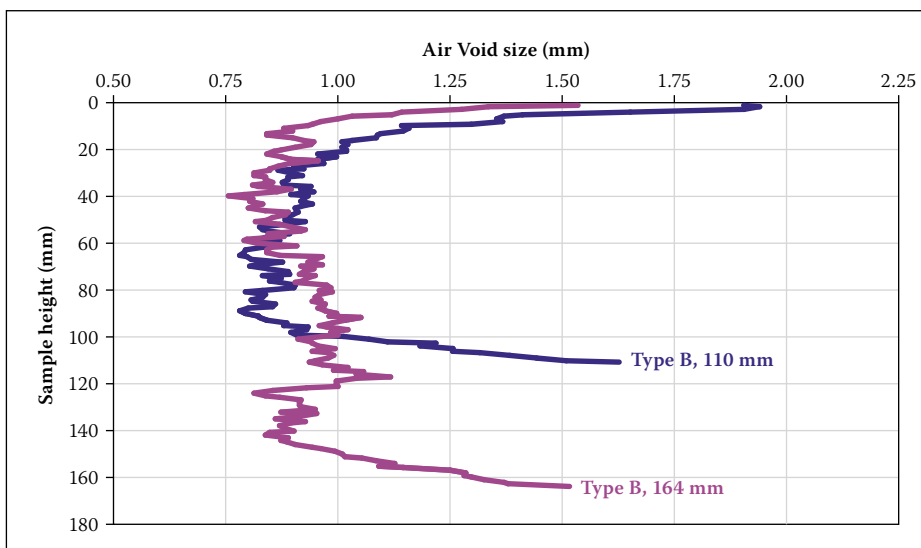
reported with thick layer lifts – synonymous to higher laboratory sample mould heights. In their construction work with PPs, Walubita *et al* (2010a) concluded that thin layer lifts of less than 100 mm yielded better compaction and *in situ* density results than thick layer lifts of 125 mm and higher for coarse-graded SFHMA mixes. The general observation from this study (Walubita *et al*

Figure 11 AV size comparisons – 164 mm high samples

Figure 12 Vertical distribution of AV size for the Type D mix

Figure 13 Vertical distribution of AV size for the Type B mix

2010a) was that compacting at the lower lift thickness such as 75 mm yielded a more constructable mix than using thicker lifts greater than 100 mm, as gauged by attaining the target in-place density and layer interface bonding. Furthermore, compacting at the lower lift thickness also required less compactive effort in terms of the rolling pattern and number of passes. Compacting at a greater lift thickness tended to cause the mixes to segregate vertically, creating highly voided areas capable of detrimentally

trapping moisture. Figure 9 shows a comparative illustration of the compacted lift thickness for a 25 mm NMAS coarse-graded SFHMA layer whose *in situ* target density was 96% (Walubita *et al* 2010a).
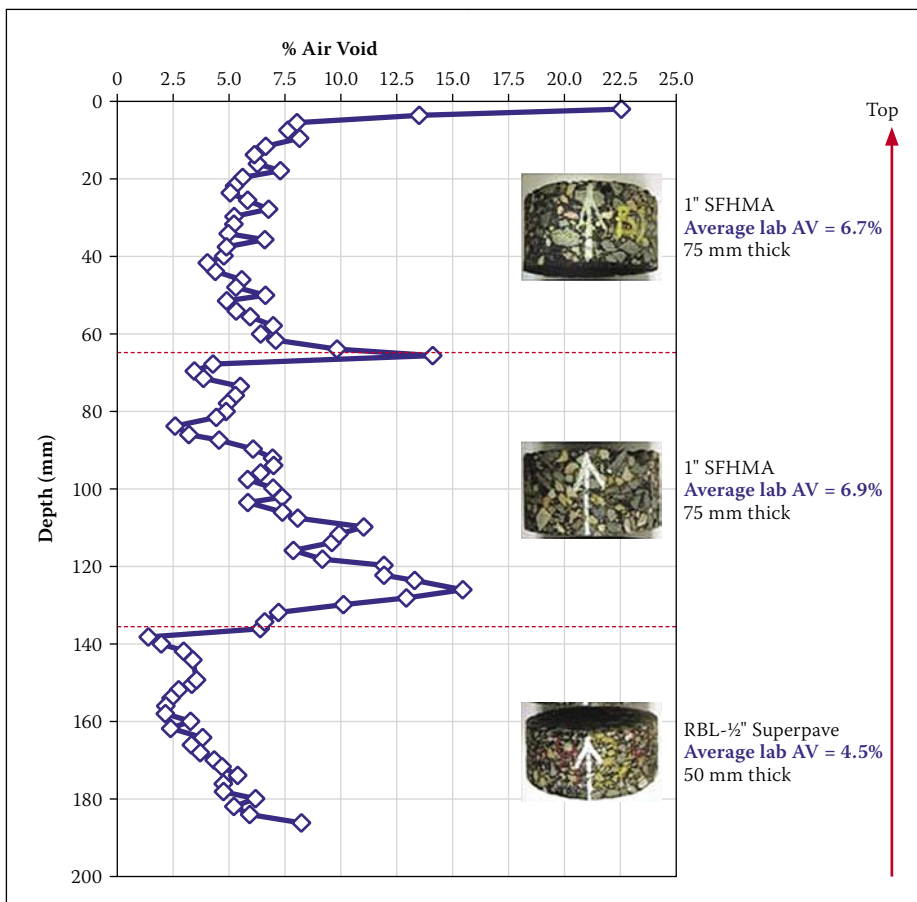
Figure 9 shows better construction quality for the 75 mm and 100 mm layer lift-thicknesses (cores #1, #8 and #3) with no visual evidence of vertical segregation or debonding. Also, the measured average AV content using the traditional water-displacement method at 7.3% was fairly reasonable as opposed to about 12.6% for the 125 mm layer lift-thickness (cores #7). Synonymous to the conclusions made for the results in Figures 7 and 8, Walubita *et al* (2010a) also recommended that a thinner layer-lift thickness (i.e. ≤ 100 mm) was appropriate for the coarse-graded SFHMA mixes in terms of yielding acceptable field compaction and *in situ* density results during construction (Walubita *et al* 2010a). In either case, however, the aspect ratio and NMAS coverage requirements must still be met as specified below for laboratory-moulded samples and field compaction layer-lift thickness respectively (Bonaquist *et al* 2003; Cooley (Jr) & Brown 2003):

- Aspect ratio (*ar*) (longest side divided by the shortest side): $1.5 \leq ar \leq 2.0$
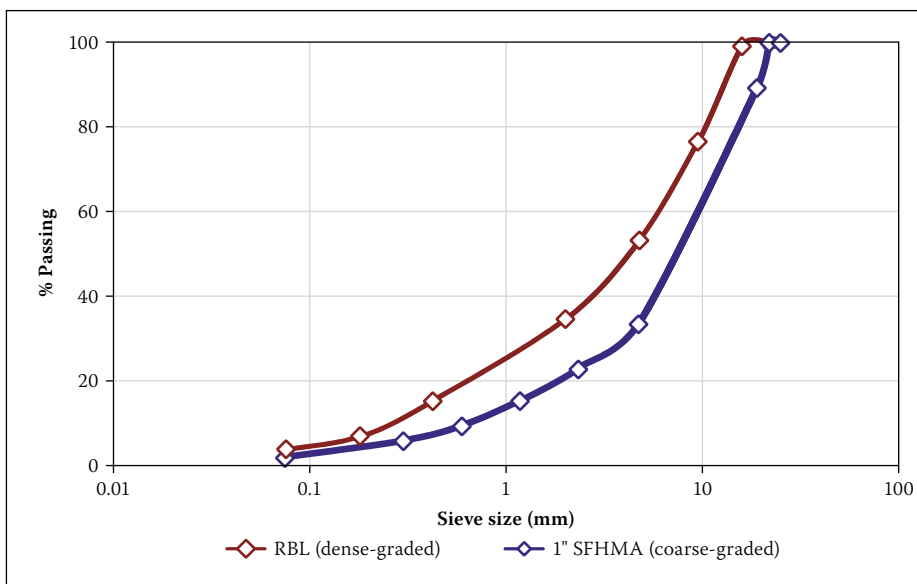- NMAS coverage (*NMAS_C*): $1.5 \times NMAS \leq NMAS\_C \leq 3.0 \times NMAS$

Distribution of air voids (AV) size: laboratory-moulded samples

Interestingly for SGC samples of similar height, there was no significant difference in the trends of the vertical AV content distribution (Figures 5 through 7) or total AV content values (at an average of 8.3%) between the Type B and D mixes. By contrast, and as shown in Figures 10 through 13, there was a considerable difference in the AV sizes. The more coarse-graded Type B mix exhibited relatively larger AV sizes in magnitude compared to the more fine-graded Type D mix, as theoretically expected.

Based on the vertical distribution of the AV size shown in Figures 10 and 11, the Type B mix exhibited larger AV size values across the entire SGC sample height than that of the Type D mix. In fact, the average AV size was 0.95 and 0.82 mm for the Type B and Type D samples respectively. Also the variability of the AV size, measured in terms of the coefficient of variation (COV), for the Type B mix (i.e. COV = 28%) was higher than that for the Type D mix (COV = 18%). Based on these COV values, it would be expected that the Type B mix would be associated with more AV size variability during SGC sample fabrication as when compared to the Type D mix.

Figure 14 Vertical distribution of AV content for field cores – coarse vs fine-graded

Figure 15 Aggregate gradations of the 1" SFHMA and RBL mixes

the convenience of preferring (based on the current compaction SGC parameters) shorter compaction mould heights to promote uniformity in the internal structure of the SGC samples. One of the possible causes of having higher AV content and AV size at the ends, in addition to aggregate segregation, is the restriction of the top and bottom metallic surfaces of the SGC device that limits the movement of the aggregate particles and decreases the compaction efficiency at these zones of the sample (Thyagarajan *et al* 2010).
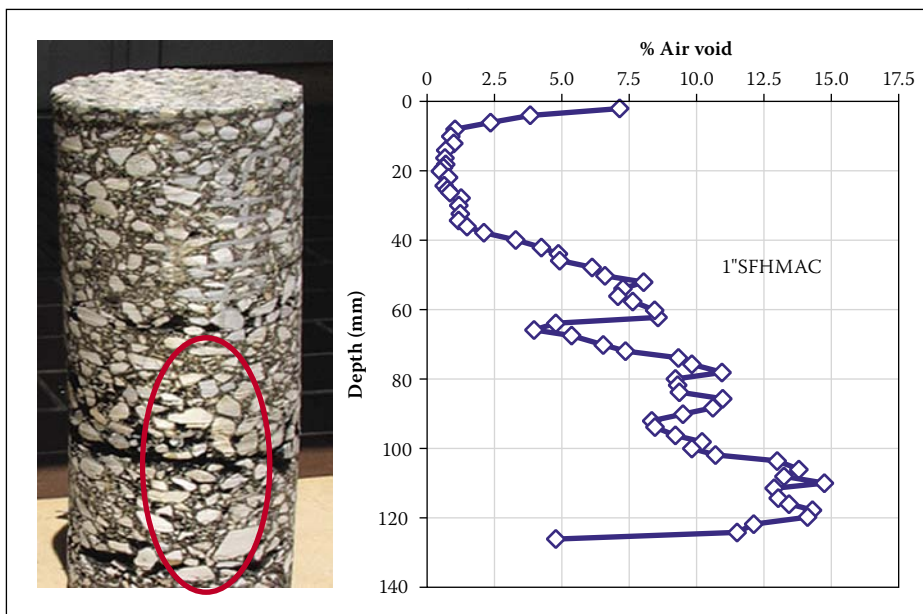
Distribution of air voids (AV) content: field cores

Figure 14 shows the AV content distribution of a core extracted from a newly constructed PP section prior to opening to conventional traffic (Walubita *et al* 2010c).

The SFHMA layers represent coarse-graded mixes of 25 mm NMAS, whose target *in situ* density was 96%, and was compacted in 75 mm layer lift-thickness. The RBL layer represents a dense- to fine-graded mix of 12.5 mm NMAS, whose target *in situ* density was 97% at a layer lift-thickness of 50 mm (Walubita *et al* 2010a). The aggregate gradations for these HMA mixes are shown in Figure 15.
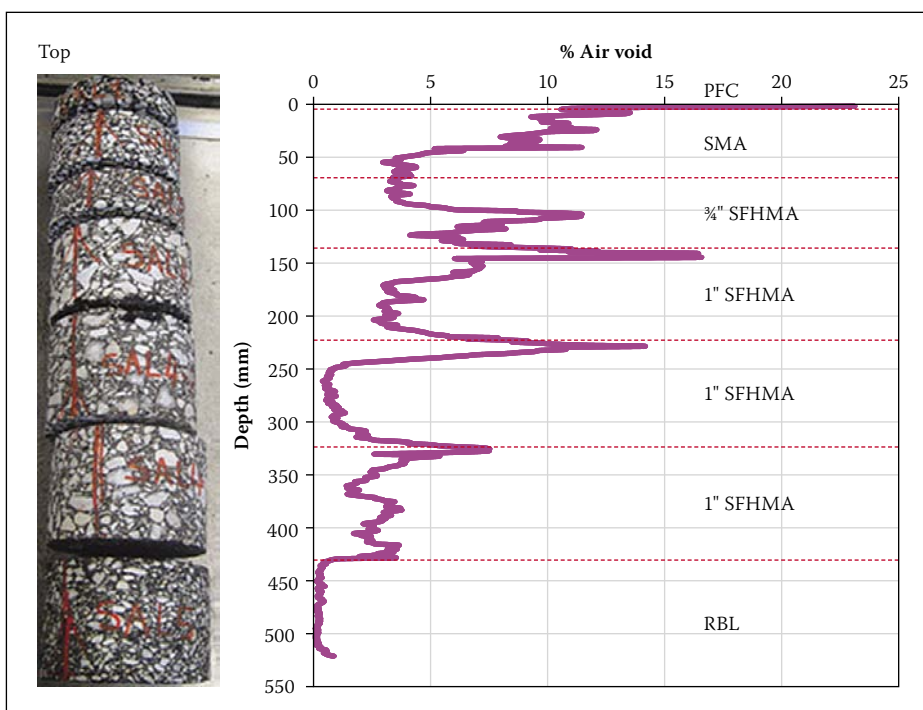
As echoed by the laboratory AV content determined using traditional methods, Figure 14 shows that the AV content for the RBL (fine-graded) is lower than that for the SFHMA layers in magnitude. This is consistent with theoretical expectations and supports preceding results. Similarly, the AV content seems to be relatively higher in magnitude at the ends – in this case at the bottom zones of the layer and lift interfaces, among other reasons possibly due to vertical segregation of the aggregates, which is illustrated by the example shown subsequently in Figure 16 (Walubita *et al* 2010c).

The AV content distribution pattern depicted in Figure 8 for the SGC sample of the coarse-graded Type B mix (22 mm NMAS) suggested the possible occurrence of vertical segregation in the aggregates, i.e. larger aggregate particles gravitationally moving to the bottom. Figure 16 provides this visual evidence with a core from a PP section. This core consists of a coarse-graded SFHMA mix that was compacted in 125 mm layer-lift thicknesses, with a target *in situ* density of 96%. The aggregate gradation was shown in Figure 15. Clearly, this figure highlights the potential construction problems of thicker layer-lift thicknesses, particularly for coarse-graded mixes such as the SFHMA mixes. If water infiltrates through and gets trapped within this high AV content mix, it could undesirably damage the HMA pavement (Walubita *et al* 2010a).

Compared to the fine-graded mixes, coarse-graded mixes with larger AV sizes would thus be more susceptible to oxidative ageing and/or moisture damage due to the possibilities of easy air or water infiltration. However, future research based on image analysis should focus on the computation of AV connectivity (i.e. content and vertical distribution) to validate this hypothesis. The connected AV serves as paths for water movement (defining the mix permeability) and air circulation through the mix, which undesirably creates favourable conditions

for oxidative ageing and/or moisture damage. In addition, it can intuitively be stated that coarse-graded mixes require more meticulous work and caution during laboratory sample fabrication. As subsequently discussed, similar results were also observed with field cores.

As discussed for the vertical distribution of the AV content, Figures 12 and 13 suggest that taller moulding heights would be more prone to heterogeneous distributions of the AV size and variability than shorter moulding heights. These findings further support
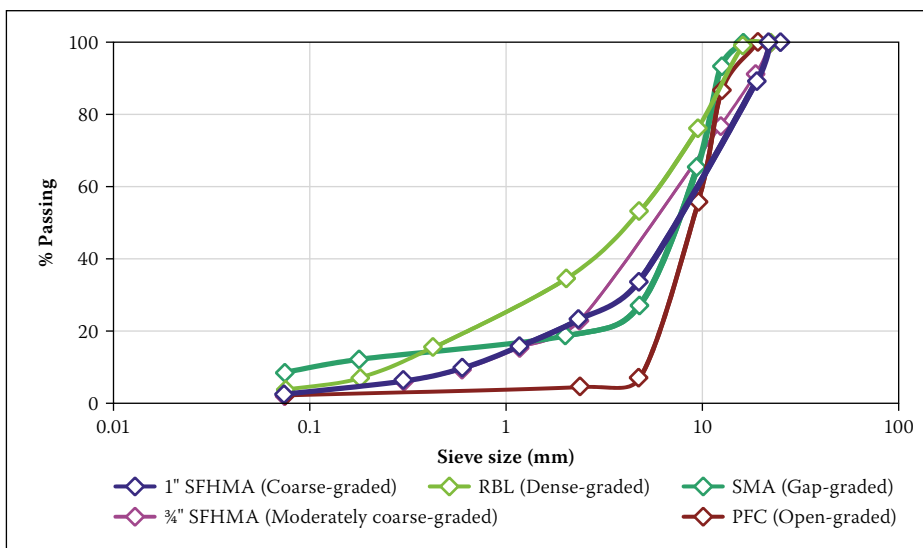
Figure 16 Effects of vertical segregation of aggregates on the AV content distribution

Figure 17 Vertical distribution of AV content in field cores-various layer comparison

Figure 18 Aggregate gradations of the PFC, SMA, SFHMA and RBL mixes

Figure 17 shows another comparison of the vertical distribution of AV content for different layers of an approximately 525 mm thick multi-layered PP core, with the fine-graded RBL exhibiting the most AV uniformity (i.e. the lowest AV content distribution variability).

Because of its functionalities within the PP structure, such as preventing bottom-up fatigue cracking and upward water intrusion from the base/subgrade, the RBL is typically compacted to a relatively higher *in situ* target density than other layers (i.e. 97% versus 96% specified for SMA and SFHMA, or 80% specified for PFC mixes). Combined with its fine aggregate gradation and rich asphalt-binder content (average 5.4%), this partly accounts for its superior AV content uniformity compared to the other layers (Walubita *et al* 2010a). The comparative aggregate gradations for these PP cores are illustrated in Figure 18, with the RBL having the finest aggregate gradation.
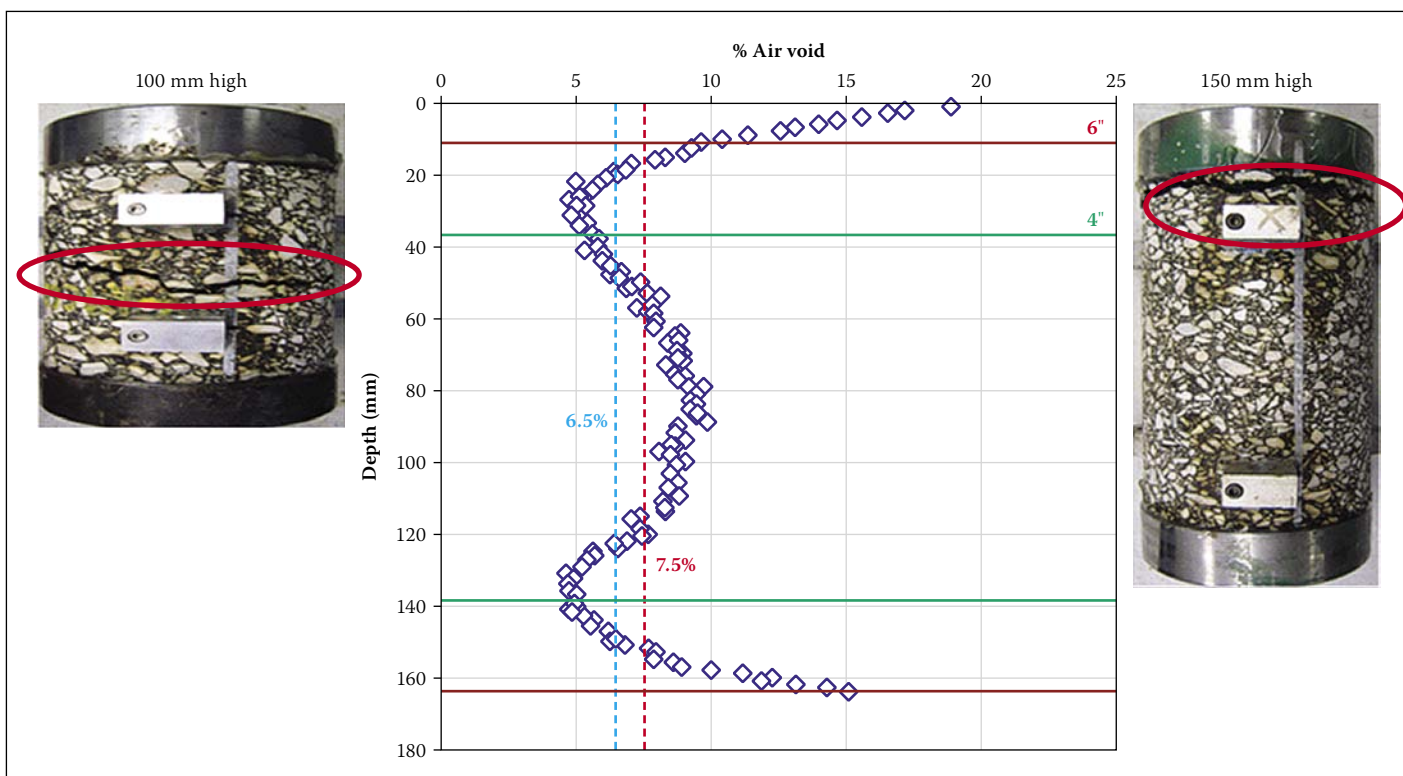
Just like the RBL in Figure 18, Table 1 indicated a finer aggregation gradation (Figure 3) and more asphalt-binder content for the Type D mix compared to the Type B mix. Conversely, and just like in Figure 17, the fine-graded and rich Type D mix exhibited better AV uniformity than the coarse-graded Type B mix (refer to the preceding results in Figures 5 through 13).

The PFC, as theoretically expected, shows the highest AV content values, ranging from about 10% to 25%. Again, the AV content peak at the layer- and lift-interfaces is clearly visible, particularly for the coarse-graded SFHMA mixes. Actually, if the SFHMA layers are analysed separately, their AV distribution patterns do not differ significantly from Figures 5 through 8 for the laboratory-moulded samples. These high AV content peaks suggest potential for debonding problems, which is undesirable. In fact, debonding problems were experienced with some SFHMA cores – see Figure 9 (Walubita *et al* 2010c).

In addition to possible vertical aggregate segregation, the heterogeneous AV content distribution exhibited in Figures 14 through 17 may have been contributed by many other factors, including but not limited to the following:

■ Temperature segregation within the HMA mix during construction. At the bottom of the HMA mix, the existing layer (which is at a relatively lower temperature) may be promoting rapid cooling and therefore low density at the interface. At the surface, the compactor wheels, as well as the effects of the environment, may have a rapid cooling effect on the top portion of the HMA mix.

Figure 19 DT failure zones and vertical distribution of AV content (Type D mix) (Walubita *et al* 2010c)

- Heterogeneous distribution of the compaction energy, which is applied at the surface and dissipates decreasingly with depth.
- In the case of the coarse-graded SFHMA mixes, conjecture is that the large angular aggregate particles do not receive sufficient compactive energy at the bottom of thicker lifts to promote adequate reorientation, and thus contribute to the poor AV distribution structure. This problem is exacerbated by the low asphalt-binder content (Table 2) that limits the effective lubrication to allow reorientation of the aggregate particles (Walubita *et al* 2010a).

Effects of air voids (AV) distribution on the tensile failure mode

Figure 19 shows a typical vertical distribution of AV content in a 164 mm high SGC compacted cylindrical sample (Type D mix) and a side by side comparison including the tensile failure zones for a specimen tested under DT loading.

In Figure 19, the **red** horizontal boundaries represent the AV content distribution for cutting the sample to 150 mm high, while the **green** boundaries represent the AV content distribution for cutting the sample to 100 mm high HMA test specimens. With respect to the target AV content tolerance, the dashed **blue** and **red** lines represent the lower and upper allowable limits respectively; i.e. 7±0.5% for this particular case for DT testing (Walubita *et al* 2010a).

Clearly, Figure 19 shows that the AV content distribution is not homogeneous, leading to weaker zones at the ends of the

sample. For DT testing, the tensile failure zone should be in the middle, as exhibited by the 100 mm high test specimen in Figure 19 (Walubita *et al* 2010b). End-failures, such as the one exhibited by the 150 mm high test specimen (on the right side of Figure 19), are undesirable. For the 150 mm high specimen, Figure 19 in fact shows a maximum trim depth of about 10 mm, which yielded undesired results with the DT tensile testing. A minimum trim depth of 20 mm would likely yield the desired failure mode as evidenced by the 100 mm high test specimen. Similarly, the irregular distribution of the AV content in the HMA mix specimens can lead to problems for testing and evaluation of other HMA characteristic properties, such as permanent deformation resistance, stiffness, and/or moisture damage susceptibility.

CONCLUSIONS AND RECOMMENDATIONS

Based on the research work that was conducted and the data presented in this paper, the following conclusions and recommendations were drawn:

- In general, there is potential for aggregate vertical segregation and AV content variability in SGC samples moulded to taller heights in the laboratory. Where possible, shorter mould heights that would allow sufficient trim depth should be used so as to optimise the AV content uniformity of HMA test specimens. For the SGC compactor and sample types considered in this study, a sample height of less than

164 mm – that does not compromise both the aspect ratio and NMAS coverage requirements – would be preferred.
- For the type of SGC samples discussed in this paper (i.e. 110 mm and 164 mm high with 150 mm diameter), trimming a minimum of 20 mm on either side is recommended. This is envisaged to optimise the total AV content uniformity. *In general, test specimens should always be cut from the middle zone of the SG-moulded samples where the total AV content is less heterogeneously distributed.* With shorter mould heights, however, caution should be exercised to satisfy the test specimen aspect ratio and NMAS coverage requirements.
- As evidenced by the field core data presented in this paper, there is also a high potential for compaction problems, including aggregate vertical segregation and *in situ* density variations, when opting for thicker layer-lift thicknesses in the field during construction. Where possible, thin layer-lift thicknesses should be used that will optimise the construction quality without compromising the NMAS coverage requirements.
- For the materials and HMA mixes evaluated in this study, the coarse-graded mixes exhibited more susceptibility to aggregate vertical segregation and AV content variability with larger AV sizes than fine-graded mixes. Thus, care should be exercised both in the laboratory and field to optimise density/AV content uniformity. Fine-graded mixes on the other hand are

more compactable with better density/AV content uniformity characteristics. Overall, this study has demonstrated that the X-ray CT scanner, coupled with image analysis, can be satisfactorily used to characterise the AV content distribution of both laboratory-moulded samples and field cores. This non-destructive system has the potential and capability to measure both the AV content and AV size as a function of depth or sample height. However, the accuracy of the image analysis is also considered to be a function of the maximum scanning resolution of a specific X-ray CT device that is used, and where applicable, some data correction adjustments may be warranted to optimise the accuracy of the test results.

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DISCLAIMER

The contents of this paper reflect the views of the authors who are solely responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of any agency or institute. This paper does not constitute a standard or specification, nor is it intended for design, construction, bidding, contracting or permit purposes. Trade names were used solely for information purposes and not for product endorsement.

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