Microstructural Characteristics of Bituminous Mix Using X-ray CT

Subhashree Jena[1], Bignya Ranjan Pathi[2] and Mahabir Panda[3]

[1]Department of Civil Engineering, National Institute of Technology, Rourkela, Odisha, 769008, India.

E-mail: subhashreejena021@gmail.com

[2]Department of Civil Engineering, National Institute of Technology, Rourkela, Odisha, 769008, India

E-mail: bignyaranjan@gmail.com

[3]Department of Civil Engineering, National Institute of Technology, Rourkela, Odisha, 769008, India.

E-mail: panda.mahabir@gmail.com

Abstract

Study of the internal structure of bituminous paving mixes is very essential to understand its air void characteristics which ultimately relate to the strength of these mixes. Air void (AV) distribution significantly influences the structural and functional performances of bituminous mixture. The lack of proper investigation of the AV parameters and their distribution often leads to major distress related issues. The present study is an attempt to investigate the AV properties and their distribution in a profound and precise manner using an effective and quick 3D high resolution technology such as X-Ray micro computed tomography combined with the digital image processing tools. Using the 3D Images obtained from imaging technique, the internal structure of bituminous mix was visualized and then image analysis was done to determine various AV parameters such as AV content, number of AV, AV size and shape of AV of the compacted bituminous specimen. With the help of continuous spatial data of above mentioned properties obtained from volumetric images, the homogeneity of AV distribution was evaluated. Variation of AV parameters along the vertical, horizontal and radial directions were plotted and further analyzed to find the inconsistency in their distribution. Compared to vertical direction, a significant variation was observed in the horizontal direction where the inner region contained more number of AV than that in the mid and outer regions.

Keywords: X-Ray CT, AV parameters, sphericity,AV distribution.

1. Introduction

Bituminous mixture is a heterogeneous composite material comprised of coarse and fine aggregates, bitumen and voids. Aggregates that constitute 80-90% of total volume of the mixture vary in shapes and sizes and have random locations; while bitumen is a viscous material and its mechanical performances are very sensitive to the temperature. The physical and mechanical properties of individual components along with the chemical and physical interactions among them have a significant effect on the performance and efficiency of bituminous pavement. Sashidhar et al. (2000) utilised photoelastic techniques to study the load distribution characteristics of bituminous mixture. He demonstrated that the material behaves more like a granular material and the load transmission takes place in the form of force chains and particle-to-particle contact exists in the formation of these chains. It was also stated that different aggregate gradations having different aggregate structures produce different load distributions in the pavements. Thus, a comprehensive understanding of the internal structure of bituminous mixes is necessary for a realistic prediction of its performance. In this direction, several attempts have been made to quantify the microstructure of granular materials using imaging technology. Initial investigations focused on two-dimensional (2-D) measurements conducted on cut sections of the material (Oda, 1972; Oda et al., 1985; Muhunthan et al., 1996; Tashman et al., 2001). However, this approach is laborious, destructive and causes defects to the sample and hence, limits the amount of data that can be extracted from the image (Mahmud et al., 2017). Some studies focused on capturing air voids on two-dimensional sections of specimens impregnated with resin and fluorescent dye (Eriksen and Wegan, 1993; Kose et al., 2000). However, this approach seems to work better for specimens with high air void connectivity to allow the resin to reach most of air voids. Investigations further established that X-ray micro computed tomography (X-Ray CT) is a completely nondestructive technique which can be utilised to conduct 3D reconstruction of a specimen and detailed information related to its geometry can be obtained. It has been successfully used to determine 3-D microstructure of soils (Desruses et al., 1996; Shi et al., 1999; Geraud et al., 1998; Desrues, 2004) and cement concrete (Landis and Keane, 1999; Hall et al., 2000). The specimen is scanned by using X-ray CT to obtain cross-sectional CT images and 3-D microstructure is reconstructed by processing the X-Ray CT images using image processing techniques. One of the advantages of using X-ray imaging techniques is that the same specimen can be used for further mechanical testing in order to relate the microstructural properties to mechanical response of the material.

The lack of laboratory techniques to capture the air void (AV) distribution has limited most of the previous investigations to focus on the average volume of air voids in designing and specifying bituminous mixes. There are many conventional techniques to measure AV contents, just like a rubber membrane method, the parafilm methods, the theory of linear elastic material method, and parallel plate method, which can only give the AV contents, but not put forward their distributions in the mixes. This study presents the directional and spatial distribution of AVs present in bituminous mixture using X-ray CT coupled with digital image processing.

Various AV parameters such as AV content, number of AV, AV size and shape of AV has been computed in a properly prescribed manner. The distribution of AV characteristics along various directions was also evaluated so as to check the homogeneity within the specimen.

1.1 Objective and Scope of Work

The primary objective of this study is to quantify the directional and spatial distribution of AVs of bituminous mix. For achieving this objective, the scope of work covers the following:

- Preparation of the requisite mix specimens.
- Application of X-Ray imaging technique for the evaluation of microstructure of AV.
- Analysis of variation of AV parameters in vertical, horizontal and radial direction.

2.Experimental Program

2.1 Material Preparation

Materials used in this study included locally available stone aggregates, viscosity graded bitumen VG 30 and stone dust as filler. The specific gravity, softening point (R&B) and the ductility at 27ºC was found to be 1.01, 48ºC and 100+ cm respectively. The stone dust had specific gravity of 2.62 and specific surface area of 272.47 m^2/kg. The gradation used is as per MoRTH (2013) and is depicted in Figure 1. Different ingredients were mixed and compacted using a Marshall hammer for 75 blows on both sides and the specimen was allowed to cool at room temperature. The compacted specimen was then scanned by using X-Ray micro CT.

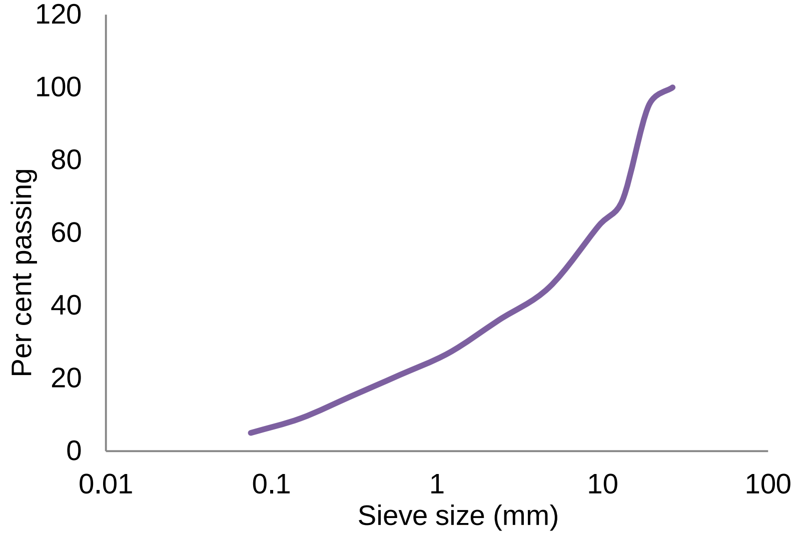
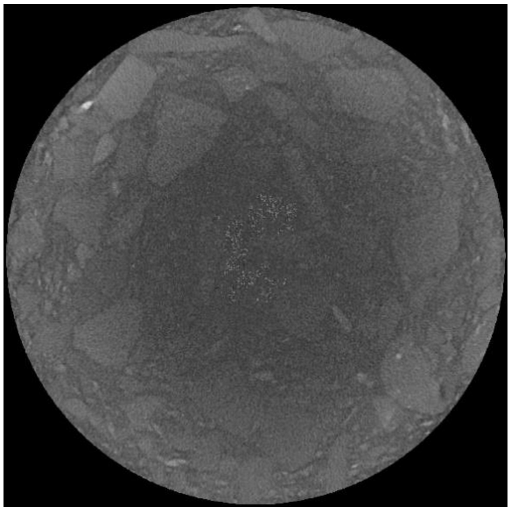


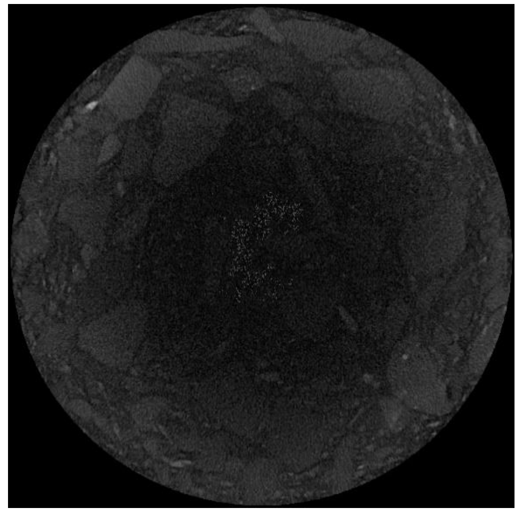
Fig. 1 Aggregate Gradation used

2.2 Application of X-Ray micro computed tomography

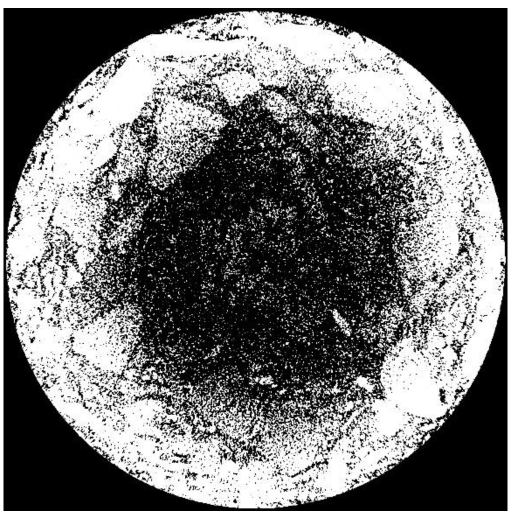
A GE Phoenix vItomeIx s industrial CT scanner was used to scan the compacted specimen. This X-Ray micro CT system used a focal X-Ray source and an image intensifier detector with the test specimen placed on a rotating turntable. Unlike old systems, this X-Ray source used cone beam geometry to capture the volumetric data while light was allowed to transmit through the specimen on the turntable rotating with a constant speed. The intensity of X-Rays was measured before and after their entry through the specimen and 3D images were generated containing different grey values. This image was subjected to defect analysis with an appropriate threshold value using the system integrated high end software, VGStudio Max. The 3D volumetric image was divided into three sub divisions and then defect analysis was performed on each sub volume. Further, vertical as well as horizontal slices were captured for a multi-phase segmentation in the imaging software ‘Image J’. The segmentation of each material present in the mix was done using a suitable range of threshold value. Fig. 2(a) – (d) represents the images produced by using image processing and segmentation technique as explained earlier. A clear distinction between the AV, aggregate and the mastic phase was conducted and then their 3D images were subjected to image analysis for further computation of AV parameters. Fig. 2(c) represents a binary image. Where the black spots are AVs and the white space is the rest of the materials present in it.



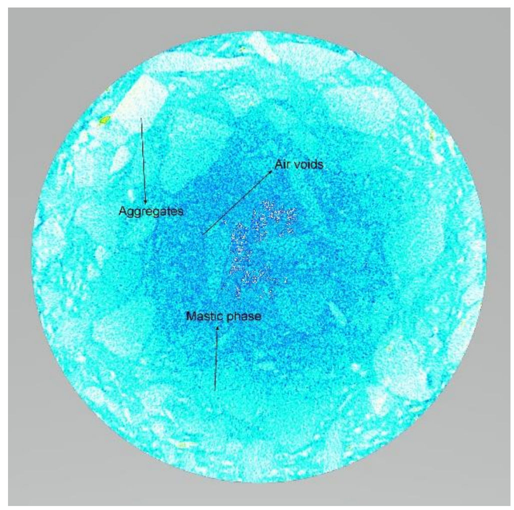
(a) Gray scale image



(b) Threshold image



(c) Binary image



(d) Multi-phase segmentation

Fig. 2 Various stages of image processing

2.2 Computation of AV parameter

The distribution of AV in the bituminous mixture was analysed in terms of content, number, shape and size. The size of AV was studied by computing the mean diameter, and sphericity describes the shape of AV present in the specimen. The formulae used to calculate various AV parameters are presented in Eq. 1 to 3, which were described in the research work carried out by Alvarez et al. (2009) and Scholes et al. (2007).

1. AV content: AV content was determined by calculating the total volume of all the AVs present and then finding its percentage with respect to the total volume. Volume of each individual AVs were found out in the defect analysis.

$$AV\ (\%) = \frac{sum\ of\ volume\ of\ individual\ AV}{Total\ volume\ of\ the\ specimen} X\ 100 \qquad \text{Eq. 1}$$

2. Sphericity: It measures the extent of spherical or flatness nature of AVs. Its value lies in between 0 to 1, the upper extreme giving a perfectly spherical shape. It can be expressed as follows.

$$S = \Pi^{1/3} X \frac{(6\ X\ volume\ of\ the\ AV)^{2/3}}{Area\ of\ the\ AV} \qquad \text{Eq. 2}$$

3. Mean diameter of AVs: If an AV is assumed to be perfectly spherical having volume equal to that of the AV, then the corresponding diameter of the sphere is known as the diameter of AV. The mean diameter of AVs refers to the arithmetic mean of diameter of all the AVs present inside the specimen.

$$R\ (mm) = \left(\frac{3\ X\ volume\ of\ the\ AV}{4\pi}\right)^{1/3} \qquad \text{Eq. 3}$$

3. Results and Discussion

3.2 AV Distribution

Table 1and Table 2 present various AV parameters determined along the depth and radial directions respectively. From Table 1, it can be observed that the AV parameters except sphericity varied in all the three regions considered. Likewise, wide variation of AV parameters in all the three radial regions can be seen in Table 2. This necessitates further investigation of spatial distribution of AV parameters in bituminous mix in all possible direction. So, a brief analysis on AV distribution has been carried out in the following sections.

Table 1 AV parameters in all three vertical regions

AV Parameter	Overall	Top	Middle	Bottom
AV content	3.343	3.786	1.303	3.728
Sphericity	0.499	0.499	0.498	0.499
Mean diameter	1.137	1.546	0.649	1.253

Table 2 AV parameters in all three radial region

AV Parameter	Overall	Outer	Mid	Inner
AV content	3.343	0.911	2.529	5.461
Sphericity	0.499	0.494	0.498	0.504
Mean diameter	0.927	0.917	0.744	0.849

3.2.1 Vertical Distribution

Figure 3 through 5 represent the variation of AV parameters along the depth of the specimens. It can be observed that all the parameters have large variation in distribution at its top most and bottom most part. Also, Figure 3 shows that number of AV in the central middle part is less than the other regions of the specimen. From Figure 4 and 5, a prominent spike can be observed in the distribution of mean diameter and sphericity of AV. Sphericity had lower values at the topmost and bottom most part where as this is just opposite in case of mean diameter. This shows that the higher the size of the AV, more elongated it will be giving rise to a lower sphericity value. These inconsistencies in the distribution of AV parameters show the non-homogenous distribution of AV parameter along the depth of the specimen.

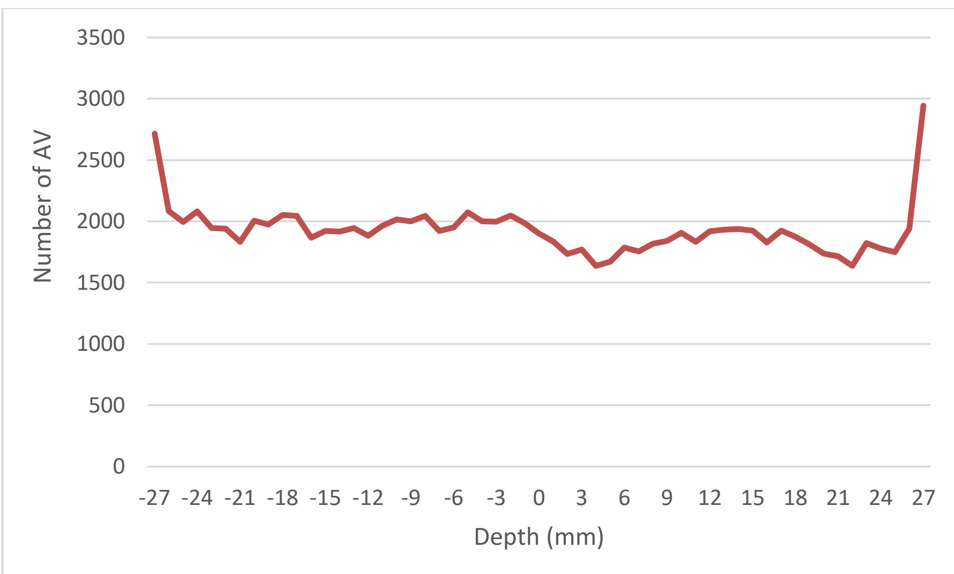


Fig. 3 Variation of number of AV along vertical direction

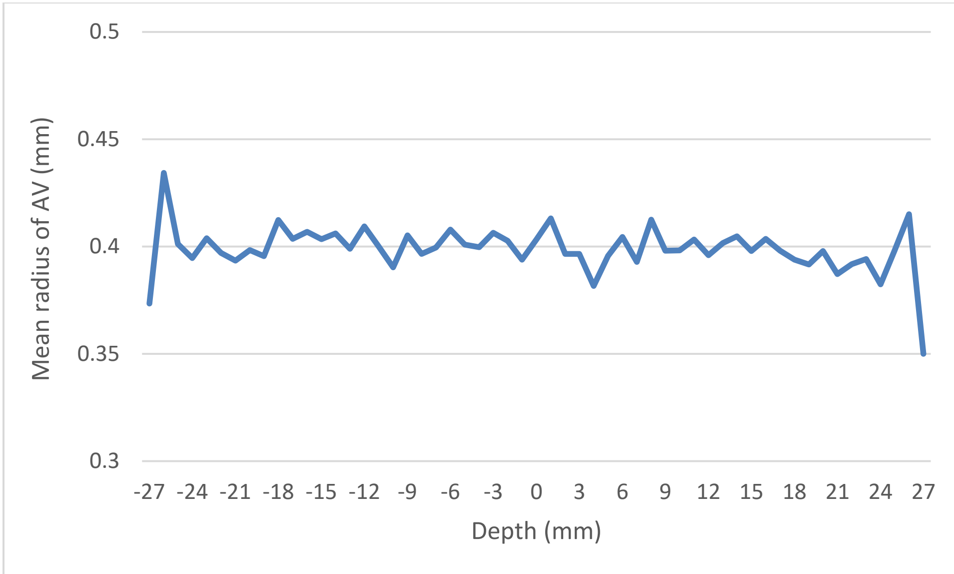


Fig. 4 Variation of mean diameter of AV along vertical direction

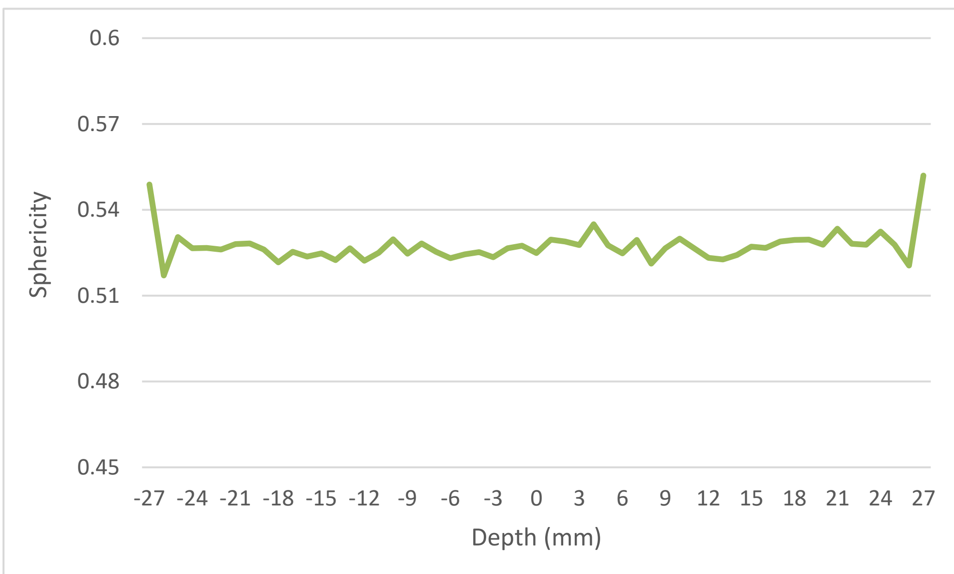


Fig. 5 Variation of sphericity along vertical direction

3.2.2 Horizontal Distribution

In this case the specimen is divided into several thick ring of particular radius from inner to outer radius and then the distribution of AV parameters along these ring was analyzed which are shown in Figure 6 through 8. All these variations show that the mid region contributes the major part of these AV whereas the outer part has very negligible amount of AV. Figure 6 shows the number of AV distribution in bituminous mix specimen which rapidly decreases as we move from inner to the outer region. Figure 7 and 8 show the variation of sphericity and mean diameter which follows the opposite trend in their distribution and higher size of AVs can be found out in the outer region compared to the mid region. These analyses proved that AV distribution is non-homogenous along horizontal direction also.

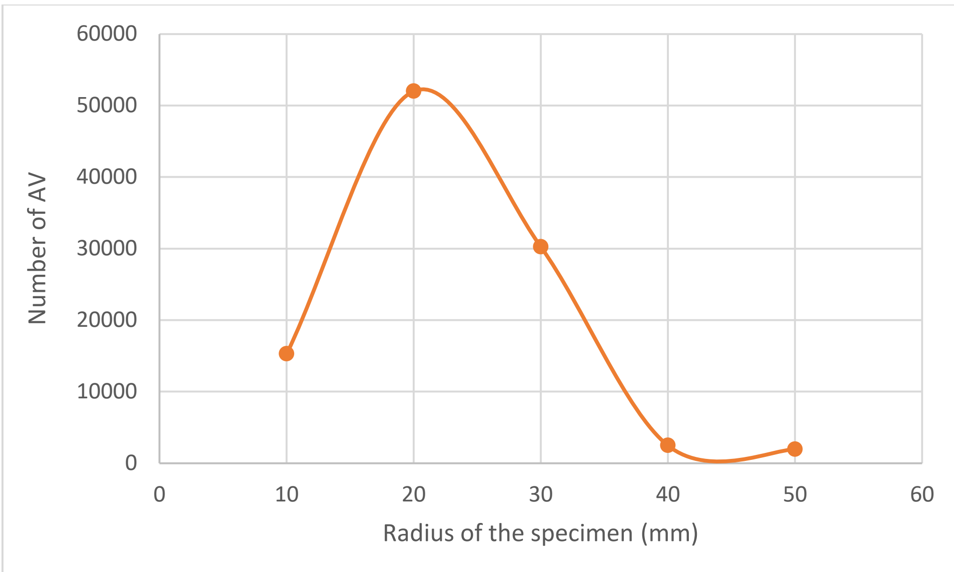


Fig. 6 Variation of number of AV along horizontal direction

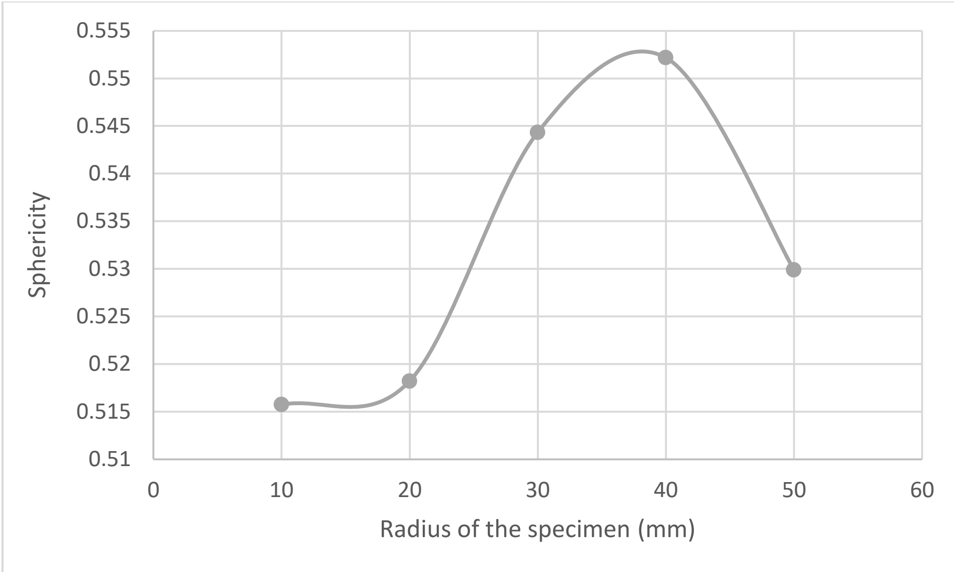


Fig. 7 Variation of sphericity along horizontal direction

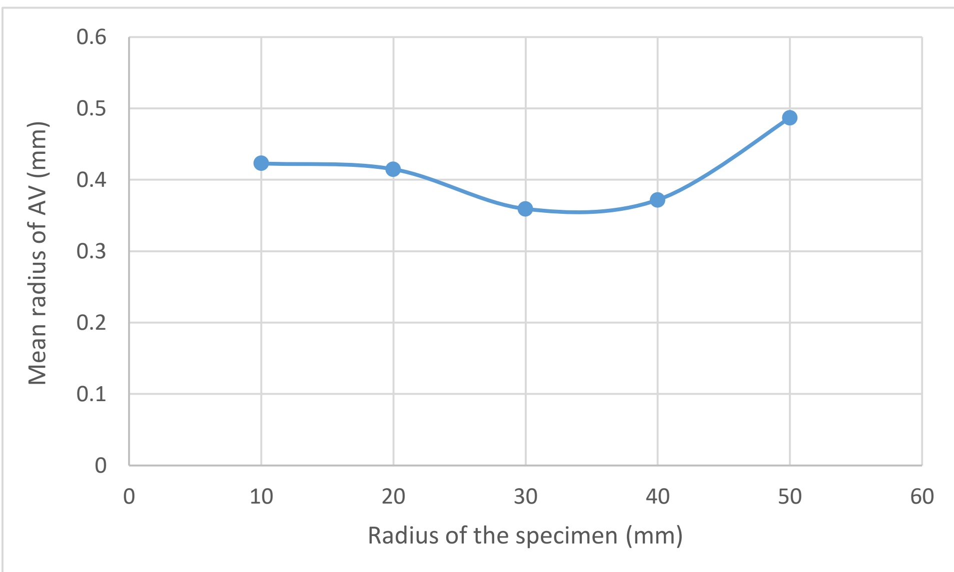


Fig. 8 Variation of mean radius of AV along horizontal direction

3.2.3 Radial Distribution

In this case, the entire 360^0 of the specimen was divided into various parts and the AV distribution in each part was analyzed which are shown in the Figure 9 through 11. These figures show the variation of the AV parameters in a polar diagram where each circular line represent a particular value of the corresponding parameter. It can be observed from Figure 9 that distribution of number of AV along the radial direction is also non-homogenous and one half of the specimen showed higher number of AV compared to the other half. Form Figure 10 and 11, it can be noticed that mean diameter and sphericity of the AVs showed a uniform variation in their distribution along the redial direction. So, the variation in radial direction is quite homogenous as compared to the other two directions.

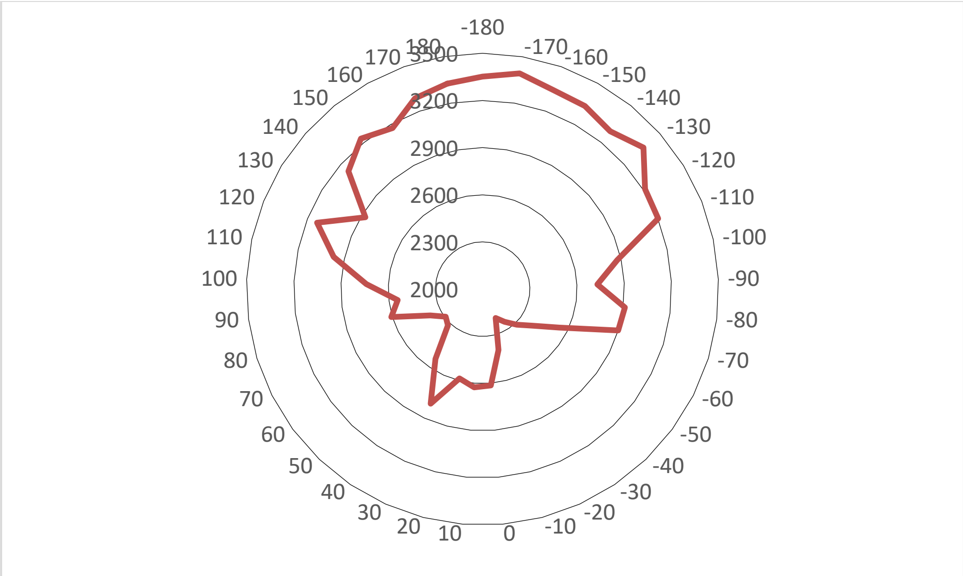


Fig. 9 Variation of number of AV in radial direction

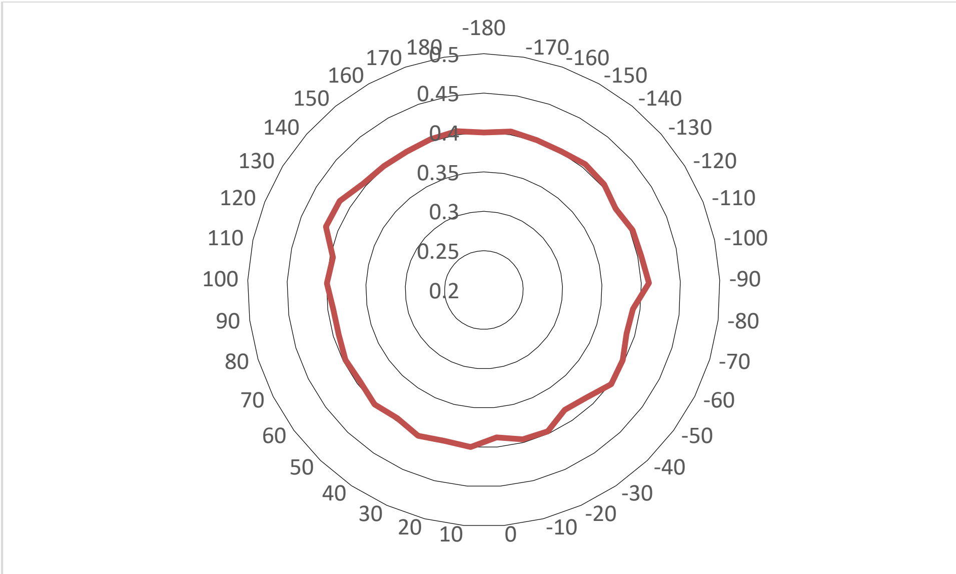


Fig. 30 Variation of mean radius of AV in radial direction

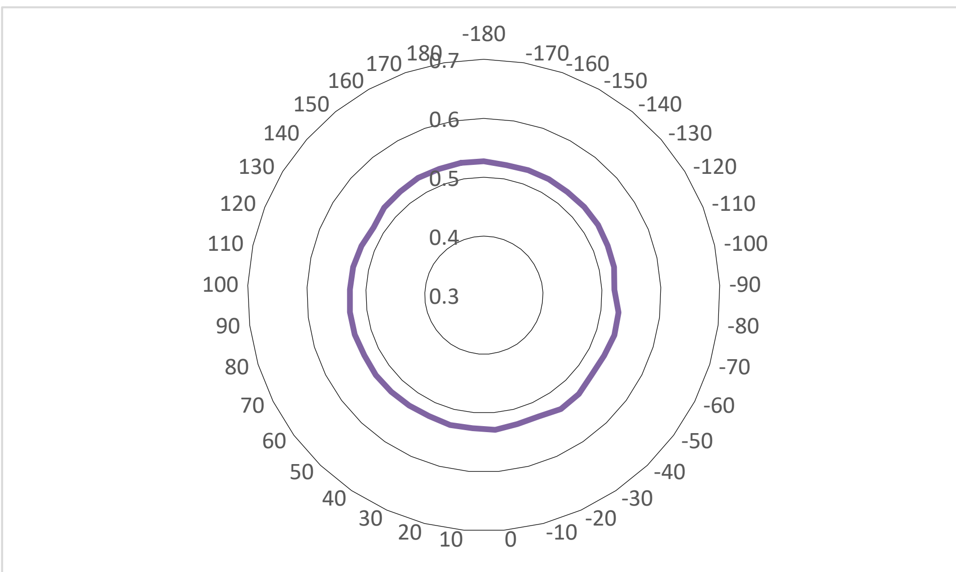


Fig. 11 Variation of sphericity in radial direction

3.3 Air void size distribution

As AV size is a major parameter which influences the strength characteristics of the bituminous mix specimens, it was decided to investigate the AV size distribution in various region of the specimen. Figure 13 and 14 shows the number of AV of a particular size range present in various regions of the specimen along both vertical and horizontal direction. It can be observed form Figure 13 that the maximum number of AV size ranges from 0.2 mm to 0.6 mm. The size distribution is quite uniform in the vertical distribution implying all the vertical regions contains almost equal range of a particular AV size range. But this is not the same in case of distribution across horizontal direction. Figure 14 shows that there is a wide variation in the number of AV of a particular size range in all three horizontal regions namely outer, mid and inner. For all AV size range, inner part showed highest amount of AV followed by mid and outer region. This shows the non-homogeneous distribution of AV size across the horizontal direction in a bituminous specimen. From the above analysis, it can be concluded that the variation of AV size range is quite uniform or homogenous in the vertical direction compared to the horizontal direction. This could be attributed to different degree of compaction these regions are subjected to because of the manual compaction.

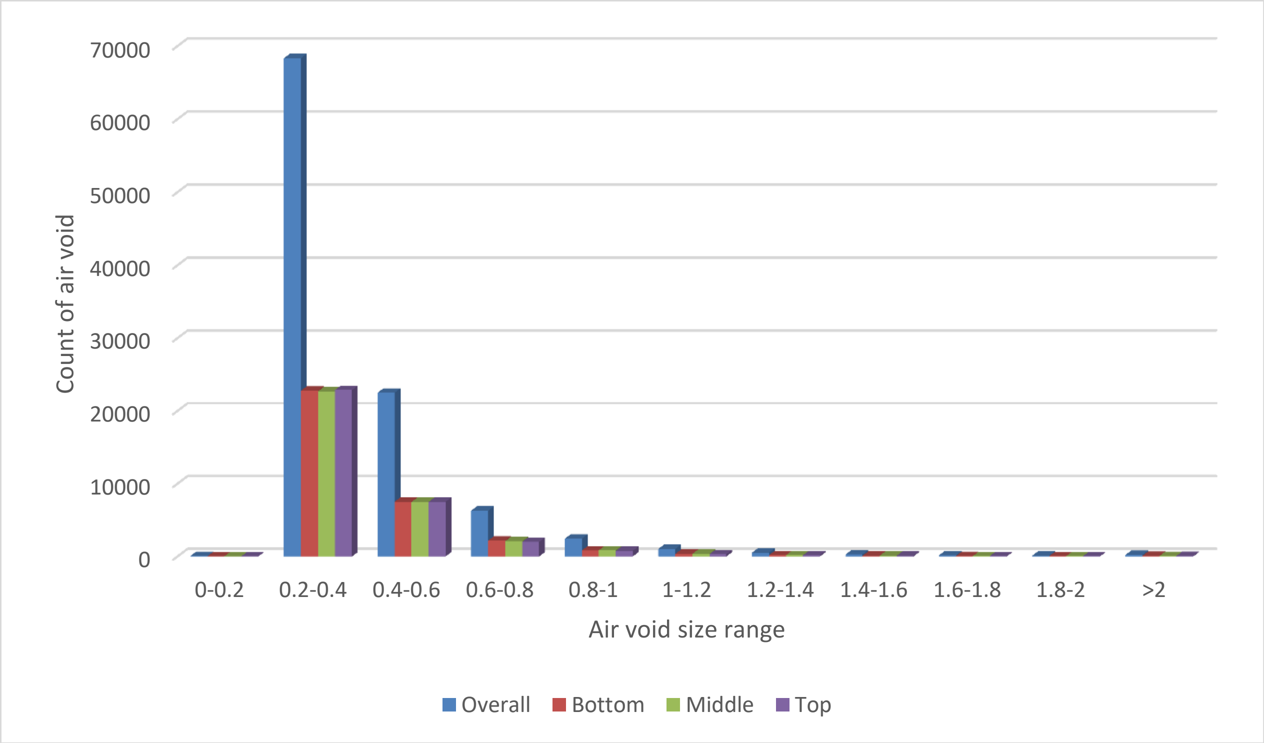


Fig. 4 AV size distribution in all vertical regions

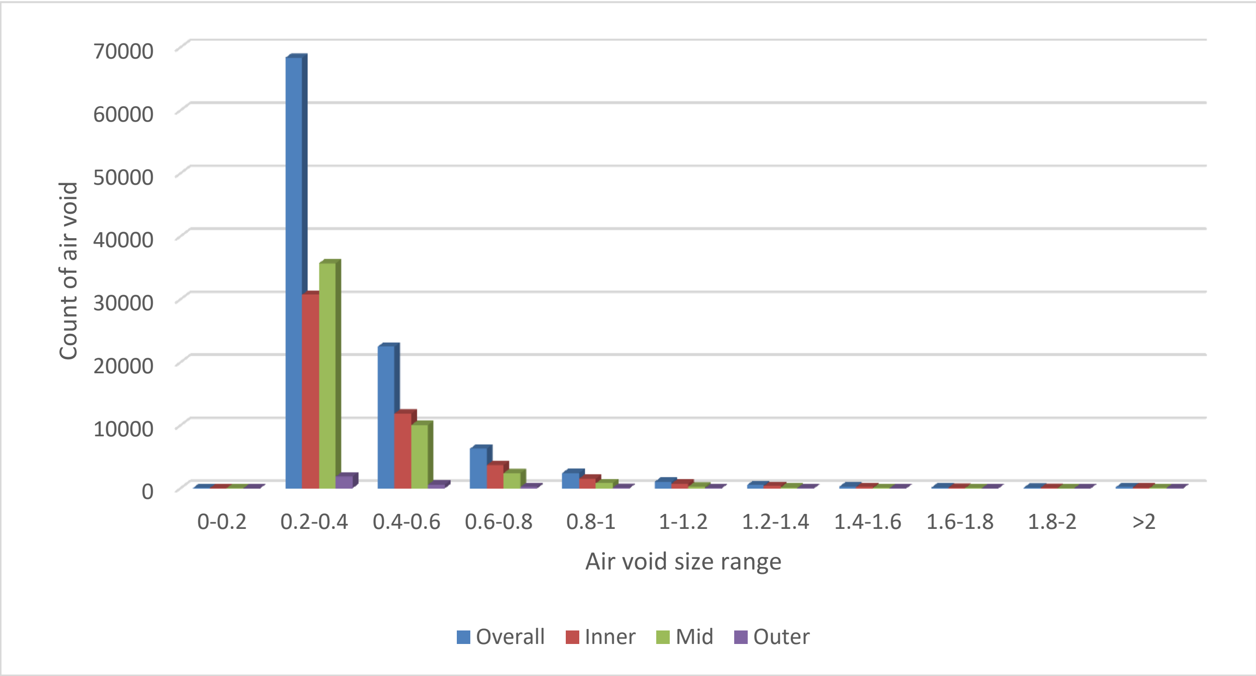


Fig. 5 AV size distribution in all radial regions

4. Conclusions:

A detail analysis of the AV distribution was conducted with the help of the continuous spatial data obtained from the imaging technique and the following conclusions can be drawn.

- X-Ray micro computed tomography along with the digital image processing tool were found to be an excellent non-destructive technique for the measurement of various micro-structural properties which were impossible to measure using conventional methods.
- The distribution of AV parameters inside the bituminous mix specimen was found to be non-homogeneous which could lead to different mechanical properties.
- The variation of AV parameter distribution is quite prominent in case of the vertical and horizontal direction compared to radial direction. Mid region showed higher number of

AV compared to the outer region in case of horizontal direction whereas Top and bottom most part showed higher number of AV in vertical direction.

- AV size distribution was found to be more non-homogeneous in the horizontal direction giving rise to almost negligible amount of a particular size of AV in the outer region compared to the inner region.
- From the above analyses it can be easily concluded that the AV parameters are non-homogeneous in their behavior indicating a major flaw in the traditional way of measurement of the AV parameters which considers the average value of AV and correlate those average values to the strength parameters.

4.2 Future Scope

Effect of non-homogeneous distribution of AV parameters on various mechanical properties and permeability can be predicted. This will help in the accurate and error free deteremination of strength parameters which will develop the pavement life span.

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