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OGPA Void Shape Characterisation Methods - Scoping Study

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Disclaimers and Limitations

This report ('**Report**') has been prepared by WSP exclusively for Waka Kotahi NZ Transport Agency ('**Client**') in relation to research into methods to assess OGPA void shape ('**Purpose**') and in accordance with Contract no. 6026 (WBS60063697). The findings in this Report are based on and are subject to the assumptions specified in the Report. WSP accepts no liability whatsoever for any reliance on or use of this Report, in whole or in part, for any use or purpose other than the Purpose or any use or reliance on the Report by any third party.

1 Introduction

The frequency distribution of noise measurements suggests that particle orientation, void shape, void distribution or other void characteristics that affect air flow through Open Graded Porous Asphalt (OGPA) surfaces may explain the measured differences in noise levels between epoxy modified and standard PA7 OGPA mixes. Methods are needed to characterise the detailed void characteristics in PA7 mixes to enable comparisons between epoxy and standard mixes to support this hypothesis. Differences in void characteristics may occur during construction or later from traffic compaction.

Total air voids as a percentage of the compacted mix volume can be determined using well established standard methods, but these methods do not provide any information on individual void size or shape.

To examine the internal structure of asphalt mixes the methods most commonly employed are X-ray tomography and cross-sectional digital photography variations of which have been utilised in numerous studies over the last 30 years (Alawneh and Soliman, 2023; Taheri-Shakib and Al-Mayah, 2023). X-ray tomography can be used to generate 3-D images of the internal structure of asphalt specimens. Digital photography is a potentially cheaper methodology for measuring particle orientation and voids in 2-D cross sections of asphalt specimens. Both methods are laboratory based and would require asphalt cores taken from the field or laboratory prepared specimens.

Objective

The objective of this work is to determine whether existing x-ray tomography or digital photographic methods would be useful or could be adapted to characterise the void and particle orientation in PA7 mixes. Recommendations for an experimental programme to undertake measurements using these techniques are presented.

2 X-ray tomography

X-ray computed tomography (CT) involves taking x-ray images of compacted asphalt specimens or field cores and is non-destructive as no cutting of the specimen is needed. Different components of the asphalt (air, bitumen, aggregate) absorb x-ray radiation to different degrees depending on material properties such as density and the thickness in the beam path.

A narrow x-ray beam is aimed at a particular depth in the specimen which is rotated slowly through 360° as scans are taken. A scintillation counter is used to convert the x-rays into visible light which is recorded by a camera. The Individual scans are combined to give a 2-D image of the sample at the measurement depth. The process is repeated at different small depth increments, e.g. 0.016 mm (Alawneh *et al.*, 2023) and the virtual cross sections (slices) of the specimens are stacked to give a 3-D image. The process is illustrated schematically in Figure 1.1, an illustration of an industrial x-ray CT instrument is shown in Figure 1.2.

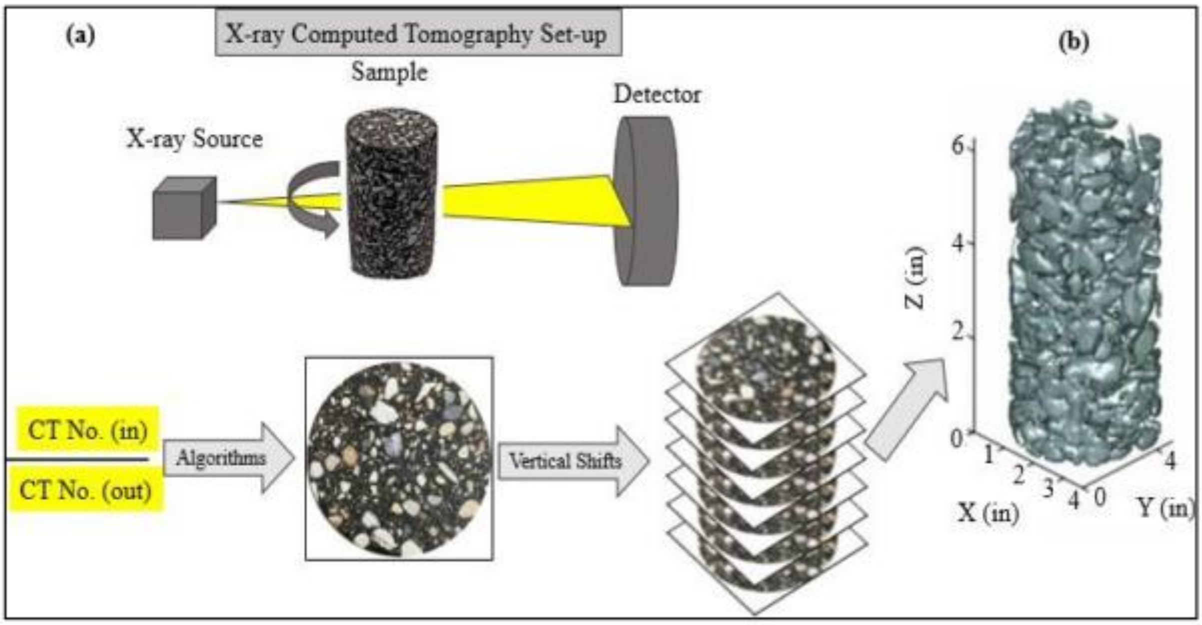


Figure 1.1 X-ray tomography of an asphalt mix specimen (Alawneh and Soliman, 2023).

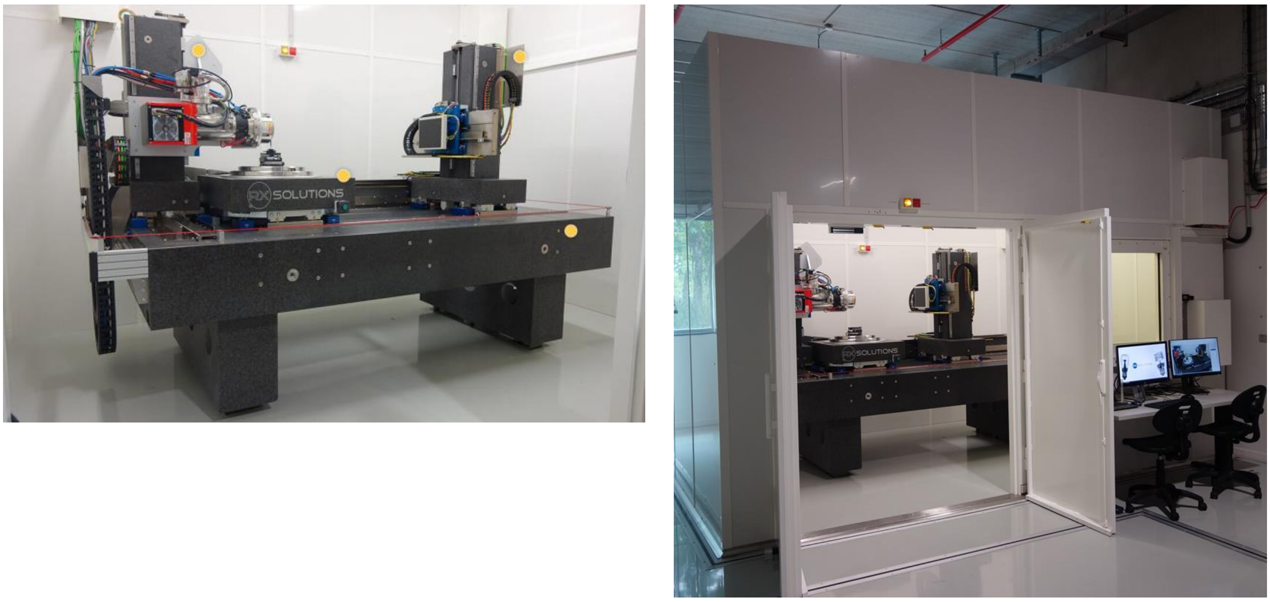


Figure 1.2 High precision (0.4 um) research grade industrial x-ray CT scanner (source: RX Solutions).

Typically the spatial image resolution depends on the pixels in the detector camera and the distance of the specimen from the x-ray source. Resolutions reported are typically in the order of tens to hundreds of microns hence very fine particles or air voids will not be clearly distinguished (Garcia *et al.*, 2019; Alawneh *et al.*, 2023; Taheri-Shakib and Al-Mayah, 2023). With more specialised equipment resolution as high as 0.7 um can be achieved although the volume of sample analysed was relatively small, about 40 mm^3 (Middendorf *et al.*, 2023).

Equipment availability

The technique involves specialist equipment and operators as precautions against the hazardous ionising radiation must be taken. There is no industrial x-ray scanning instrument available in New Zealand suitable for asphalt mix samples (*Pers. Comm.* Dane Gerneke University of Auckland, MicroCT Facility Manager). Such instruments cost in the order of 1-2 million dollars, the nearest facility is in Melbourne.

The university of Auckland operate two micro-CT instruments available to outside users designed to measure small (mm scale) low density samples. Sample sizes are limited to 75 mm diameter and 80 mm high. To create a 2D horizontal slice of a sample this size would take about 4 hours (at 27 um resolution) and cost about $600 + gst. If 200 slices were taken at 100 um intervals to allow construction of a 3D image of 20 mm depth, the cost would be in the order of $12,000+ gst (i.e. per specimen). As well as only allowing relatively small sample sizes image quality is also not likely to be high as the x-ray intensity is too low for dense materials (100 keV compared to 300 keV or more on industrial scanners).

3 Digital camera imaging

Cross sectional images of compacted asphalt slabs or cores are obtained by cutting the specimens with a diamond saw. Although such saws are normally water cooled the heat generated during cutting can lead to smearing of bitumen over the cut aggregate surfaces. Cooling or freezing the specimen prior to cutting usually alleviates the problem. The number of cross sections that can be cut from a single specimen is limited compared to the virtual cross sections obtained by x-ray tomography. In most cases the thickness of the saw blade and the practicalities of handling fragile sections (especially high void open-graded materials) limits the thickness of the sections to about 10 mm.

Cross sectional images are obtained simply by using a digital camera. In many studies a simple flat-bed scanner is used (Moon *et al.*, 2015; Middendorf *et al.*, 2023). Ma *et al.* (2020) for example obtained a resolution of 0.0211 mm per pixel using a 1200 dpi scanner. A scanner has the practical advantage of maintaining a constant distance between the sensor and the specimen surface (maintaining a constant spatial resolution for different specimens). Background lighting which will affect image quality, can also be properly controlled as opposed to simply using a camera.

4 Image analysis

Typical cross-sectional images obtained by x-ray tomography and digital photography and the resulting images after processing are shown in Figure 4.1 -4.3. With both imaging techniques the initial images obtained generally lack contrast.

In x-ray tomography this arises primarily because of similarity in the densities of the aggregate and mastic phases. Noise and variability in aggregate density also helps to reduce image definition. Digital photography images are affected by colour variations in the aggregate, variations in lighting, reflections and surfaces in the back of shallow air voids.

The greyscale distribution for unprocessed x-ray cross sectional images of three different mix types are shown in Figure 4.4. Air voids are black (0) whilst dense aggregate components are white (256). Ideally the distribution would show three distinct peaks but the separation between bitumen mastic (around 160-170) and the aggregate peak at about 200 is poor, especially for the dense asphaltic concrete (AC) sample. For both imaging methods processing is needed to enhance the images

A great deal of research has been published dealing with sophisticated methods for improving image quality, filters for removing noise and determining aggregate boundaries etc.(Zelelew *et al.*, 2013; Xing *et al.*, 2019; Peng and Yang, 2023). A review of these methods is beyond the scope of the current project but ultimately a decision must be made to determine greyscale threshold boundaries that separate the image into the three components: aggregate, bitumen mastic and air voids (Taheri-Shakib and Al-Mayah, 2023). A common approach is to calibrate parameters in the image enhancement procedures so that the asphalt mix properties calculated from the images reflect the actual (physically measured) aggregate gradation or total air void content (Moon *et al.*, 2015).In some cases asphalt specific software has been developed (Coenen *et al.*, 2012; Yohana Ribas and Padilha Thives, 2019) but most researchers utilise general purpose image analysis packages such as Matlab (Mathworks) , Avizo (Thermofisher Scientific) or Image -J (National Institutes of Health, University of Wisconsin).

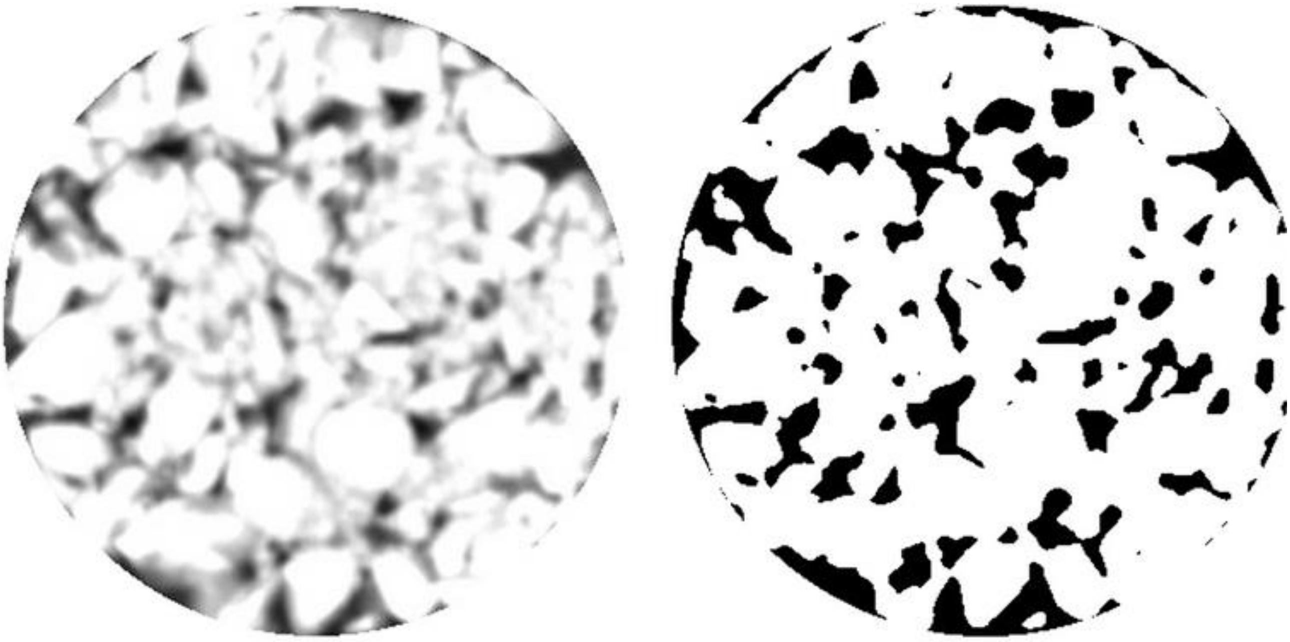


Figure 4.1 X-ray tomography cross section of 20% air void porous asphalt mix specimen, before (left) and after (right) thresholding into two phases to identify air voids (in black), Jiang *et al.* (2015).

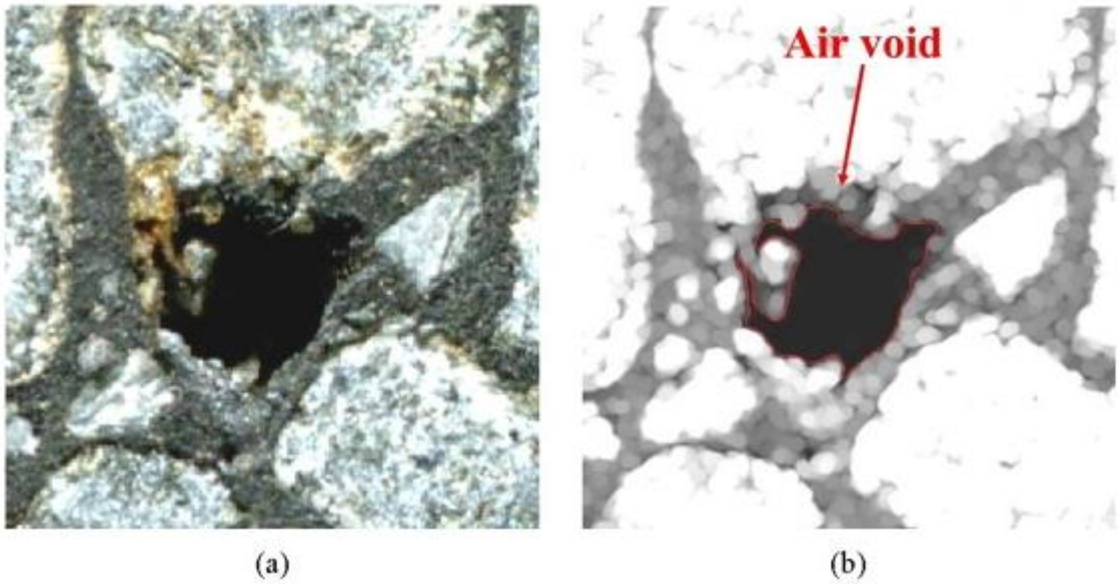


Figure 4.2 Zoomed digital photography (flatbed scanner) image of a cut 20% air void porous asphalt mix cross section, before (left) and after (right) processing to determine air voids (Ma *et al.*, 2020).

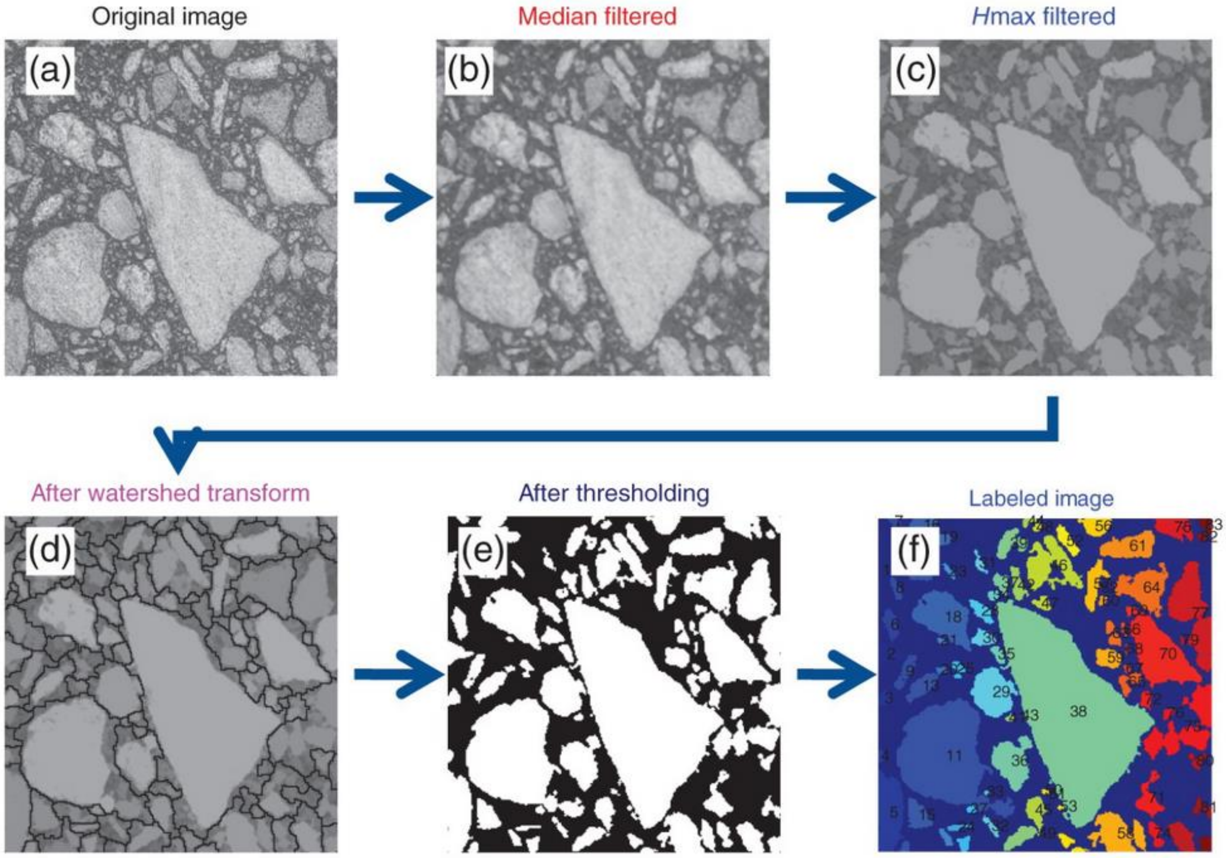
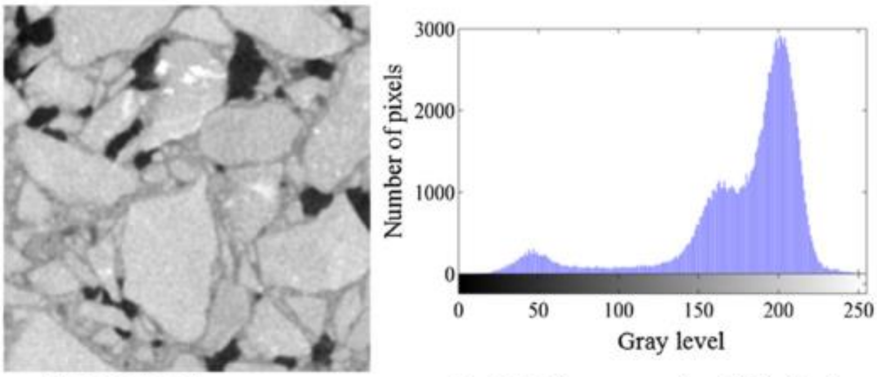
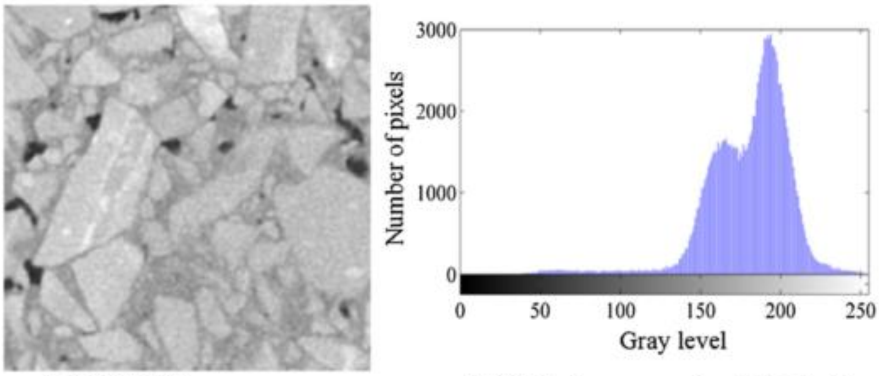


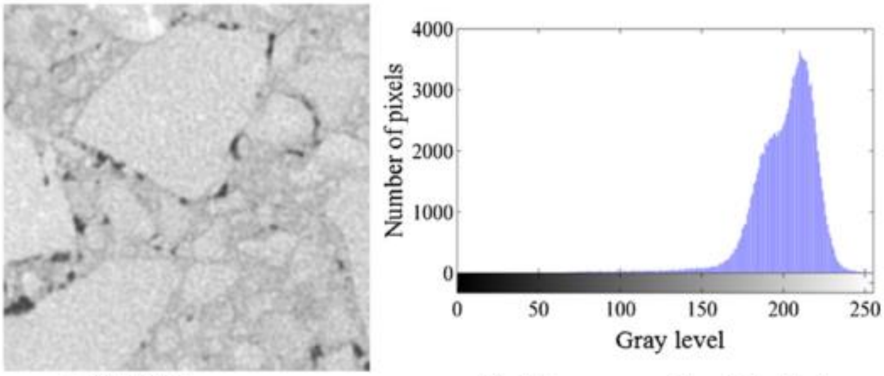
Figure 4.3 Typical processing steps of a 2-D digital image of dense mix asphalt for the purposes of aggregate structure characterisation (Coenen *et al.*, 2012).



(a) OGFC CT image (b) OGFC image gray level distribution



(c) SMA CT image (d) SMA image gray level distribution



(e) AC CT image (f) AC image gray level distribution

Figure 4.4 Greyscale distributions from x-ray 2D images before enhancement (Xing *et al.*, 2019).

5 Imaging analysis for void shape analysis of porous asphalts

A number of studies have used a mixture of x-ray tomography and digital photography to study characterise air voids in porous asphalt mixes for various reasons. These studies are summarised in Table 5.1. Although a full review of this work is beyond the scope of the current project two studies in particular demonstrate the potential for use of imaging techniques to relate void characteristics to acoustic effects in porous asphalts.

Table 5.1 Recent imaging studies on the effects of voids in porous asphalt.

Study	Imaging method	Source
Effect of voids on rutting rates	2D photography	Ma *et al.* (2020)
Void distribution and shape comparison	2D photography and x-ray tomography	Middendorf *et al.* (2023)
Void interconnectedness and acoustic absorption coefficient	x-ray tomography	Li *et al.* (2022)
Void characterization	x-ray tomography	Mahmud *et al.* (2017)
Effect of voids on permeability, clogging, acoustic absorption coefficient, Cantabro loss, shear strength, wheel tracking	x-ray tomography (2D images only)	Jiang *et al.* (2015)
Air void distribution	2D photography	Xu *et al.* (2019)
Air void clogging	x-ray tomography (asphalt and 3D printed models)	Garcia *et al.* (2019)
Air void shape	x-ray tomography	Norhidayah *et al.* (2014)

Li *et al.* (2022) used x-ray tomography to generate a 3D model of epoxy modified porous asphalt mixes. The total percentage voids, surface area of voids (from the individual 2D scans), connected void fraction, equivalent diameter (i.e. diameter if the void area was circular) and curvature (related to the length of connected voids) were determined. A good correlation was determined between the percentage of interconnected voids and acoustic emission values as shown in Figure 5.1.

Jiang *et al.* (2015) used 2D images from x-ray tomography i.e. without stacking to create a 3D model to study the effect. The authors found that for four different porous asphalt mixes the average void equivalent diameter correlated with the peak acoustic absorption coefficient measured in an impedance tube (Figure 5.2).

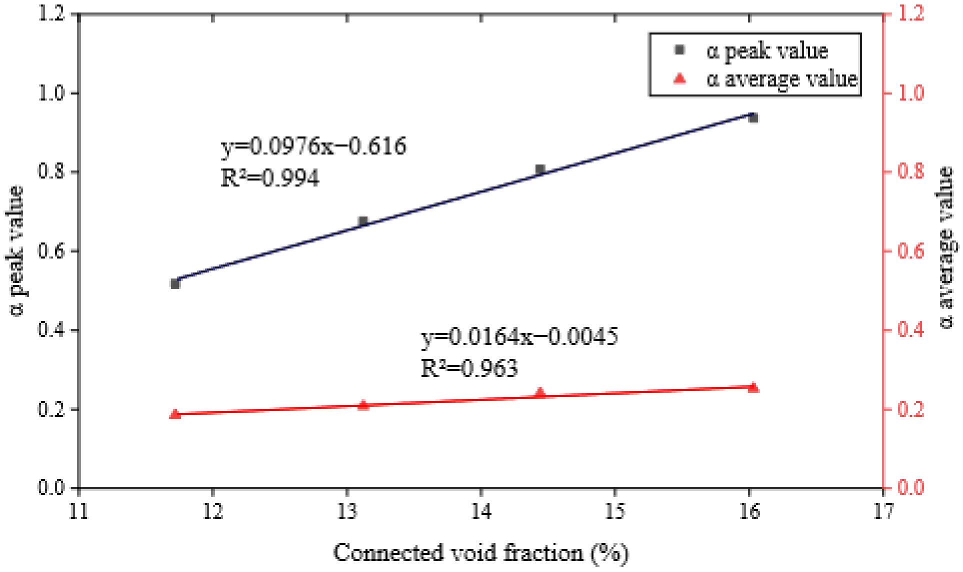


Figure 5.1 Relationship between acoustic absorption coefficient (α) and connected void percentage (Li *et al.*, 2022).

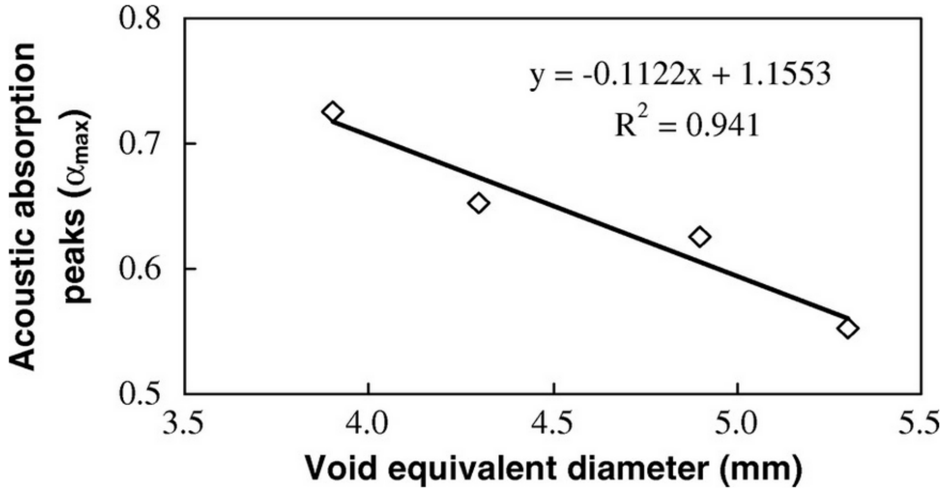


Figure 5.2 Relationship between the maximum acoustic absorption coefficient (α_{max}) and air void equivalent diameter, measured from the specimen cross section (Jiang *et al.*, 2015).

6 2D versus 3D analysis

A 3D analysis of voids or aggregates in porous asphalts obviously provides volumetric information unavailable by 2D analysis but is practically much more difficult and expensive to undertake given the absence of suitable instrumentation in New Zealand. For a comparative study of void shape and orientation between mixes made using standard and epoxy binders, 2D measurements would be adequate as demonstrated in the literature (Table 5.1). A 2D analysis can provide data on void shape including:

- Area
- Major axis length
- Minor axis length

- Perimeter
- Feret diameter (see Figure 6.1)
- Orientation of the void's major or minor axis in the plane of the cross section (see Figure 6.2).

As well as derived parameters such as aspect ratio, equivalent diameter and circularity if required:

$$Aspect\ ratio\ = \frac{Length\ of\ major\ axis}{Length\ of\ minor\ axis}$$

$$Circularity\ = \frac{Area}{(perimeter)^2}$$

$$Equivalent\ diameter\ = 2\ \times \left(\frac{Area}{\pi}\right)^{0.5}$$

Orientation of the air void cross sections can be characterised using the vector magnitude Δ and the average inclination angle (α_{mean}) (Curray, 1956):

$$\Delta = \frac{100}{N}\sqrt{\left(\sum \sin 2\alpha_k\right)^2 + \left(\sum \cos 2\alpha_k\right)^2}$$

$$\alpha_{mean} = \frac{\sum|\alpha_k|}{N}$$

Where N is the total number of voids and α_k is the orientation angle of the kth void relative to the horizontal (see Figure 6.2). The value of Δ varies between 0 for completely random orientation to 100 if all the voids are aligned in the same direction.

Analysis of cross sections perpendicular to the surface would also provide information on the distribution of voids through the compacted mix. Information on void connectivity and the length of connected voids is not available in a 2D analysis but this is not essential if the purpose of the exercise is primarily to determine differences in void shape, orientation or distribution.

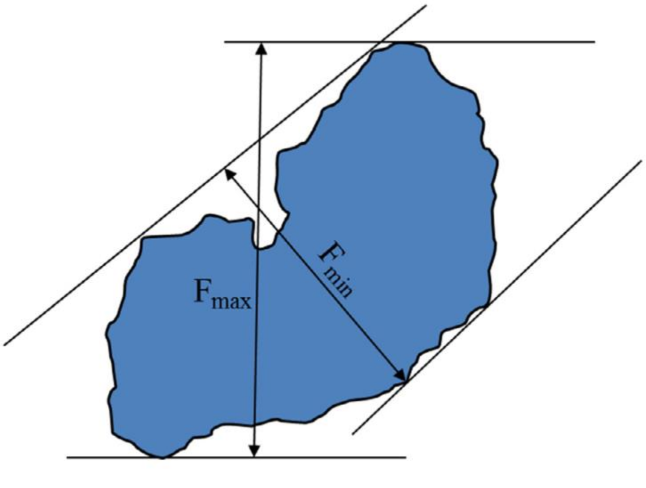


Figure 6.1 Feret diameter definitions. The Feret diameter in 2D is defined as the perpendicular distance between two parallel lines at a specified angle and bordering the object. Diagram from Jiang *et al.* (2015).

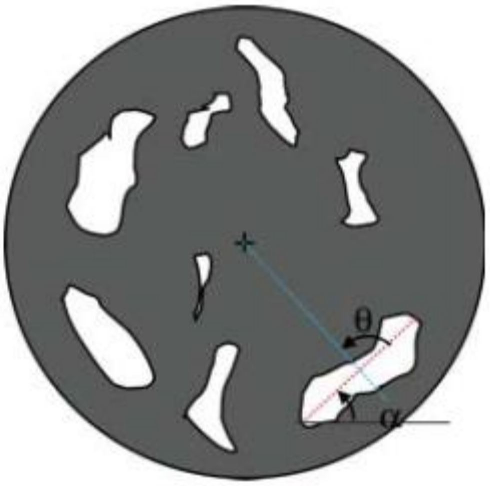


Figure 6.2 Air void orientation, relative to the horizontal (α) and relative to the radial axis (θ). From Coenen *et al.* (2012).

7 Conclusions

- A 3D analysis of porous asphalt specimens using x-ray tomography would require sending samples to Australia and would be expensive relative to generating 2D physical cross section images. The latter could be readily undertaken in New Zealand and requires no specialist equipment other than an asphalt saw. If necessary a suitable scanner could be purchased for under $1000. Image processing could be undertaken using commonly available software including Matlab or open source Image-J.
- Research in the literature shows that the analysis of 2D photographic images of physical cross sections should provide sufficient information to allow useful comparisons to be made of void shape, orientation and distribution between mixes. The 2D analysis would determine if use of epoxy modified bitumen results in void characteristics that differ significantly from those in mixes using the same aggregate but using standard bitumen (other factors also being equal). An initial 2D analysis may suggest that a more comprehensive 3D analysis is warranted.

8 Outline methodology for 2D image analysis

The following is a suggested methodology for a 2D analysis of air voids in epoxy and standard porous asphalt mixes.

1. Specimen preparation:

a. An initial analysis would be carried out using laboratory prepared 100 mm diameter by 90 mm high cylindrical specimens (gyratory compacted) of epoxy modified and standard PA7 OGPA using the same aggregate and grading. When the methodology is fully developed and proven then the work could be extended to cores taken from relevant road sections.

b. Specimens would be wrapped to prevent slumping and heated at 40 °C and then 80 °C for a few weeks to harden the epoxy binder, facilitate cutting and prevent distortion during handling.

c. Specimens would be measured to determine total air voids according to ASTM D3203. It would be useful to know the proportion of (internal) interconnected voids in each mix type. This is likely to be the majority of voids in OGPA. Connected voids could be estimated by evacuating the specimens submerged in water in a vacuum chamber to saturate the connected voids and measuring the weight under water. Knowing the density (and hence volume) of aggregate and bitumen the submerged weight can be corrected for buoyancy and the connected void volume calculated. The difference between the connected void volume and total void volume gives the unconnected void volume. This assumes water absorption by the aggregate is negligible.

2. Cross section preparation:

a. The specimens would be dried, cooled at -18 °C in a freezer and cut vertically or horizontally with a diamond saw to obtain cross sections. Either two vertical or two horizontal cuts 10-15 mm apart would be made to give two *independent* cross sections. If the cuts are too close the void data obtained from each cross section may not be independent especially as the individual voids may be quite large.

b. A variation to this procedure could be investigated. This would involve cutting off the top 30-40 mm of the specimen and saturating the connected voids under vacuum with a coloured or fluorescent, low viscosity epoxy resin. The resulting block of cured resin with the OGPA specimen encased, would be cut to give a horizontal or vertical cross section. A related approach was taken by Middendorf *et al.* (2023) to give a much higher contrast photograph of porous asphalt specimens and removes the problem of noise generated by light reflecting from the back of void spaces during scanning.

c. The prepared cross sections would be scanned on a flatbed scanner. A 1200 dpi scanner would result in an image resolution of 21 μm per pixel.

d. For vertical cross sections the images would be cropped to exclude about 10 mm from the vertical sides and 30 mm from the surface, to avoid artefacts due to the mix being compacted against the steel sides of the mould and simulate the depth of typical OGPA surfacings. The top surface would be assumed to be representative of a real mix rolled by a steel roller. This would give a total vertical section image area of about 7200 mm^2 (80 mm x 90 mm). Horizontal cross sections would also be cropped 100 mm from the edge giving an area of about 25,447 mm^2.

3. Number of specimens:

a. Most researchers base their studies on samples sizes in the hundreds- aggregate particles or voids. The intention in the present work would be to compare both the mean values of various parameters and also their distribution so a large sample size of voids is desirable. Jiang *et al.* (2015) studied voids in 20% air void porous asphalt mixes. For each mix variant studied they scanned 25 cross sections of 100 mm diameter, to give a total of about 2000 individual voids- i.e. about 85 voids per cross section or 0.0027 voids/mm^2 of image area.

b. In the proposed work this would translate to about 40 voids per specimen for vertical sections and 140 voids per specimen for horizontal sections (assuming the data from each of the two sections can be combined in each case).

c. Hence for horizontal sections 10 specimens for each mix (20 in total) would give about 1400 voids for analysis. This would require about 50 kg of mix. For vertical sections 30 specimens (60 in total) would be needed to give 1200 voids needing about 72 kg of mix.

For both horizontal or vertical sections a total of about 80 specimens would be needed, resulting in 160 cut cross sections for scanning and analysis.

4. Image processing:

a. Image processing would consist of removal of noise, water-shedding (i.e. determining aggregate and air void boundaries) and thresholding to give an image with two greyscale levels (aggregate and air voids). There is no recognised standard method for this process and exact procedures will depend on the quality of the raw images and the software available. Open source software such as Image -J or JMicroVision should be sufficient.

b. As discussed above, some researchers adjust processing parameters so that the average area of air voids measured in the cross sections is a constant proportion of the physically measured void volume. In the present case the aggregates and air voids in both standard and epoxy modified OGPA specimens will be essentially the same and small apparent differences in the measured void volumes will be strongly influenced by the precision of the test method. Hence simply using a standard set of processing parameters is a reasonable approach.

5. Image analysis:

a. Various parameters and their distributions through the depth of the specimens would be determined (see section 6). Differences would be determined by statistical comparison of mean parameters and parameter distributions.

6. Staging of the project and cost estimate:

a. A first stage of the project would involve manufacture of 2-3 specimens of each type. (standard and epoxy bitumen). These would be used to verify that the proposed procedures do not present unforeseen difficulties and to determine whether the flooding of the voids with coloured epoxy resin (see 2 above) is necessary or beneficial. Stage two would complete the testing and analysis.

b. The cost of the project as outlined above and with the full 80 specimens would be in the order of $85,000 + gst if conducted by WSP Research Petone. Obviously this could reduced substantially if fewer specimens were used or only vertical or horizontal sections cut and examined. The latter option would be more preferable.

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