Application of X-ray Computed Tomography for Air Voids and Damage Characterisation in Asphalt Mixtures

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BACKGROUND

Asphalt mixtures are complex heterogeneous materials composed of air voids, mastic and aggregates. It has been well recognised in principle that the combination of these three components plays a significant role in the resistance of asphalt pavements to major pavement distress. These individual components have different physical and mechanical properties. Their proportions, distribution, and interactions within the internal structure of the asphalt mixture affect the resulting mechanical performance, and indicate their complex relationship.

Previous work have demonstrated that different compaction methods have a significant effect on the aggregates and air void distribution even though the specimens are designed with identical volumetric properties. This arises from the fact that two replicates of a test specimen sometimes show a variation in their performance which leaves researchers to produce at least three replicates for verification. Therefore, characterisation of the asphalt mixture's properties at the microstructure level is important when studying the behaviour of the asphalt mixture.

In fact, without a clear understanding of the internal structural properties, the evaluation of the mechanical performance will be very limited. However, due to the difficulty associated with quantitative measurements, particularly in viewing the internal structure, most investigations are restricted to mechanical testing which relates to the macroscopic behaviour, particularly the stress and the strain.

Recently, the technology of X-ray computed tomography (CT) has attracted the interest of researchers in the study of the material microstructure properties. X-ray CT is an advanced imaging technique, which generates an image from the density distribution of a specimen's cross-section. It is used to visualise features in the interior of a solid object to obtain digital information from the captured images.

The first commercial X-ray CT scanner was invented by Sir Godfrey Hounsfield in Hayes in 1973 at EMI Central Research Laboratories [1]. This technique which was first designed for medical diagnosis has led to its development as a powerful non-destructive tool for characterising many engineering materials such as concrete, rock, metals and asphalt mixture. It is a promising technique for viewing the internal structure because of its accuracy and non-destructive nature, whereby the mixture would still be intact for further mechanical testing.

The examined objects or materials could range in sizes and types, where no prior preparation of the specimen surface would be necessary. Therefore, X-ray CT combined with instrument testing and image analysis techniques would provide us with the capability to improve the characterisation of microstructure properties and monitor the damage evolution. Figure 1 shows the X-ray CT machine which is used for scanning. This technique provides the means to advance the field of asphalt mixture characterisation for enhancing Malaysia's engineering research and interest through the introduction of the latest technology in pavement engineering. However, it should be highlighted that this technology is practical for any engineering material.

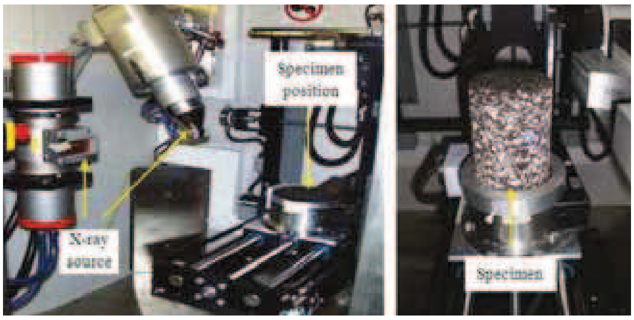


Figure 1: X-ray CT machine

X-RAY COMPUTED TOMOGRAPHY IMAGING

This scanning technique makes use of the ability of short wavelength electromagnetic radiation to penetrate an object. Figure 2 shows the illustration of X-ray CT components that consist of the X-ray source, the detector and the object which is placed at the middle. The principle behind this is that when X-rays pass through an object, they are attenuated by absorption and scattered depending on

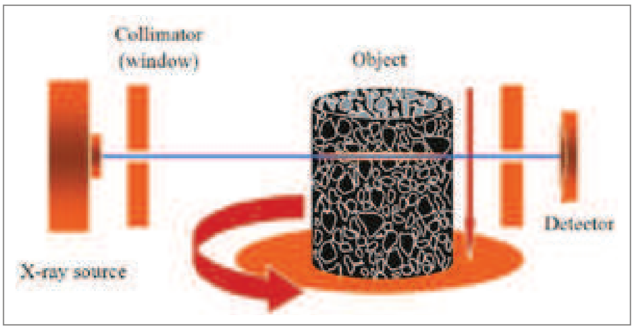


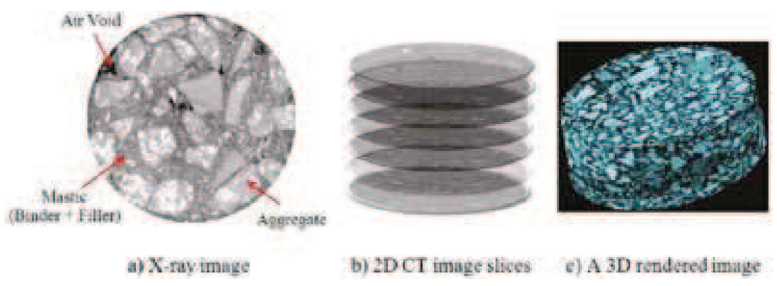
Figure 2: Components of X-ray CT system [2]

the properties of materials. The amount of absorption is a function of density and thickness of the object. The CT image is highly sensitive to small density differences in the materials.

The intensity of the X-ray is measured before and after it passes through an object. The portion of radiation that penetrates an object forms a grey scale projective image that will indicate the presence of an internal defect and material distribution. Scanning of a slice is complete after collecting the intensity measurements for a full rotation of an object cross-section. Then, the object is shifted vertically by a fixed interval between slices and the entire procedure is repeated to generate additional slices.

The captured images are interpreted to provide information concerning the internal features. The higher the difference in densities, the better each of the individual components may be identified and distinguished from each other. The grey colours in the image show the different density of the objects in a two-dimensional (2D) image. An 8-bit image consists of 256 (28) grey levels starting from 0 (black) to 255 (white) that correspond to different densities within the specimen.

In a typical 2D slice from an asphalt mixture specimen, aggregates are the brightest with the highest density, followed by mastic (bitumen and fine particles) and the darkest are the air voids with the lowest density (Figure 3). The 2D image slices can be rendered to produce a three-dimensional (3D) volume image. Using imaging software packages, the 3D image can be virtually cut in vertical and horizontal directions at any angle. This volumetric image enables more studies to be conducted on various aspects of the asphalt mixture.



a) X-ray image b) 2D CT image slices c) A 3D rendered image

Figure 3: Reconstruction of 2D CT slices to generate a 3D CT image [3]

MICROSTRUCTURE CHARACTERISATION

A number of successful studies have used X-ray CT combined with image analysis techniques to analyse the microstructure properties of asphalt mixtures. The properties include the distribution of air voids particularly the content, number, size and shape, while the damage can be characterised in terms of the changes in air void properties and crack growth. Using the 'thresholding' technique, the air voids and cracks can be clearly distinguished and segmented prior to analysis as shown in Figure 4.

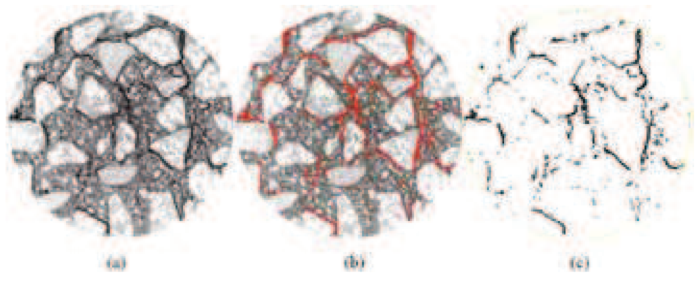


Figure 4: (a) the X-ray image, (b) thresholding and (c) air voids and cracks

AIR VOIDS

Air voids play an important role in determining the resistance of asphalt mixtures to major pavement damage including rutting and fatigue cracking [4]. Though air voids possess no mechanical strength, their distribution is important in determining the overall mechanical response of the material. Air voids which are either too great or too low can cause a significant reduction in pavement performance. Two specimens with the same air voids content may have different distributions. Therefore, it would be of considerable interest to capture and analyse the microstructure properties of air voids such as their size, number and locations.

Previous studies have successfully utilised X-ray CT to quantify the air void distribution at different depths in the asphalt mixture specimen [2, 5]. Imaging software is used to analyse the air voids on each image as a percentage of the air voids area to the total area of the 2D image. This technique applies the concept of 'stereology' which extracts quantitative information about 3D material (volume) from a measurement made on 2D sections of the material (area).

For validation, the average percentage of air voids measured from the laboratory should compare favourably with the average percentage of air voids measured from X-ray images. In previous work, it was found that air void distribution in gyratory specimens exhibit a "bath-tub" shape where more air voids are present at the top and bottom parts of a specimen. This shape is more pronounced at higher compaction efforts as shown in Figure 5.

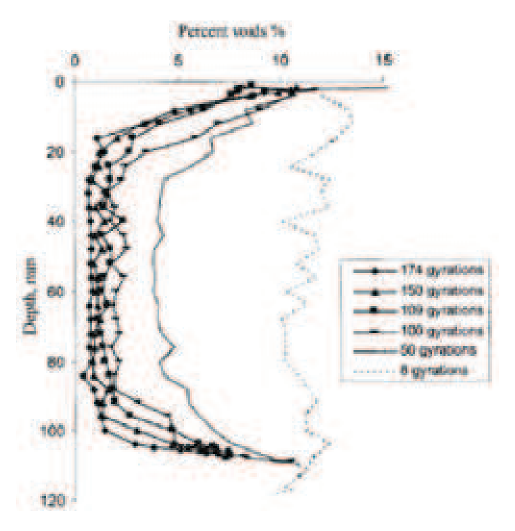


Figure 5: Distribution of air voids in gyratory specimen [2]

DAMAGE

The damage in asphalt mixtures can be defined as the result of micro-cracks that initiate at the interface between the aggregates and binder (adhesive failure) and within the binder (cohesive failure) [6]. The damage distribution has been shown to be non-uniform and it is not sufficient to visually quantify the damage and relate it to the overall deformation. When an asphalt mixture is subjected to repeated loading, micro-structural damage tends to occur in the form of micro-cracks. These micro-cracks and existing air voids will propagate and grow under loading to become macro-cracks that significantly decrease the mixture's strength.

Therefore, detailed analysis of damage distribution within the asphalt mixture needs to be carried out to better define its failure criteria. A few researchers have used X-ray CT imaging technique to capture images of cross sections in different orientations to quantify the damage distribution. These images were used to yield damage parameters that quantify the properties of cracks and air voids in a specimen.

Subsequently, many damage parameters for measuring cracks and air voids properties were introduced, including their distribution and changes in content, size, shape and average spacing amongst the voids. These parameters are able to reflect the accumulation of damage under different loading conditions. Since it is non-destructive, X-ray CT can be performed on the specimen before and after undergoing the mechanical testing. The same specimen can be continuously tested for increased loading to monitor the damage evolution at different loading stages until it reaches ultimate failure. A study was conducted where asphalt mixture specimens were X-rayed before and after being deformed to prescribed strain levels in a triaxial compression set up [7].

Three distinct regions were identified in the tested specimen, namely the top, middle and bottom regions. Then, the increments in the air void content and crack growth were compared between these regions (Figure 6). Instead of air void content, statistical analyses of air void size and its spatial distribution were found to give valuable information leading to a better understanding of the damage mechanisms in asphalt mixtures [8].

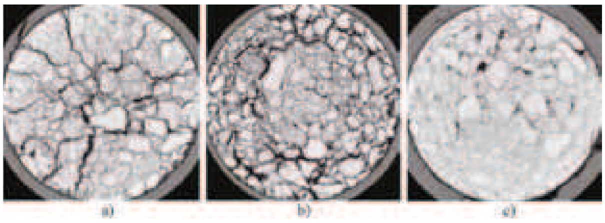


Figure 6: Slices of X-ray images after damaging

The larger the average size with smaller average spacing between air voids, the larger the interaction among the damaged surfaces; therefore, the lower the resistance to fatigue and rutting. Another study addressed the same point in developing a comprehensive methodology to characterise fatigue cracking in asphalt mixtures [9].

CONCLUSION

The application of X-ray CT in characterising asphalt mixtures can considerably provide valuable information and contribute towards a deeper understanding of the pavement from a microstructure perspective. This enables the optimisation of the various parameters that describe the internal structure and relate them to pavement performance in a scientific way, particularly the mechanical behaviour. Moreover, this technology can serve as a powerful forensic tool in the hands of pavement engineers that will provide a foundation for building more durable and long-lasting pavement structures. ■

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