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Characterisation of micro-structural damage in asphalt mixtures using image analysis

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HIGHLIGHTS

- X-ray CT Scanning and Digital Image Processing.
- Validating the 2D analysis and image Slices Verification for Damage Comparison.
- Extracting the damage area from X-ray CT images.
- Microstructural Changes in Air Voids Properties and Analysis of the Damage for Specimen Subjected to Compression.
- Quantification of crack formation and crack propagation and analysis of the Damage for Specimen Subjected to Fatigue.

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ABSTRACT

This paper is an attempt to provide information on the application of an image analysis technique to characterise the internal structural damage of asphalt mixtures captured on X-ray images. In this paper, two modes of failures under uniaxial monotonic compression and indirect tensile fatigue were employed for illustrating the procedures undertaken. Air voids and crack properties as a result of the applied stresses and strains were analysed using two-dimensional image analysis and introduced as damage indicators for characterising the micro-structural damage of asphalt mixtures. A set of procedures for extracting and verifying the damage area were also established by comparing the X-ray images before and after the loading application. The proposed damage parameters were showed to be useful for interpreting the damage behaviour particularly the changes in air void properties and the characteristics of crack formation and crack propagation. In addition, it was also found that the damage parameters adopted are subjected to failure type.

1. Introduction

Researchers have been able to utilise X-ray CT images to monitor the evolution of internal failure in engineering materials such as soils, mortar and metal and relate this damage to measured strain. Internal failure is measured in terms of internal displacement associated with the permanent deformation of the materials and the formation of cracks within the materials [1–3]. The utilisation of this advanced imaging technology along with image analysis techniques has also led to the investigation of asphalt mixture damage particularly at the micro level. This technique requires no specimen preparation prior to scanning and therefore the specimen is still intact for further mechanical testing after scanning which can be effectively used for damage investigation [4–6]. For asphalt mixtures, X-ray technology has been extensively used to characterise air void distribution and microstructural damage evolution within asphalt mixture specimens. Air void plays a major role in asphalt mixture performance with their distribution being very significant in determining the overall mechanical response of the mixture [7–9]. Under the loading action, the existing air voids might coalesce resulted in micro-cracks that initiate at the interface between the aggregates and the mastic. The micro-cracks propagate and grow under the deformation to become macro-cracks and lead to an increase in the air void content [10]. Therefore, it would be of considerable interest to analyse the damage behaviour in asphalt mixtures by characterising the properties of the cracks once the specimens undergo deformation.

Works done by previous researchers in characterising asphalt mixture damage using image analysis were prepared with details on the air voids distribution and air voids properties but not much emphasis on the crack properties. Wang et al. [4,5,11] proposed

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damage parameters, namely specific damaged surface area (area per unit volume), average spacing between the damaged surfaces and the average size of defect (average segment length in different orientation). These parameters can be used to describe the damage and the strength of the interaction between two damaged surfaces. Tashman et al. [6] measured the changes in the voids properties throughout compacted asphalt specimens to characterise the damage evolution before and after the deformation caused by triaxial compression. They were able to relate changes in the voids properties to the materials behaviour at different strain levels and confining pressures. Song [12] quantified microstructure damage in terms of the amount of voids and characteristics of voids such as voids area, average voids perimeter as well as the average radius of the voids and cracks and relates them to changes in stiffness. Khan [13] used voids parameters including voids fraction (area), number of voids and average voids size to characterise the damage in asphalt mixtures by conducting Monotonic Compression and Tension Compression Fatigue Tests which corresponded to the increase in strain to failure. The author correlated the area of the defects (voids fraction) measured from the X-ray images to the strain and stiffness values obtained from the mechanical testing.

This paper is aimed at providing information through examples on the establishment of image analysis procedures and parameters for quantifying the air void and crack properties for damage characterisation including the verification method. In addition, the examples provided is not only to quantify the changes in the air void properties after the damage but also to identify the damage concentration area and the established crack parameters are used to describe the severity of the damage. The authors' motivation in writing this paper arises from our observation that, this subject of image analysis is widely used in various engineering material characterisation including asphalt mixture, but details of the procedures involved is inadequately highlighted in the technical literature and often for complex problem. Even though most of the current studies involved with three-dimensional analysis and it seems crucial in getting a valid analysis to represent the actual sample, but the understanding of the basic two-dimensional measurements in damage analysis is also significant as it could provide an example of parameter for a specific problem. This is important for beginners (who started to get involved in image analysis) to better understand the application of image analysis for microstructural damage characterisation. Using the same concept, further analysis on the damage could be extended for a complex problem in either three-dimensional or four-dimensional analysis [14,15]. Hopefully the images selected and the accompanying discussion will help to promote a clearer picture of the image analysis procedures for micro-structural damage investigation.

2. Material and methods

2.1. Specimen preparation and testing

In this study, a gap graded mixture of Hot Rolled Asphalt (HRA 60/20) was selected in accordance to BS 954-1:2005 [16]. The HRA 60/20 contains 60 percent coarse aggregate with a maximum aggregate size of 20 mm. The specimen was compacted using gyratory compactor with a vertical pressure (0.6 MPa), angle of gyration (1.25°) and gyration speed (30 rpm). Details of the mix design, specimen dimension and test condition are shown in Fig. 1 and Table 1. For damage evaluation, a total of 16 specimens were damaged under the Uniaxial Monotonic Compression (UMC) and Indirect Tensile Fatigue (ITF) Tests with four replicates for each condition as specified in the table. For the Uniaxial Monotonic Compression test, the specimens were conditioned at the target test temperature and the test was performed at a constant strain rate of 0.1 mm/s. This strain rate was adopted in such a way that the load was sustained for 100–200 s. This test length was chosen to ensure that the tested specimens reached the failure stage within a reasonable testing time, thereby reducing the effect of aging on the other queued specimens (under conditioning) waiting to be tested. For the Indirect Tensile Fatigue Test, the repeated load acts along the vertical diameter and produces various magnitudes of vertical compressive stress and horizontal tensile stress along the diameter of the specimen. The application of non-destructive imaging technique, X-ray CT has reduced the number of specimen for this investigation. The specimens were X-rayed before and after the mechanical tests.

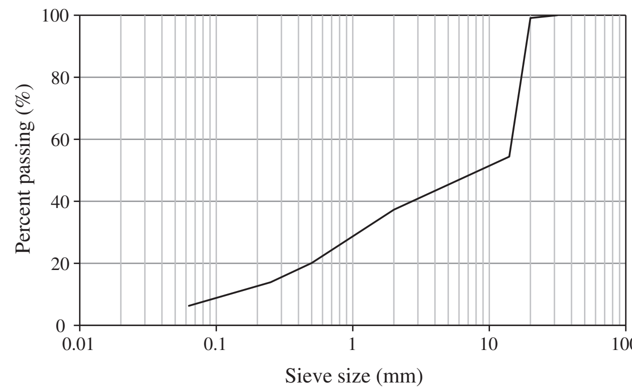

Fig. 1. Aggregate gradation curves of HRA 60/20.

2.2. X-ray CT Scanning and Digital Image Processing

In this study, the X-ray CT was used to capture digital images of the internal structure of asphalt mixtures. There are three main components of the X-ray CT machine including the X-ray source, specimen position and the detector of the X-rays intensity after penetrating the specimen. The measured intensities are then converted to a map of internal structure distribution in grey scale which depends on the density and size of the object. For 8-bit image, the grey scale consists of 256 levels. Brighter regions (close to white) correspond to the higher density materials while darker regions (close to black) correspond to the lower density materials. The captured images were then processed for quality enhancement before quantitatively analysed for measuring and interpreting the properties using an image analysis technique. Fig. 2 shows the different stages undertaken in the image processing technique for extracting the image of air voids within the asphalt mixture specimen. Basically, the digital image processing involves a set of procedures that apply various algorithms to enhance the image quality, threshold and extract the object of interest within the captured digital images. In this study, these procedures were undertaken using ImageJ, the public domain Java Image processing program, inspired by National Institute of Health (NIH) Image. Details of the proposed digital image processing can be found in Abdul Hassan Airey [17].

3. Proposed Microstructural Damage Analysis

The following procedure has been established for characterising the microstructural damage. It consists of details for verifying the image slices (by X-ray) before and after deformation for damage comparison made on 2D images and the proposed methods for extracting the damaged area (i.e. identifying increases in voids and cracks after deformation). For damage analysis, two main categories of damage parameters are specified based on different damage mechanisms, namely microstructural changes in void properties and the quantification of crack formation and crack propagation.

3.1. Validating the 2D analysis

To better interpret the measurements made on the X-ray images from 2D analysis, it is necessary to ascertain the image slice interval required to obtain an unbiased characterisation of the specimens' microstructural properties. The chosen interval was considered practical with respect to obtaining optimal results and the time necessary to scan, as more images will need more time to complete the CT scanning. An asphalt specimen was X-rayed and analysed for air voids distribution at different slice intervals (between 0.1 mm and 8 mm) as shown in Fig. 3a. It can be seen that the curves of the air voids distribution analysed at 0.1–2 mm are very close with minimal different in the air voids content along the height of the specimen. They also seem to convey