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A novel method for evaluating hot mix asphalt fatigue damage: X-ray computed tomography

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HIGHLIGHTS

- An innovative image-based method was employed for the quantification of air voids and fatigue damage.
- Asphalt beams were scanned using X-ray CT prior to and following the four-point bending test.
- Both 2D and 3D image analysis proved suitable for evaluating HMA fatigue damage.
- The developed method was applied to evaluate and rank the asphalt beams fatigue performance.

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ABSTRACT

This paper presents a framework for employing X-ray computed tomography (CT) for the assessment of hot mix asphalt (HMA) fatigue damage. The analyses were carried out on asphalt beams in order to quantify the damage created by four-point bending load. A new algorithm has been developed for calculating the thresholding levels of the images acquired before and after testing. The thresholding level prior to testing was estimated using laboratory air voids. To determine the post-testing thresholding level, the proposed algorithm matches 16-bit image histograms obtained before and after the test. This process is implemented only for the portion of the histogram that represents the aggregate colour intensities that remain unchanged during the testing.

The results and analysis reveal that the developed technique is a valid method for successfully quantifying and evaluating HMA fatigue damage in large specimens. Because of the high degree of precision they provide, 16-bit images are recommended for this type of analysis. It was found that the distributions of air voids and damage are not uniform in asphalt beams and that they vary significantly throughout the length of a single beam as well as from beam to beam. This study also confirms the effectiveness of X-ray CT for quantifying HMA fatigue damage in asphalt beams following crack propagation.

1. Introduction

Recent studies have demonstrated the applicability of X-ray computed tomography (CT) for characterizing the internal structure of hot mix asphalt (HMA). This technique has been employed for describing aggregate and air void distribution in compacted mixtures. However, it has rarely been applied for the quantification of HMA damage because of challenges related to material complexity, lack of a standard processing method, and computational cost. The work presented in this paper involved the development of a framework for employing X-ray CT in order to visualize and quantify HMA fatigue damage.

Although significant effort has been devoted to the evaluation of HMA fatigue resistance, no single method has been widely approved for varied mixtures and testing conditions. Previous research has resulted in the development of a number of testing devices and protocols for evaluating and comparing the fatigue resistance of asphalt mixtures, with the standards typically suggesting the use of flexural tests [1]. Common analysis approaches for investigating fatigue include traditional, fracture, continuum damage, and energy and dissipated energy [2,3]. In the traditional approach, a 50% reduction in initial stiffness is considered to be a failure criterion, which can be achieved without clear damage status [4]. In other approaches, the damage can be computed or predicted based on prior assumptions about HMA microstructure. One valuable avenue is to apply X-ray CT as a non-destructive tool that can directly interpret and quantify HMA fatigue damage. To the

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authors' knowledge, the current study represents the first attempt to use X-ray CT for the assessment of fatigue damage in asphalt beams subjected to the four-point bending load. This research offers a unique approach to the high-resolution scanning of large asphalt specimens.

2. Background

Digital images can be expressed as a two-dimensional function f (x,y) that signifies the intensities at points (x, y), where x and y refer to spatial coordinates that can be presented in a form of matrices. An image is composed of small elements called pixels that have specific locations and intensity values [5]. In 8-bit greyscale images, the pixel intensity varies from 0 to 255 for black and white, respectively. Histograms are statistical forms employed for representing the distribution of the colour intensities of image pixels. They provide a simple and effective method of revealing regions and colour variations in an image.

Image-based analysis can be implemented in three steps: acquisition, processing, and analysis [6]. Images can be acquired in either two or three dimensions (2D or 3D). For 2D image acquisition, digital cameras, microscopes, and scanners have been used for capturing asphalt images. In the image processing step, a set of operations or algorithms (e.g., filtration and thresholding) are applied in order to separate out each individual component, such as aggregate and voids. The processed image is then analyzed in order to quantify the properties of each component, such as shape or geometry. X-ray CT, a non-destructive technique that can be used for 3D image acquisition, has recently been applied more extensively for use with civil engineering materials [7]. Once 2D images have been acquired and processed, a stack of image slices is then combined through a process called reconstruction in order to build a 3D model of the object [7,8]. In this case, the images are represented as small cubes called voxels.

2.1. Applicability of X-ray CT for HMA characterization

Encouraging outcomes have been obtained using X-ray CT for computational simulation and for describing the interior structure of asphalt concrete mixtures [9]. Image-based modeling has been employed for simulating HMA performance, with realistic model geometry being obtained from 2D and 3D images [8,10–13]. This technique also enables an investigation of the effects of HMA microstructure, such as air voids and aggregates, because the mechanical behavior of each individual component can be defined separately. These models can thus be considered more realistic than ones obtained using conventional methods, which are based on the assumption that asphalt is a single homogenous body.

With respect to the internal structure of HMA, X-ray CT has been used to quantify the distribution of air voids and to characterize the aggregate skeleton in the compacted mixture [6,7,14–16]. Air void distribution is influenced by the gradation of the aggregate, the type of compactor, and the level of compaction [17–20]. The aggregate skeleton is characterized by the organization of the particles in the mixture, such as the contact points, orientation, segregation, packing, and gradation. In some research, the gradation of the HMA has been calculated based on 2D and 3D images [16,21,22]. Yue and Morin [23] were able to quantify aggregate orientation in both laboratory and field-compacted samples. Kutay et al. [16] developed an advanced algorithm for processing 3D images in order to successfully compute the size, location, contact points, and orientation of the aggregate particles.

X-ray CT is an effective tool for analyzing changes in the internal structure of a material as a result of damage [24], where 2D and 3D images have been employed for such analyses [15,25–27]. Elseifi et al. [25] used X-ray CT in order to quantify the damage produced by dynamic modulus and flow tests. Their results revealed insignificant damage in the dynamic modulus specimens, but notable heterogeneous damage was detected in the flow test specimens, especially in the middle third of the specimen's height. Hassan et al. [26] attempted to characterize the specimen damage resulting from uniaxial compression and indirect tensile fatigue tests. Crack properties were analyzed for an area 40 mm wide that extended the entire thickness of the specimens. Hu et al. [15] studied the influence of high-temperature deformation on the morphology and distribution of air voids and aggregate particles. All of these prior studies were conducted either on small test specimens with low resolution or with a focus on the damage resulting from deformation tests. The technique has not previously been used for quantifying fatigue damage in large asphalt beam specimens at higher resolutions. Research is thus required in order to characterize changes in the 3D microstructure that result from asphalt fatigue tests, particularly with respect to the flexural mode, in order to provide an understanding of the mechanisms involved in this common pavement distress and its mitigation. These considerations provided the motivation for this study.

3. Study objectives

The goal of this study was to establish a framework for employing X-ray CT for the quantification of HMA fatigue damage. The framework was developed to enable the scanning and analysis of asphalt beams subjected four-point bending load and prepared for high-resolution imaging. For analysis purposes, an algorithm was created that uses the voxel intensities of the 16-bit aggregate images when the same beams are scanned twice so that the extent of the damage to the beam can be automatically quantified following the test.

4. Preparation of the materials and specimens

For this study, four asphalt beams prepared from four dense-graded HMA mixes were investigated. The design, specimen preparation, and testing of these mixes were conducted at the Centre for Pavement and Transportation Technology (CPATT) laboratory at the University of Waterloo in Canada. The aggregate type was 12.5 mm nominal maximum aggregate size (NMAS). Two asphalt binders of the same performance grade (PG 64-28) were used: unmodified and modified by incorporating styrene-butadiene-styrene (SBS). Two levels of binder content were used: optimum and optimum plus 0.5%. The mixes were designed according to the Superpave^{MT} method at the optimum binder content. Details about the mix design are listed in Table 1. The asphalt beams were compacted using an Asphalt Vibratory Compactor (AVC) under vibration force of 115 kPa. Each beam was then sawn to a length, width, and height of 380 mm, 63 mm, and 50 mm, respectively. The air void target for the prepared samples was 7% ± 1%. Details about the test beams are provided in Table 2.

5. Four-point bending test

A four-point flexural beam test was performed using a universal testing machine (UTM). The test was carried out in accordance with the procedure given in AASHTO-T321-07. The test beams were subjected to repeated flexural loading at a frequency of 10 Hz and a strain level of 700 microstrains. A temperature of 20 ± 0.5 °C in a controlled chamber was maintained for 2 h before and during the test. These testing conditions were selected to allow the specimen to undergo to a sufficient number of load cycles to accumulate visual damage before failure.