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Characterization of Asphalt materials using X-ray high-resolution computed tomography imaging techniques

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Keywords
air-void distribution, damage evolution, internal structure, segregation analysis, asphalt pavements, compaction, computerized tomography, image analysis, strength of materials

Disciplines
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Comments
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Characterization of Asphalt Materials using X-ray High-Resolution Computed Tomography Imaging Techniques

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Abstract
X-ray Computerized Tomography (CT) has emerged as a powerful, nondestructive tool to study and quantify the three-dimensional internal structure of HMA. Studies, in conjunction with modeling and computational techniques, have focused on characterization of HMA internal air-void distribution, internal structure evolution during laboratory compaction, damage evolution in specimens during laboratory tests, segregation analysis, forensic investigation of pavements using cores, and the quantification of HMA microstructural properties. The Center for Nondestructive Evaluation (CNDE) at Iowa State University (ISU) has an in-house built high-resolution CT system with customized software for data acquisition, volumetric file reconstruction, and visualization. Preliminary studies were conducted at the CNDE to investigate the capabilities and resolution levels of the imaging systems in studying asphalt materials. Researchers at both ISU and Iowa Department of Transportation are currently using the advanced imaging facilities available at the CNDE and the latest developments in image analysis techniques to develop a deeper understanding of the HMA internal structure, develop and optimize the various parameters that describe the

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internal structure and relate them to the performance of pavements in a scientific way. This will provide the foundations to building more durable and long-lasting pavements.

Introduction

Hot-Mix Asphalt (HMA) is a strongly heterogeneous material consisting of asphalt cement, coarse and fine aggregates, and voids. These individual materials and components have different physical and mechanical properties and behavior that have a significant effect on the performance of HMA mixes (Yue and Morin 1996).

Realistic characterization of the failure of asphalt mixes (in terms of cracking, etc.) necessitates the consideration of HMA internal structure. The internal structure of asphalt mixes refers to the content and the spatial and directional distribution of air-voids, aggregates and asphalt as well as the chemical and physical interactions among these constituents (Masad and Button 2004). Internal structure is typically referred to as microstructure in materials science and as fabric in geomaterials. It has been well recognized that the internal structure of asphalt mixes plays a significant role in the mechanical properties of HMA and in the resistance of asphalt pavements to major distresses including rutting, fatigue, thermal cracking and low-temperature cracking (Yue et al 1995; Masad et al 1999b).

The past mechanistic models of asphalt mixes have concentrated mainly on the macroscopic behavior of HMA (e.g., indirect tensile strength, resilient modulus, etc.) and have been constructed on the general principles of continuum mechanics (Roque and Ruth 1990; Monismith 1992). However, Sashidhar et al (2000) have demonstrated, using photoelastic techniques, that HMA behaves more like a granular material in terms of load distribution characteristics. Load transmission in HMA takes place in the form of force chains and particle-to-particle contact exists in the formation of these chains (at relatively high temperatures, the binder is soft and has little restraint on the particles). It was also shown using Discrete Element Modeling (DEM) that different aggregate gradations have different aggregate structures and therefore produce different load distributions in the pavements (Shashidhar et al 2000).

There are many key evidences that support the significance of aggregate structure or internal structure in HMA. The better performance of Stone Matrix Asphalt (SMA) is attributed to better coarse aggregate skeleton in these mixes compared to the dense graded HMA (Brown et al 1998; Scherocman 1991). The Bailey method of gradation selection (Vavrik et al 2001) reportedly produces an aggregate blend that is packed together in a systematic manner, to form an aggregate skeleton with the required interlock and packing. This method has been successfully used by the Illinois Department of Transportation (IDOT) to design and control mixes for their projects (Vavrik et al 2002). The internal structure distribution has been long recognized in all design methodologies through requiring certain aggregate gradations, aggregate shape and mechanical properties, compaction methods and limits, and asphalt mix volumetrics (Masad and Button, 2004). Thus, quantifying the HMA internal structure directly and establishing its relationship to performance will be most beneficial.

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By thorough examination of the HMA internal structure, aggregate matrices that exhibit enhanced performance can be identified and steps can be taken to develop compaction techniques that can produce this structure. The variation in aggregate structure within a pavement layer can be better quantified, thus improving the accuracy of QC/QA methods. Also, by investigating the aggregate structure, the cause of premature failure of an asphalt pavement may be determined (Shashidhar 1999).

In recent years, there has been significant research on qualitative or/and quantitative assessment of HMA internal structure using two-dimensional (2-D) and three-dimensional (3-D) image analysis techniques (Masad et al 1999a; Masad et al 1999b; Tashman et al 2001; Saadeh et al 2002; Wang et al 2004a). These imaging methods quantify the distribution of aggregate skeleton, voids in the mineral aggregate, and air voids in HMA by analyzing images of the internal structure acquired three-dimensionally with an X-ray computed tomography system (Masad and Button, 2004).

X-ray computed tomography (X-ray CT or CT) is a viable nondestructive tool that has promising applications in characterization, modeling and computational simulation to optimize HMA mix design, predict performance and conduct investigative forensic studies (Wang et al 2004a). This paper discusses the various emerging imaging techniques related to HMA internal structure characterization based on the research studies reported in the literature with special emphasis on X-ray tomography. A preliminary study was conducted at the Center for Nondestructive Evaluation (CNDE) at Iowa State University using an in-house developed X-ray High Resolution Computed Tomography (HRCT) system (Zhang et al 2005) to investigate the imaging capabilities and resolution accuracies of the system in studying asphalt materials.

Imaging Technique

Any image analysis technique will involve three major steps: image acquisition, image processing, and image analysis. The image-capturing device can range from a simple digital scanner to a sophisticated X-ray Computed Tomography (X-ray CT) system. The quantitative information that can be extracted from the images will greatly depend on the quality of acquired images. Saadeh et al (2002) used hydrofluoric acid to discolor different types of rocks in asphalt mixes, which facilitated capturing quality photographic images that allow separating aggregates from the other phases on the basis of differences in color.

The CT imaging technique has a significant advantage of obtaining cross-sectional (2-D) images non-destructively that can be used in reconstructing the volumetric (3-D) image of the HMA specimen. Of the main imaging techniques available, CT has the advantage of imaging a 150-mm diameter core of HMA with sufficient resolution and clarity for quantitative analysis.

In image based characterization methods, the acquired images are digitized as 8-bit, 12-bit, or 16-bit images depending on the required resolution. In an 8-bit grayscale image, the grayscales are divided into $2^8 = 256$ levels, and each pixel (picture element) in the image has an intensity value ranging from 0 (black) to 255 (white). Since the accuracy of information

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extracted from an image depends greatly on the image quality (resolution, clarity, etc.), great care is taken in enhancing the image and filtering out the noise. Readymade image processing and analysis software packages like Image-Pro Plus® (by Media Cybernetics, Inc.) may be used for this purpose. Such software has several in-built features and it also facilitates writing macros to automate user-friendly image analysis procedures. Typically, during the image analysis phase, numerous operations are performed on the image such as assigning labels to objects of interest (e.g., aggregates > 1 mm), collecting their centroid positions, analyzing their shape and orientation, etc. The major steps involved in an image analysis technique are illustrated in Figure 1.

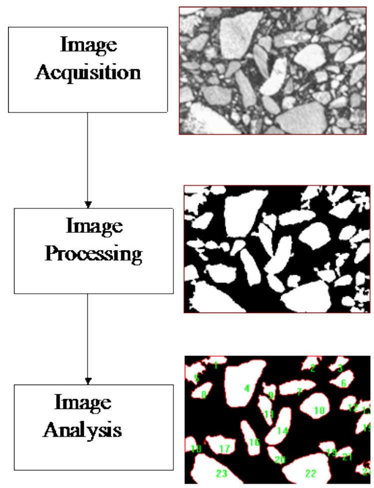

Figure 1. Major steps involved in image analysis techniques.

X-ray Computed Tomography

After the breakthrough of medical Computed Tomography (CT) in 1970, investigators worldwide began to look for possible applications of this new image-producing nondestructive testing method in other fields. Studies were performed to investigate the feasibility of using CT for denser materials, such as concrete, steel, iron, brass, uranium and others. Several investigators have illustrated the use of CT scans for the nondestructive evaluation of soils (Petrovic et al 1982; Aylmore and Hainsworth 1983; Alshibli et al 2000; Halverson et al 2005). CT imaging has gained increasing applications in civil engineering materials research in recent years (Braz et al 1999; Shashidhar 1999; Hall et al 2000; Wang et al 2001; Masad and Button 2004; Wang et al 2004b).

A CT system typically consists of an X-ray, a rotating turntable to hold the sample, and a detector. The X-ray beam is usually modulated into a fan or cone beam by using a collimator. The schematic is illustrated in Figure 2.

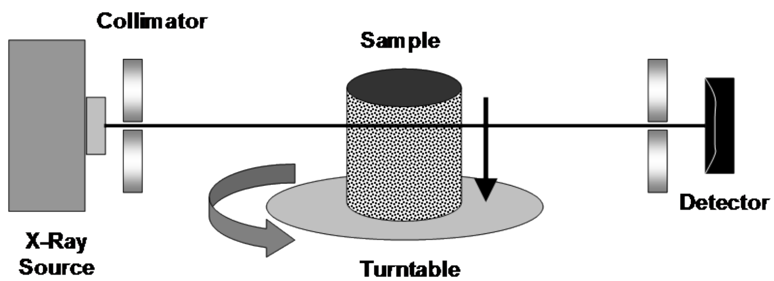

Figure 2. Schematic of X-ray computed tomography system.

Basically, an X-ray beam transmitted through a sample along several different paths in different directions is detected, manipulated electronically, and stored in a computer. The intensity of X-rays is measured before it enters the sample and after it passes through it. The transmitted ray beams have a modulated intensity dependent on the overall linear attenuation characteristics of the intervening material. This modulated or varying intensity with respect to distance is referred to as a profile. This profile information is then manipulated to produce a reconstructed image of a slice of the sample.

The resulting CT image is a spatial distribution of the linear attenuation coefficients, where brighter regions correspond to higher values of the coefficient. Therefore, if two aggregates with different linear attenuation coefficients are present in an HMA specimen, they show up as having different brightness. The linear attenuation coefficients vary as a function of the composition and density of the material. The CT is highly sensitive to small differences (<1%) between materials (Masad et al 2002). In a typical slice from a HMA specimen, the aggregate is the brightest, followed by mortar (mixture of asphalt and very fine particles), followed by air voids (Shashidhar 1999). The sample is then shifted vertically by a fixed amount (slice spacing) and the entire procedure is repeated to generate additional slices. These slices from a single sample can be put together and rendered to produce a volume image.

Figure 3 illustrates a 3-D rendered image from a series of 2-D slices of an HMA specimen scanned in a CT system (ACTIS 600/420 CT system, Bio-Imaging Research, Lincolnshire, Ill.) housed in FHWA's Turner-Fairbanks Highway Research Center at McLean, Virginia (Gopalakrishnan and Shashidhar 2000).

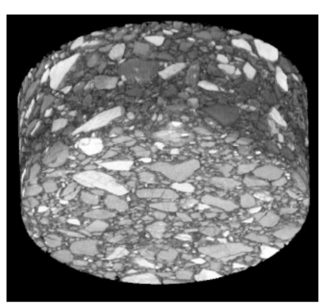

Figure 3. A 3-D rendered image from a series of X-ray CT sectional images.

There are four parameters that affect the quality of a tomographic image, i.e., spatial resolution, contrast resolution, noise, and artifacts. The spatial resolution of the image

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depends on the size of the sample and the system characteristics, namely detector pixel size and the x-ray source spot size. For example, using a 150-mm diameter HMA core and a detector with a 512 pixel profile, a pixel size of 150/512 = 0.29 mm/pixel can be obtained (Shashidhar et al 2001), which implies that features as small as 1 mm could be imaged. Finer resolution can be obtained with an X-ray high resolution tomography system using a 160-kV microfocal X-ray source. Resolutions down to 10 μm can be obtained with this technique. The contrast resolution is usually determined by the system specifications and the detector characteristics play a huge role in the contrast resolution. An increase in the contrast resolution leads to resolving materials that have much smaller differences in their linear attenuation coefficients.

Digital image analysis has been used to qualitatively and quantitatively characterize the internal structure distribution of HMA in conjunction with CT imaging. The following sections discuss some of the recent applications in the study of HMA.

Quantifying HMA Compaction and Mechanical Performance

Masad et al (1999b) used image analysis techniques in studying the difference in internal structure of HMA specimens compacted with the Superpave Gyratory Compactor (SGC) and the Linear Kneading Compactor (LKC). The orientation and distribution of aggregates and the aggregate-to-aggregate contacts were used as quantifying measures in studying the internal structure of HMA. The results showed that aggregates have preferred orientation toward the horizontal direction in SGC specimens and a relatively random distribution in the case of LKC specimens. This indicates that different compaction methods cannot not be used interchangeably in preparing mixes for mechanical testing and volumetric analysis (Masad and Button, 2004).

In a related research, Masad et al (1999a) measured aggregate orientations in HMA specimens compacted to different numbers of gyrations and in field cores. They found that the anisotropy in gyratory specimens became more pronounced with increase in the compaction effort (more gyrations) up to a certain point. However, a further increase in the compaction effort caused a reduction in the anisotropy level and produced a more random distribution of the orientation. Tashman et al (2001) reported a similar relationship between aggregate orientation and compaction effort. Aggregate anisotropic distribution was found to be higher in field cores than in SGC specimens (Tashman et al 2001; Saadeh et al 2002). Measurements of aggregate contacts using image analysis have shown field cores to have more stone-on-stone contacts than gyratory specimens (Tashman et al 2001), and the contacts were higher in LKC than in SGC specimens (Masad et al 1999b). Segregation analysis revealed a tendency for coarse aggregates to move toward the circumference in SGC specimens (Masad and Button 2004; Hunter et al 2004).

As a part of Federal Highway Administration's (FHWA) SIMAP (Simulation, Imaging, and Mechanics of Asphalt Pavements) program, Gopalakrishnan et al (2005) used nearest-neighbor distance methods such as Delaunay triangulation and Voronoi tessellation schemes to quantify the degree of compaction in LKC compacted HMA specimens using image analysis and computer simulation techniques. The results indicated that changes in inter-particle distances during compaction could be measured using two-dimensional image analysis of HMA specimens.

Based on a sequence of 3-D CT images, Synolakis et al (1996) developed a new method for computing the microscopic internal displacement fields associated with permanent deformations of HMA cores with complex internal structure. Braz et al (2000) analyzed the CT images of HMA specimens subjected to indirect tensile strength tests (IDT) and Marshall tests. Azari et al (2005) used CT images of HMA specimens to study the effect of radial inhomogeneity on shear properties of asphalt mixtures. The results of this study indicated that predicting the performance of the same material in the field based on the properties of laboratory-made specimens will lead to over-prediction of the field performance and as a result under-design of pavements.

Dessouky et al (2003) related the aggregate structure stability measured during compaction in the SGC to the aggregate orientation. The stability was measured using a Contact Energy Index (CEI), which reflects the amount of shear energy needed to compact the mix (Masad and Button 2004). The results indicated that the gravel mixes and those with natural sand experienced more aggregate sliding (reorientation) and loss of contacts during compaction than their counterpart limestone mixes. Romero and Masad (2001) used CT techniques to determine the Representative Volume Element (RVE), which is the size of an HMA specimen that should be tested in the laboratory to provide a response that represents the global properties of the material and not certain localized phenomena.

Three-Dimensional Visualization and Microstructure Characterization

Several cross-sectional images of a single HMA specimen or core acquired using a CT system can be put together and rendered to produce a volume image. The volumetric images permit study of various aspects of HMA such as the structure of the aggregate skeleton, the orientation of particles, any lack of homogeneity (segregation) in aggregate sizes, distribution of air-voids, presence of cracks, the distribution of asphalt, etc. Information such as the inter-connectivity of air-voids, the number and the direction of aggregate-to-aggregate contacts and aggregate orientation cannot be accurately determined from two-dimensional images.

Masad et al (1999b) found that the air voids in HMA gyratory specimens were non-uniformly distributed along the horizontal and vertical directions. More air voids were present in the outer region and in the top and bottom regions of a specimen. This phenomenon was strongly noticed at high compaction efforts.

Wang et al (2001) evaluated the void systems of three original WesTrack mixes using CT images and stereology methods. A forensic analysis of Arizona's US-93 Superpave sections using CT images revealed that the void structure contributed significantly to the distress of these sections (Shashidhar et al 2001). Shashidhar (1999) studied field cores using CT and observed the relatively high voids content present at asphalt mixture interfaces. Tashman et al (2002) observed a uniform air voids distribution in the horizontal direction and a non-uniform distribution in the vertical direction from field cores studied using CT.

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Ketcham and Shashidhar (2001) developed a software program, BLOB3D®, to analyze 3-D images of HMA quantitatively. The BLOB3D® program implements a 3D version of what is traditionally called a "blob analysis" for extracting objects from 2D images. The three-dimensional rendering of a sub-volume for HMA quantitative analysis using BLOB3D® software is shown in Figure 4 (Gopalakrishnan and Shashidhar 2000). Ketcham and Shashidhar (2001) demonstrated that it is possible to extract particle size, location, aggregate-to-aggregate contact vectors, and contact area using the BLOB3D® program.

Several key air void properties, including the shape of the air voids and length of flow paths, which are related to permeability of HMA mixes were determined by Al-Omari et al (2002) with CT and image analysis techniques. A numerical scheme was developed to simulate fluid flow in HMA microstructure captured using CT and calculate permeability (Al-Omari and Masad 2004).

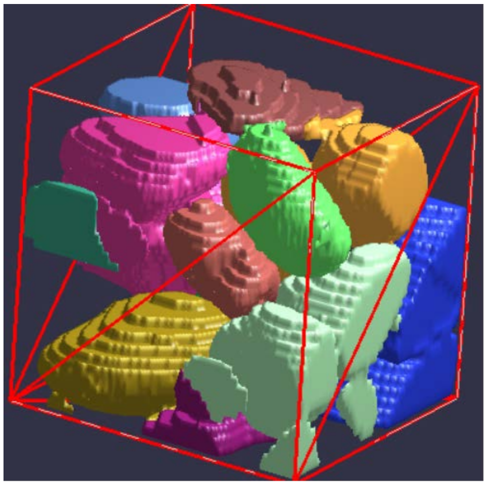

Figure 4. Quantitative analysis of 3-D images of HMA using BLOB3D® software.

Damage Evolution

CT has been used for crack detection in asphalt mixes (Read 2000; Offrel and Magnusson 2002). Braz et al (1999; 2000; 2004) applied computerized tomography techniques to detect and follow the evolution of a crack, when an asphalt mixture is submitted to fatigue testing.

Tashman et al (2004) used CT to capture the microstructure of HMA specimens before and after loading in triaxial compression tests at high temperatures and used image analysis techniques to characterize the evolution of air voids and cracks throughout the deformation process. The study showed the need for preparing homogenous HMA specimens in the laboratory and suggested that the HMA permanent deformation models should account for the effect of damage localization on accelerating permanent deformation.

Computational Simulation

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CT imaging has been used to reconstruct virtual samples for applying computational simulation techniques including the Finite Element Method (FEM), Discrete Element Method (DEM), and the Boundary Element Method (BEM).

Masad et al (2001) used 2-D digitized images of HMA cross-sections and analyzed them with FEM procedures. Wang et al (1999) achieved 3-D FEM simulation of HMA properties using CT imaging. Buttlar and You (2001) and You and Buttlar (2005) applied Microfrabic DEM (MDEM) modeling and image processing techniques to model the complex surface morphology of aggregates in asphalt mixes, but on a 2-D structure. Recently, Wang et al (2004a) developed a new methodology to use CT imaging and a clump technique to represent the true 3-D particle shape for DEM simulation.

Wang et al (2003) presented methods to quantify damage parameters from 3-D reconstructed CT images of HMA specimens and also presented relation between the quantified damage parameters and their applications in mechanical modeling. A simplified mixture theory to address the effect of void inhomogeneity of asphalt concrete, and the stresses induced by the inhomogeneous void distribution was proposed by Wang et al (2004c). Methods to quantify the field variables of the proposed mixture theory were developed using CT imaging.

Preliminary Studies Using X-ray High Resolution Computed Tomography (HRCT)

X-ray high resolution computed tomography (HRCT) can resolve features to 10 μm (or even lower) in size and detect density differences as small as 0.1 percent. Microtomography is similar to CT, except that it uses a microfocus X-ray source and a high resolution X-ray detector making it possible to measure the internal structure of materials in three dimensions at high resolution. HRCT has been successfully used to examine properties of cement concrete in recent years (Shah and Choi 1999; Landis and Keane 1999; Stock et al 2002; Naik et al 2004) as well as for characterizing the physical properties of soil and particulate systems (Macedo et al 1999; Halverson et al 2005).

The application of HRCT to the study of HMA has been very limited so far, at least as reported in the literature. Shashidhar (1999) used HRCT to study a 32-mm diameter core from a pavement at the FHWA's accelerated loading facility. The HRCT captured the mineralogical variation within the aggregate used in the mix. The aggregate had three components – a dark siliceous phase, a denser aluminosilicate phase, and the brightest (densest) ferrous phase. It was also observed from HRCT images that although some asphalt mortar coated the large particles with a layer that was a few millimeters thick, the rest of the asphalt mortar occurred in pockets. This study indicated the potential of HRCT for studying asphalt film thickness in HMA.

The Center for Nondestructive Evaluation (CNDE) at Iowa State University has an in-house X-ray HRCT system including customized software for data acquisition, volumetric file reconstruction, and visualization. The HRCT used in this study utilizes a 130-kilovolt microfocal X-ray source capable of 2.5 μm resolution and 1400 × 1400 × 500 voxel data volumes (Zhang et al 2005). Results from two different studies are reported in this paper.

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In the first study, a random sample from an actual core obtained from a stripped HMA pavement in Iowa was investigated using the HRCT. The core exhibited signs of severe moisture damage. The front and back side of the investigated HMA sample with varying dimensions is shown in Figure 5. Typical cross-sectional images captured using HRCT are displayed in Figure 6. This Figure clearly shows the presence of large voids (in black) within the HMA sample and the separation of aggregates from the surrounding matrix at several places due to stripping.

Figure 5. Front and back views of stripped HMA sample used in this study.

During the second study, three samples were prepared to assess the accuracy of HRCT in capturing coarse and fine aggregates in the presence of asphalt. Aggregates retained on five different sieve sizes were considered: 12.7 mm (0.5 in.), 9.5 mm (0.375 in.), 4.75 mm (0.18 in.), 600 µm, and 300 µm. The first sample (referred to as CA) was created by randomly placing the 12.7-mm, 9.5-mm, and 4.75-mm aggregates in a cylindrical plastic container of 2.5-cm diameter and 5.5-cm height and pouring asphalt into it. For all three samples, similar sized cylindrical plastic containers were used. The second sample (referred to as FAC) consisted of 4.75-mm, 300-µm, and 600-µm particles mixed together in the cylindrical container prior to the pouring of asphalt. The third container (referred to as FAS) contained aggregates of same three sizes as FAC, but were arranged in three different layers prior to the pouring of asphalt.

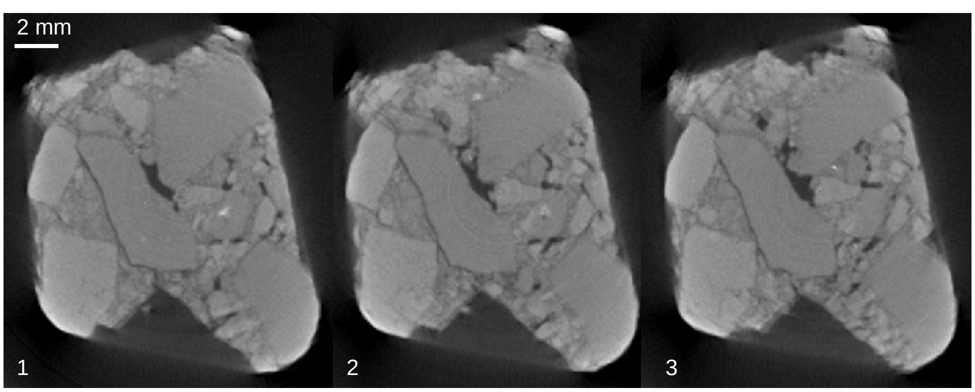

Figure 6. X-ray high resolution tomography cross-sectional images of stripped HMA sample.

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Figure 7 illustrates the X-ray shadow images obtained for FAS sample at two different voltage and current combinations. The linear attenuation coefficients of the asphalt are significantly lower than the aggregate coefficients. Therefore, x-rays can penetrate the asphalt at the low kilovoltage/current settings while they can not penetrate the aggregates in the lower portion of the image. The x-rays from the higher voltage/current setting can penetrate the aggregates and form an image of the aggregates section but they can not be stopped sufficiently to form an image of the asphalt section.

Three distinct aggregate layers corresponding to three different particle sizes are clearly visible at higher voltage and current. In Figure 8, sequence of X-ray microtomography cross-sectional images captured at the interface between 300-µm and 600-µm particles in FAS sample are displayed. The HRCT cross-sectional images obtained for samples FAC and CA are illustrated in Figures 9 and 10, respectively.

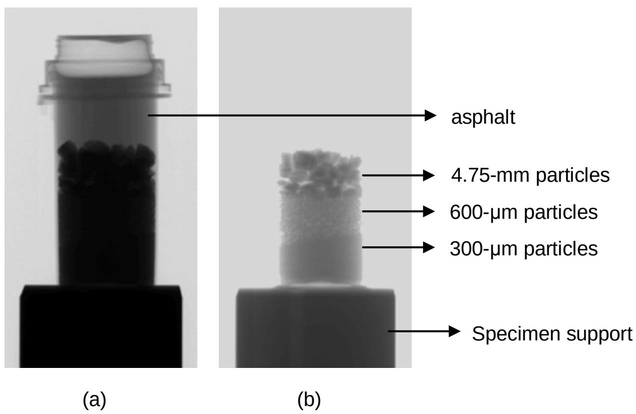

Figure 7. X-ray shadow images of FAS sample: (a) 80-kVp, 0.10-mA; (b) 120-kVp, 0.40-mA.

This study indicated the potential of HRCT in the study of asphalt mortar (or mastic) properties, asphalt film thickness and for forensic investigation of pavement failures, which will be some of the areas for future research. Future research will also focus on the application of CT and HRCT techniques for characterizing air void systems in Portland Cement Concrete (PCC) and for characterizing geomaterials.

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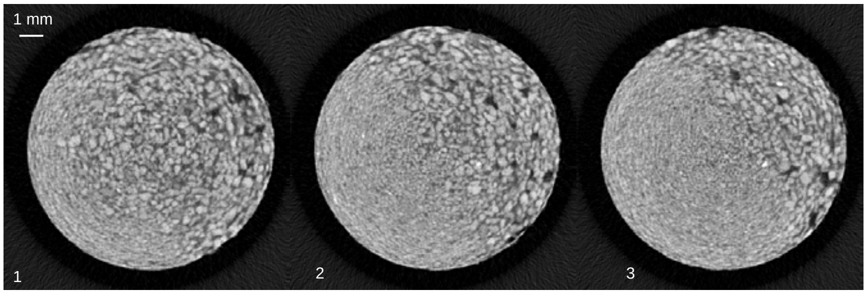

Figure 8. X-ray high resolution tomography cross-sectional images for FAS sample at the interface between 300-µm particles and 600-µm particles.

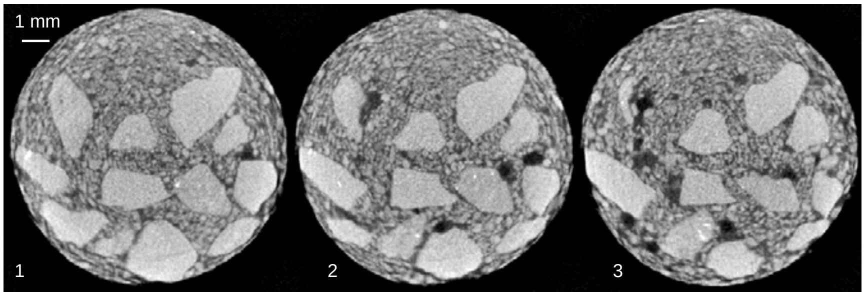

Figure 9. X-ray high resolution tomography cross-sectional images for FAC sample (aggregates of three different sizes [4.75-mm, 300-µm, and 600-µm] floating in asphalt).

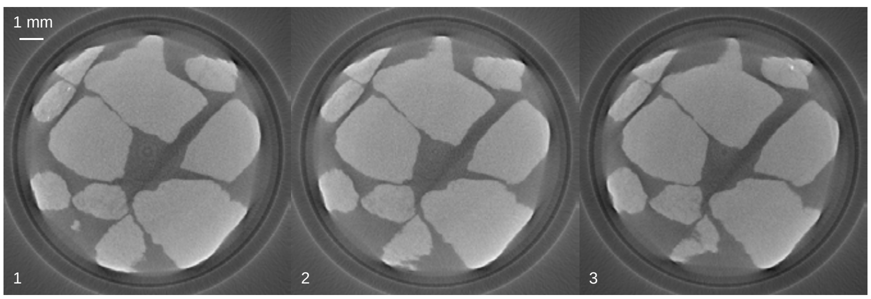

Figure 10. X-ray high resolution tomography cross-sectional images for CA sample (aggregates of three different sizes [12.7-mm, 9.5-mm, and 4.75-mm] floating in asphalt).

The use of X-ray high resolution tomography can be very valuable in the study of Hot-Mix Asphalt which is a multi-phase composite containing aggregates spanning a two-decade range particle size distribution. Using HRCT, it is possible to obtain quantitative information regarding fine aggregate particles, asphalt mortar, asphalt film thickness, etc. which is not possible using the conventional X-ray CT systems due to resolution limitations.

Summary and Observations

The importance of aggregate structure or internal structure in the performance of Hot-Mix Asphalt (HMA) pavements is well recognized. In recent years, there has been significant research on qualitative or/and quantitative assessment of HMA internal structure using two-dimensional (2-D) and three-dimensional (3-D) image analysis techniques.

X-ray computed tomography (X-ray CT or CT) is a viable, nondestructive, 3-D imaging tool that has promising applications in characterization, modeling and computational simulation to optimize HMA mix design, predict performance and conduct investigative forensic studies. A significant benefit of using CT is that CT cross-sectional images can be used to reconstruct the 3-D internal structure of a sample for computer simulation; meanwhile the sample remains intact and can be used for determining other macro properties

This paper reviewed some of the emerging imaging techniques related to HMA internal structure characterization based on the research studies reported in the literature. These methods have been applied recently in studying the differences among different laboratory compaction methods, improving the simulation of laboratory compaction to field compaction, segregation analysis, quantifying the effect of laboratory strength testing on HMA internal structure properties in terms of damage evolution, characterizing air void distribution properties and predicting the permeability of HMA mixtures. CT imaging has also been used to reconstruct virtual samples for applying computational simulation techniques in conjunction with mechanical modeling.

Preliminary studies were undertaken at the Center for Nondestructive Evaluation (CNDE) at Iowa State University to study asphalt materials using an X-ray high resolution tomography (HRCT) system. This study indicated the potential of HRCT in the study of asphalt mortar (or mastic) properties, asphalt film thickness and for forensic investigation of pavement failures, which will be some of the areas for future research.

By quantifying the internal structure of HMA using the state-of-the-art imaging techniques and through mechanical modeling and numerical analysis that account for the internal structure, it will be possible to quantitatively relate the raw material properties to pavement performance. By thorough examination of the HMA internal structure, aggregate matrices that exhibit enhanced performance can be identified and steps can be taken to develop compaction techniques that can produce this structure. Imaging techniques may also be used for forensic investigations to determine the cause of premature failure of an asphalt pavement and for evaluating segregation.

In summary, researchers at both Iowa State University and Iowa Department of Transportation can take advantage of the advanced imaging facilities available at the CNDE and the latest developments in image analysis techniques to develop a deeper understanding of the HMA internal structure, develop and optimize the various parameters that describe the internal structure and relate them to the performance of pavements in a scientific way. This will provide the foundations to building more durable and long-lasting pavements.

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