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A micromechanical approach to investigate asphalt concrete rutting mechanisms

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ABSTRACT

In this study, a new approach was used to evaluate changes in asphalt concrete microstructure under full-scale accelerated pavement test loading with a Heavy Vehicle Simulator (HVS) of composite pavement. The approach compared X-ray computed tomography (CT) images taken before and after HVS rut testing. Results were used to identify the differences in the movement of aggregate and changes in air-void content and distribution occurring during rutting accumulation of rubberized gap graded and polymer modified dense graded mixes for two overlay thicknesses (64 and 114 mm). Although high air void content for the sections constructed with rubberized gap graded mix were expected to cause more densification related rutting and earlier failure related to this densification, the actual reason behind the earlier failure was determined to be primarily greater shear flow to the sides of the wheelpath associated with the gap gradation and small aggregate size. Significant movement of aggregate was observed in the direction of travel as well as to the side under the pushed wheel. Important differences in aggregate movement and air-void changes were also observed between different overlay thicknesses indicating the depth of the rut phenomenon, important information for the design of overlays on aged asphalt concrete as well.

1. Introduction

The general trend in truck tires used to haul heavy freight has indicated the need for changes in tire technology to reduce rolling resistance and improve fuel economy, including the switch from bias-ply to radial tires beginning 45 years ago, and continuing with the movement to wide-base single tires over the last 20 years. At the same time, tire inflation pressures have generally been increasing for the same reasons. The combined effects of each of these tire technology changes and increasing inflation pressures and truck traffic have increased the risk of rutting of asphalt concrete (AC) and a need for high performance pavement structures [1]. Therefore, new pavement design and construction specifications have been developed to reduce the risk of early failure of pavement structures [2]. Three other trends affecting the design and construction of asphalt mixes are: (1) the change of focus from designing and constructing new pavements to rehabilitation and maintenance; (2) the increased use of modified asphalt binders and gap-, open- and stone-matrix type aggregate gradations rather than dense-gradations; and (3) of the increasing use of specifications to reward or penalize the contractor for performance-related construction quality or performance [3]. Together, these trends require the use of design methods that consider material properties, structural design (particularly the use of relatively thin modified asphalt overlays on concrete and aged existing asphalt layers), and the effects of traffic and climate to deliver the required future performance of the constructed structure.

Mechanistic–empirical (ME) design methods are developed by calibrating critical mechanistic responses of pavement structures calculated using theoretical structural models with responses measured in the field, and then correlating those responses with empirical performance data. The structural models are developed based on generally accepted theories such as linear elastic theory (LET) and finite element (FE) theory, with specific constitutive relations that consider the effects of environmental conditions and traffic loads, and dimensions. The structural models use laboratory test results to characterize the damage in the materials (usually loss of stiffness or permanent deformation) resulting from the pavement response (stress and/or strain). Structural models are calibrated based on measured pavement performance that is generally determined from accelerated pavement testing (APT) and/or less commonly field test results [4]. APT is also commonly used to calibrate responses with observed distresses because it offers controlled experiments with the ability to comprehensively and cost-effectively characterize

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the pavement and measure responses and distress development, or to relate material properties to full-scale performance [5]. However, ME design methods use greatly simplified models (such as relating elastic strains to plastic strains) [4,6,7] that rely on correct conceptual understanding of causal relationships between responses that can be measured in APT or in the field and distress development. There has been considerable theoretical, laboratory testing and modeling work to relate material properties to performance of modified binder mixes and different aggregate gradations. However, the densification and shearing processes that cause rutting of asphalt mixes have not had experimental measurements of the movement of aggregate and changes in air-void content and distribution that explain rutting failure at a microstructure scale. The literature also indicates that greater attention has been paid to the mechanics of thick asphalt layers as opposed to the thinner overlays on existing stiff layers that make up the majority of the applications in California and many other locations.

Asphalt concrete is a composite material which consists of aggregates, air-voids and mastic, and each phase plays a role in development of total accumulated rutting. Asphalt concrete mixes act as continuum materials at low temperatures when the stiffness of the asphalt binder and the aggregate are close [8]. However, at high temperatures, i.e. the critical conditions for rutting deformation accumulation, stiffness of the aggregate can be two to three orders of magnitude higher than the asphalt binder stiffness. As a result, asphalt concrete pavement layers start to act as particulate structures where the contact points between the aggregates become more important in terms of rutting deformation accumulation [9]. Therefore, permanent deformation accumulation mechanisms predicted by using continuum mechanics may not reflect the actual mechanism under the in situ truck traffic. This has been recognized in recent years and has lead to increased use of multi-phase continuum mechanics and discrete element method approaches [10–15]. These methods consider the properties of the aggregate (shape, texture, gradation, modulus), of the asphalt binder (visco-elasticity) and distribution of air voids in the asphalt concrete layers. However, as noted, experimental measurements for validation of these models for permanent deformation under full-scale loading and for thin overlays has not been available to date.

Microstructures of AC laboratory samples have been analyzed by various researchers. Masad et al. [16,17] characterized the air-void distribution in AC samples using the Weibull model and concluded that the method of laboratory specimen compaction significantly influences the air-void size distributions. Masad and Button [18] developed a procedure to quantify the distribution of aggregate skeleton and air-voids by analyzing images of the internal structure. You et al. [10,11] processed the AC X-ray computed tomography (CT) images to develop 2D and 3D discrete and finite element models to evaluate the effect of binder, aggregate and air-void interaction on AC performance.

Changes in material microstructure under laboratory testing were also evaluated by various researchers. Braz et al. [12,19] analyzed the propagation of cracks under diametral compression testing to determine the effect of AC air-void distributions on cracking performance. Warr et al. [13] analyzed the 2D transitional and rotational motion of granular particles under laboratory loading by using the images collected by high-speed photography. Wang et al. [14] used photograph images taken before and after Georgia Loaded Wheel Test loading (GLWT) to determine the 2D permanent strain field of an asphalt concrete specimen. Wang et al. [20] also calculated the plastic strain field in asphalt concrete laboratory samples accumulated for specimens tested with the Asphalt Pavement Analyzer (APA). It was concluded that permanent deformation of asphalt concrete is localized mainly in the soft mastics due to low mastic stiffness at high test temperatures (60 °C). Synolakis et al. [21] used X-ray CT images that were taken before and after the application of a diametral load on a cylindrical laboratory sample to calculate the plastic displacement field.

In this study, changes in AC microstructure were determined using full-scale test sections and Heavy Vehicle Simulator (HVS) loading, and X-ray CT images taken before and after HVS testing. Asphalt concrete blocks sawn from four HVS test sections were scanned to determine the microstructure of the blocks before testing. 3D distributions of air-voids, location and shape parameters for the aggregates were determined using these images. Scanned AC blocks were installed back into their original locations using a fast-setting epoxy. HVS tests were conducted at high temperatures (50 °C at 50 mm depth) that are critical for rutting until the surface failure was observed. Deformed AC blocks were re-sawn to perform X-ray CT scanning after HVS loading. Deformed and un-deformed 3D air-void and aggregate distributions were compared to determine the changes in air-void content distributions and aggregate positions. Changes in air-void content distributions were used to identify the contribution of densification to total accumulated downward rut, while changes in aggregate positions were used to determine the displacement field under full-scale wheel loading and explain the reason behind the earlier failure of rubberized gap graded AC mixes when compared to polymer modified dense graded AC mixes. Changes in air-void distributions and displacement field can also be used to validate and/or calibrate micromechanical finite element or discrete element models.

This study is the first in situ investigation of micromechanical changes in AC layers under full-scale loading, and provides experimental data for continued development of multi-scale continuum mechanics and discrete element method analysis approaches. Results of the analyses will give important information about the rutting failure mechanisms of gap-graded rubberized and polymer modified dense graded asphalt mixes. The method used in this study can be used to develop additional experimental data for other mix types and under different testing conditions.

2. Objectives

The main objectives of the work presented in this paper were:

- Use the X-ray CT imaging method to identify changes in microstructure caused by the rutting process, namely aggregate displacements and changes in air-void content and distribution, under full-scale loading and for different thicknesses of overlay on very stiff underlying layers.
- Use the experimental measurements to perform a first-level assessment of the micromechanical phenomena to provide insight into mix performance for mix design and development and understanding of laboratory tests, and information regarding the mechanics of rutting that can be used to improve micromechanical analysis approaches.

3. Heavy vehicle simulator testing

The HVS is a mobile load frame that uses a full-scale wheel (dual or single) to traffic the pavement test section. The trafficked test section is 8 m long, of which 1 m on each end are used for turnaround of the wheel and are discarded.

Composite pavement HVS test sections were constructed at the Advanced Transportation Infrastructure Research Center (ATIRC) facility at UC Davis consisting of two thicknesses of AC overlay on non-doweled jointed plain portland cement concrete (PCC) slabs that were 178 mm (7 in.) thick, 3.7 m wide (12 ft) and 4.5 m (15 ft) long over a 150 mm (6 in.) aggregate base layer. The 6 m long HVS wheelpath included two joints and one slab.

The failure criterion was defined as an average maximum rut (defined as the summation of the downward deformation and "humping" of material sheared to the sides of the wheelpath) of 12.5 mm over the full monitored section. The pavement temperature at 50 mm depth was maintained at 50 °C ± 4 °C to assess rutting potential under typical pavement conditions.