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Preliminary investigation of the relationship between HMA compressive and tensile dynamic modulus

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HIGHLIGHTS

- In the research, CDM represented Compressive Dynamic Modulus.
- $TDM^{\perp}$ and $TDM^{||}$ used for Dynamic Modulus perpendicular and parallel to compaction.
- The research found significant difference existed between the CDM and $TDM^{\perp}$.
- The research found that CDM-$TDM^{\perp}$ relationship follows the power law distribution.
- A relatively smaller difference was observed between CDM and $TDM^{||}$.

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ABSTRACT

For resource optimization and time constraints, it is often desired to estimate and predict certain material properties of hot-mix asphalt (HMA) from a known set of existing data, generated either through laboratory or field testing; typically for the purposes of design and/or analysis. This laboratory study was undertaken to explore and investigate the relationships between the Compressive Dynamic Modulus (CDM) and Tensile Dynamic Modulus (TDM) properties of HMA based on mixes typically used in the State of New York (USA). The second objective of the study was to establish and formulate generalized statistical TDM-CDM models that could closely predict the HMA tensile dynamic modulus (TDM) from known compressive dynamic modulus (CDM) data from laboratory experimentation. Twelve different mixes of HMA were tested to determine the CDM and TDM parallel to the direction of compaction and TDM perpendicular to the direction of compaction. Two replicates were tested for each mix at different temperatures (namely 10 °C, 20 °C, 30 °C, and 35 °C) and loading frequencies (namely 25 Hz, 10 Hz, 5 Hz and 1 Hz). The corresponding laboratory test results were then used to develop statistical models that related CDM and TDM at the individual test temperatures and all the test temperatures combined. Overall, the study found that the CDM versus TDM correlation at each temperature level improved with increasing temperature from fair to good, with a correlation coefficient (R^2) ranging from 50% to 89%; whereas the correlation at all the test temperatures combined was found to be relatively strong with an R^2 value above 90%. For the mixes evaluated and the test conditions considered, the formulated models were successfully validated through statistical comparisons of the laboratory measured and the predicted TDM values.

1. Introduction

The temperature–time dependency behavior (viscoelasticity) of materials such as hot-mix asphalt (HMA) is typically defined based on laboratory measured dynamic modulus parameters. The protocol for determining dynamic modulus was originally developed by Coffman and Pagen at Ohio State University in the 1960's [1]. The protocol was adapted by ASTM in the early 1970s and AASHTO later on [1]. According to the protocol, the dynamic modulus is defined as the ratio of the amplitude of the sinusoidal stress at any given time and the loading frequency and the amplitude of the sinusoidal strain at the same time and frequency. The test may be applied in compression or tension [1–3]. And since the adaption of the protocol about 50 years ago, most of the results

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obtained are based on compression tests. However, some studies suggest that significant differences exist between the compressive and tensile strength of HMA [4–6]. A few of these studies shows the difference exists also for the HMA dynamic modulus. Nevertheless, most of these studies are limited to tests performed on HMA samples extracted parallel to the direction of compaction. To his credit, Mamlouk et al. [7] carried out displacement controlled compression tests on the vertical and horizontal cores of HMA to determine the effects of anisotropy on the compressive properties of HMA mixes. The experimental results showed that there was no significant difference. However, Mamlouk et al. [7] admitted that these results could have been affected by specimen preparation methods, testing conditions, and specimen geometry (i.e., size).

In this study, the relationship between compressive and tensile dynamic modulus of HMA was investigated. Typically, the compressive dynamic modulus is performed under uniaxial cyclic loading tests whereas the tensile dynamic modulus is determined through indirect tensile tests such as the IDT (indirect tension test) [8,9]. However, for better comparison, this study measured both the compressive and tensile dynamic modulus (denoted as CDM and TDM, respectively) through the direct uniaxial loading mode. The study used cores extracted parallel and perpendicular to the direction of compaction to determine if difference exists between the CDM and TDM of HMA. Additionally, the study also investigated and established some mathematical models that relate CDM and TDM to cost-effectively reduce the time needed for laboratory experiments. In particular, this study was set to address the following objectives:

1) Determine the cyclic dynamic modulus of HMA in both compressive and tensile loading modes, parallel and perpendicular to the direction of compaction.
2) Develop a mathematical relationship and models between compressive and tensile dynamic modulus; and, thereafter, validate the relationship/model through statistical analysis tools and graphical illustrations/interpretations.

In the subsequent sections, the laboratory experimentation and test results are presented along with the corresponding analysis; followed by the development of the CDM-TDM mathematical models and relationships. Based on laboratory test results presented and analyzed, the paper then concludes with a synthesis and summary of the key findings and recommendations.

2. Laboratory experimentation

Cylindrical HMA specimens with dimensions of 4-inch (100 mm) diameter by 6-inch (150 mm) in height were received already pre-made for dynamic modulus testing from several asphalt plants in the State of New York (USA). The HMA specimens were prepared using the procedure stipulated in AASHTO TP 62-03 to a target air void (AV) of 7 ± 1% [10]. Table 1 shows the basic mix-design volumetrics of the HMA specimens obtained from different administrative regions of the New York Department of Transportation (NYDoT) (see Fig. 1).

The specimens were firstly tested for compressive dynamic modulus parallel to the direction of compaction (CDM). Thereafter, the samples were brought to a 2-inch diameter coring cutter to extract cylindrical samples perpendicular to the vertical axis (Fig. 2). The 2-inch diameter by 3-inch long cylindrical specimens were later used for measuring the TDM perpendicular to the direction of HMA compaction. In the study, it was assumed that the non-destructive CDM tests caused little or no change in volumetric characteristics of the tested HMA specimens and thus, the same specimens were re-used for TDM testing in the direction perpendicular to compaction.

In the study, the specimens tested in tension (TDM) were connected to the testing frame components using a pretested two-part, high strength epoxy glue. The glue specifications are summarized in Table 2.

Before applying glue, the specimen and floor flange surfaces were cleaned and dried to ensure good bonding with support fixtures. The glue was then applied uniformly on the surfaces using a grooving device (Fig. 3).

Immediately after the application of glue, the specimens and the flanges were quickly put together and left to cure for about 20 h using 10 lbs curing weight. In some cases, the glue joints, which were under-cured or perhaps not well cleaned could not withstand the extreme tensile loads and hence de-bonded as shown in Fig. 4.

Prior to starting any of the HMA experimentation, a dummy specimen of the same size as the test specimen with a thermal couple inserted to its center inner core was placed into the environmental chamber to monitor and ensure that the recorded test temperatures was a true representative of the inside and outside of the test specimens. The thermal couple was connected to the Data Acquisition System (CDAS) which transferred the recorded test temperature to the computer for real time temperature display. In addition, two HMA specimens were used per mix type per test condition. And three linear variable differential transducers (LVDTs) were used on each specimen.

The tests were performed at temperatures above 10 °C to represent the zone within which most previous researchers have observed significant differences between the compressive and tensile properties of HMA [3,6,12–16]. And since the tensile properties of HMA are relatively sensitive to temperature changes, the temperature interval was kept at 10° C and below.

2.1. Compressive Dynamic Modulus Test Parallel to the Direction of Compaction

The repeated compression dynamic modulus (CDM) was performed in accordance with the AASHTO TP 62-03 protocol [10]

Table 1
Basic HMA Mix-Design Volumetrics.

Region	Mix ID	NMAS	RAP (%)	PG Grade	Asphalt Binder (%) by Weight
02	0225	25	20	64-22	4.5
04	0412	12.5	20	64-28	5.3
06	0609	9.5	0	64-28	6.16
06	0619	19	0	64-22	4.8
07	0172	12.5	20	64-22	5.2
09	0919	19	0	64-22	4.6
10	1012	12.5	20	70-22	5.3
10	1037	37.5	30	70-22	4.4
11	1112	12.5	15	76-22	5.2

Legend: NMAS = Nominal Maximum Aggregate Size; RAP = Reclaimed (Recycled) Asphalt Pavement materials; PG = Performance-Graded