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Experimental and numerical study of asphalt material geospatial heterogeneity with intelligent compaction technology on roads

Qinwu Xu [a,*], George K. Chang [b,1]

[a] Civil, Architectural and Environmental Engineering, The University of Texas at Austin, Austin, TX 78721, USA
[b] Research & Development, The Transtec Group, Inc., Austin, TX, USA

HIGHLIGHTS

- Asphalt material geospatial heterogeneity was studied with intelligent compaction technology.
- Material heterogeneity significantly affects structural response of pavements.
- A coefficient of semivariogram index is proposed to quantify geospatial heterogeneity.

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ABSTRACT

In the conventional structural analysis and design of highway pavements including the mechanistic-empirical pavement design guide (MEPDG), the layer properties are considered uniform spatially. This research studies the geospatial heterogeneity of asphalt material property and its influence on structural responses with the intelligent compaction (IC) technology on road construction. Instrumented with the satellite navigation system, accelerometer and computer system, the IC roller measured the material stiffness with 100% coverage. A three-dimensional finite element (FE) model was developed to simulate pavement responses with heterogeneous Bomag E_{vib} as elastic moduli of asphalt materials under vehicle loading. This material model considers heterogeneous material properties with geospatial distribution that more closely reflect the actual field conditions on a typical roadway. The statistics and geostatistical semivariogram model were studied to evaluate the heterogeneity of material moduli and structural responses. A coefficient of semivariogram (Cova) index is proposed to quantify the geospatial heterogeneity. Modeling results demonstrated that geospatial heterogeneity of material elastic moduli, rather than commonly used univariate statistics, affects structural responses spatially in a nonlinear fashion. Heterogeneous moduli distribution results in inferior responses than uniform model. Cova has close values and trends with that of the coefficient of variance for the analysis area with small-space, and it could be used to quantify the heterogeneity. Therefore, the geospatial heterogeneity of material property is recommended to be considered in future pavement analysis to account for the in-service conditions.

1. Introduction

Structure modeling, analysis, and design methods including the mechanistic-empirical pavement design guide (MEPDG), for the highway pavements are generally based on homogeneous or uniform layer properties (including anisotropic properties in directions) [1–3]. This may not reflect field and service conditions. Heterogeneity of field compaction on asphalt materials has long been considered qualitatively as an important factor on pavement responses and long term performance. However, spatial heterogeneity of compaction could not be quantified until the late 2000s when intelligent compaction (IC) technologies became available to measure in-situ compaction heterogeneity with one hundred percent coverage of compacted areas [4–9]. IC technology consists of vibratory rollers that are equipped with accelerometer-based measurement devices, global positioning system (GPS), and onboard display of real-time integrated measurements. ICMV is an index value relating to the level of compaction and stiffness of materials. ICMV is presented either as a unitless index value (e.g. CCV by Sakai [10]), or stiffness (e.g. K_b by Case/Ammann, with a unit of MN/m [11]), and modulus (e.g. E_{vib} by Bomag, with a unit

* Corresponding author. Tel.: +1 512 471 4921; fax: +1 512 471 0592.
E-mail addresses: qinwu.xu@utexas.edu (Q. Xu), gkchang@thetranstecgroup.com (G.K. Chang).
1 Tel.: +1 512 451 6233; fax: +1 512 451 6234.

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of MN/m^2 or MPa) [12]. As demonstrated by previous research, the ICMV is usually not uniform in field conditions [6,7]. Heterogeneous support conditions and compactions may result in heterogeneous ICMV which in turn contributes to causes for premature failure [5] or, potentially, long-term pavement distresses due to the heterogeneous pavement responses. Alkasawneh et al. [13] studied the influence of vertical heterogeneous property of materials on pavement response, where pavement layer is divided into multiple sub-layers and each sub-layer has a uniform material modulus. However, the spatial heterogeneous property is more common due to heterogeneous support and compaction conditions as identified by the IC technology. In addition, the geostatistical semivariogram has been implemented for studying the heterogeneity of infrastructure and earthwork modeling and construction [5,6,8], although it has been primarily used for other science and engineering fields such as geoscience or petroleum engineering (e.g., to estimate the oil/gas well location within a large area). Here the heterogeneity refers to the degree of how heterogeneous the property distribution is. However, these existing studies have not quantified the semivariogram model parameters on evaluating the material geospatial heterogeneity (e.g., what level of sill values of the semivariogram can be accepted for construction quality assurance).

Therefore, the objective of this paper is to study the geospatial heterogeneity of asphalt pavement materials and its influence on the structural responses with the intelligent compaction technology. The three-dimensional (3-D) Finite Element (FE) model with IC-measured heterogeneous elastic moduli of Bomag E_{vib} measurements was developed to simulate critical structural responses of asphalt materials. The coefficient of semivariogram is proposed as an index to quantify the heterogeneity and evaluate its influence on pavement responses.

2. Experimental plan

This construction project was an HMA (hot mix asphalt) overlay on existing old asphalt base course. The subbase layer is cement treated materials. The typical Poisson's ratio values of different material types are used [1]. Before paving HMA overlay, the falling weight deflectometer (FWD) tests were performed on the existing pavements in order to determine the existing layer properties. The pavement structure and back-calculated elastic moduli of existing layers are listed in Table 1. The moduli of fresh HMA overlay is determined from the IC roller measurements as discussed later.

Fig. 1 presents the designed experimental procedure. Before construction started, the GPS base station was set up, which is used to connect with satellites and GPS receiver installed on the top of roller for providing real-time kinematic (RTK) GPS information with a precision of 2–3 cm. The roller GPS was validated by comparing its readings with that of a GPS rover. Then the FWD (falling weight deflectometer) test was performed on random spots to determine the elastic moduli of each existing layer. Then vibratory roller compaction was performed on fresh HMA overlay materials, closely following the paver which dumped and leveled off asphalt materials on the existing base layer. The GPS coordinates at each in-situ test of random spots were measured using a GPS rover.

A Bomag double-drum IC roller was used to map the existing base layer to capture the stiffness of the supporting condition. Then it is used to compact the fresh HMA overlay following the paver which dumps and levels off the asphalt materials (see Fig. 2).

Fig. 3 illustrates the IC compaction system and control. The compaction roller is on a vibratory model with a high frequency of 3000 vpm (vibrations per minute). The accelerometer was instrumented to measure accelerations, including vibration

Table 1
Pavement structure and material properties.

Layer	Thickness (in./cm)	Elastic modulus (MPa)	Poisson's ratio
Fresh HMA overlay	4/10.2	Non uniform	0.35
Existing HMA	6/15.2	489	0.35
Base	7/17.8	3481	0.18
Soil	N/A	24	0.45

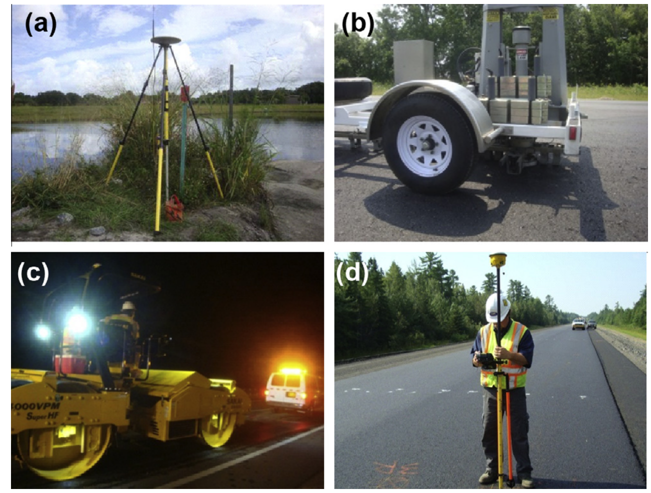

Fig. 1. Experimental design: (a) GPS base station setup; (b) FWD testing; (c) roller compaction and (d) GPS rover measurements on spots.

frequency and amplitude, and ICMV (IC roller measurement value). With this acceleration information and material deformation, the Bomag E_{vib} can be calculated from the mechanical model. An infrared thermal gauge was installed on the front of the drum to measure material surface temperature during compaction. The accuracy of IC recorded temperatures and vibration frequency/amplitude are dependent on the instruments of infrared thermal gauge and accelerometer, respectively, which have been widely used for common practices in the construction industry with acceptable accuracy. The accuracy of material stiffness ICMV (e.g. E_{vib}) is dependent on the stiffness model, the pavement structure, and the support condition. Currently the ICMV is not decoupled to each layer, and the stiffness measurement on HMA may have an influence depth deeper than HMA layer. However, results have shown that E_{vib} has a consistent linear relationship with the backcalculated modulus from FWD measurements as will be discussed later, although laboratory validation was not conducted in this research. The electronic control system is used to adjust vibration frequency, amplitude, and roller speed by the operator. A GPS receiver was installed on the top of the roller machine, which collects the three-dimensional (3-D) GPS coordinates (easting, northing, height) and inputs to the on-board computer system. A computer and information system was installed on the roller for the operator's observation and adaptive control in real-time. The operator can observe the color-coded map of material stiffness ICMV, temperature, vibration frequency, vibration amplitude, and roller pass number with 100% coverage of the compaction areas in real-time. With those real-time information observed on-board, the operator can adjust the compaction efforts to optimize the construction quality for adaptive control in real time.

Bomag E_{vib} is derived from a one-degree lumped-system of mechanical model as shown in Fig. 4, where the eccentrics (additional mass) m was mounted and rotated with a frequency of ω to produce the vibration force in both compression and shear. E_{vib} is determined from material displacement under a cylindrical roller sitting on the foundation based on Lundberg's theory [14]. As an ICMV with a unit of MPa, Bomag E_{vib} represents the elastic modulus of pavement layers. Bomag argued that E_{vib} is a vibration (dynamic) modulus of elasticity [15,16]. The relationship between Bomag E_{vib} and soil-contact force and displacement [15] are used to calculate E_{vib} as discussed in previous research [4,5].

2.1. Semivariogram model

Semivariogram is a function describing the degree of spatial dependence of a random field or stochastic process. It is defined as the expected, squared increment of the values between two adjacent locations [17,18]. It is a common tool used in geostatistics to describe spatial variation or heterogeneity. Semivariogram is calculated for each unit of lag. For a given geo-space with a defined direction (see Fig. 5), the experimental variogram, $r(h)$, for the separation or lag distance, h, is defined as the average squared difference of values, $Z(u)$, separated approximately by h for all possible locations, u [17]:

$$r(h) = M\{[Z(u) - Z(u+h)]^2\} \quad (1)$$

where u = the location; M = statistical mean; h = the lag distance (it could be a constant for the same lag areas); $Z(h)$ = the value such as ICMV and pavement responses.

Fig. 5 shows that one moves from one node (data point) to the next to determine the $Z(u) - Z(u+h)$ value for the calculation of variogram. At each lag, the semivariogram is calculated based on the data points within that lag (e.g. see Fig. 5(b)).