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Pattern recognition algorithms for density estimation of asphalt pavement during compaction: a simulation study

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ABSTRACT

This paper presents the application of artificial neural network (ANN) based pattern recognition to extract the density information of asphalt pavement from simulated ground penetrating radar (GPR) signals. This study is part of research efforts into the application of GPR to monitor asphalt pavement density during compaction. The main challenge is to eliminate the effect of roller-sprayed water on GPR signals during compaction and to extract density information accurately. A calibration of the excitation function was conducted to provide an accurate match between the simulated signal and the real signal. A modified electromagnetic mixing model was then used to calculate the dielectric constant of asphalt mixture with water. A large database of GPR responses was generated from pavement models having different air void contents and various surface moisture contents using finite-difference time-domain simulation. Feature extraction was performed to extract density-related features from the simulated GPR responses. Air void contents were divided into five classes representing different compaction statuses. An ANN-based pattern recognition system was trained using the extracted features as inputs and air void content classes as target outputs. Accuracy of the system was tested using test data set. Classification of air void contents using the developed algorithm is found to be highly accurate, which indicates effectiveness of this method to predict asphalt concrete density.

1. Introduction

The density of asphalt mixture is a key factor that affects the performance of flexible pavement. In-place air void content should range between 3% and 8% (Roberts et al., 1996). High air void content causes moisture damage, binder oxidation, and pavement raveling and cracking. Low air void content, on the other hand, causes higher stiffness, lower rutting potential, and possible bleeding (Brown, 1990). In dense-graded asphalt mixture, when the air void content drops below 3%, significant permanent deformation and shoving can occur (Brown, 1990; Roberts et al., 1996).

During the construction of asphalt pavement, the asphalt mixture is laid on a bound or unbound base by the paver. Then, the compactors roll over the loose asphalt mat expelling air voids from the asphalt mixture. The air void content is reduced after each pass of the compactor. Compaction is critical for achieving the desired density of asphalt pavement. The quality of newly constructed pavement depends to a great extent on the quality of compaction.

The change in asphalt pavement density should be monitored after each roller pass in order to ensure successful compaction. It would be beneficial to develop a tool that can collect data continuously without contacting the pavement surface, and interpret the data in real time. The operator of the compactor could then view the density formation in real time and adjust compaction parameters, such as vibration amplitude and frequency, rolling speed, number of rolling passes, sequence, and timing of rolling passes.

Existing techniques may not perform the aforementioned functions. Although laboratory measurement of cores and nuclear or non-nuclear density gauges are two of the most commonly used methods for assessing compaction quality, both methods have limitations. The coring method provides accurate information about pavement density, but coring is destructive and provides density information at discrete locations only. Furthermore, drilling samples can be obtained only after compaction, which means that density information cannot be obtained during compaction. The nuclear or non-nuclear density gauges are non-destructive, but the gauges must be in contact with pavement surface, and data collection ranges from a few seconds to several minutes. The density gauges, just like the coring method, provide information at discrete locations only and fail to provide real-time information. In addition, nuclear density gauges use radioactive material and require special licensing to transport and operate, which results in increased operational costs.

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The ground penetrating radar (GPR), a non-destructive testing (NDT) tool, has been successfully applied to estimate pavement thickness (Al-Qadi and Lahouar, 2004a,b, 2005a,b; Al-Qadi et al., 2003, 2005; Lahouar and Al-Qadi, 2008; Lahouar et al., 2002; Loulizi et al., 2003), locate anomalies beneath pavement surface (Chen and Scullion, 2008; Ni and Cheng, 2012), and predict asphalt pavement density (Al-Qadi et al., 2010; Leng et al., 2011, 2012). GPR is a special type of radar that sends and receives electromagnetic (EM) waves. GPR can collect data continuously at highway speed without destructing pavement or disturbing traffic flow (Al-Qadi and Lahouar, 2004a,b, 2005a; Al-Qadi et al., 2003, 2005, 2010; Leng et al., 2011).

In addition to these advantages, previous research has indicated that it is possible to use GPR for monitoring compaction (Leng et al., 2012; Shangguan et al., 2013). Although measuring asphalt pavement density using GPR has been achieved, it is applied only after the construction of asphalt pavement. A few researchers have used GPR to monitor compaction during construction. The effect of surface water on GPR signals is certainly the greatest challenge facing the application of GPR. During compaction, the compactor sprays a small amount of water to prevent asphalt particles from sticking to the roller. The water affects GPR signal, thus limiting direct application of GPR density prediction models, which are exclusively used on dry pavement. Therefore, the effect of water on GPR data must be considered when applying GPR for compaction monitoring. Algorithms should be developed to extract density information from GPR signals while avoiding the effect of surface moisture.

The interaction of GPR signals with pavement structure, especially in presence of surface water, must be investigated. This interaction can be studied through the numerical simulation of GPR signals. The finite-difference time-domain (FDTD) method is a popular EM wave simulation technique that solves Maxwell's equations step by step in time domain (Jin, 2010). The FDTD method, a powerful tool for solving broadband EM wave or transient problems, has been applied to simulate ultra-wideband GPR signals (Chew, 1995). It is applied in this study to simulate the propagation of GPR waves within pavements with surface water and to develop algorithms to predict air void content of asphalt pavement from simulated data.

The objective of this study is to develop algorithms to obtain the density of asphalt pavement during compaction, based on FDTD simulation GPR data. First, a calibration is conducted to ensure an exact match between simulation and real GPR signals. A successful FDTD simulation relies on providing an accurate match between the simulated signal and the real GPR signal. Second, a database of GPR signals is generated using FDTD simulation. Different air void contents and surface moisture contents are assigned to the pavement model to simulate changes in asphalt mixture density and variations in surface moisture content during compaction. Finally, an artificial neural network (ANN) based pattern recognition is performed to extract density information from the database of simulated GPR signals.

It should be noted that this paper shows part of the comprehensive research efforts into the application of GPR on asphalt pavement compaction monitoring, including computation simulation, laboratory experiments and field tests. The purposes of computation simulation are to study the effect of water content variation and effect of density variation on GPR signal and to develop algorithm to extract density without the effect of water. Laboratory experiments are conducted to calibrate the GPR data from simulation. Field data are collected to validate the algorithms. This paper mainly discusses the computation simulation work and part of the laboratory experiments that are used to calibrate the simulation results.

2. Technical background

2.1. Principle of GPR

GPR has a transmitting antenna and a receiving antenna. The transmitting antenna emits EM waves towards the ground and the receiving antenna receives the scattered EM waves. Scattered EM waves contain structure and material information, which can be obtained by proper analysis. There are two types of GPR antennae: (1) ground-coupled antenna and (2) air-coupled antenna. When applied in pavement engineering, the ground-coupled antenna requires surface contact with the pavement to be investigated. The air-coupled antenna is installed at a specific distance above the pavement, as shown in Fig. 1(a). It does not require surface contact and has a higher resolution compared with the ground-coupled antenna. It is therefore preferred to use air-coupled antennas for monitoring compaction. The most important material property for GPR applications is relative permittivity, or the dielectric constant, which represents the ability of material to polarize in response to an electric field. The dielectric constant can be obtained from amplitudes of reflected pulses. When the EM wave propagates through asphalt pavement, as shown in Fig. 1(b), part of the EM energy is reflected back at interfaces, such as the asphalt surface. The dielectric constant of an asphalt surface layer, ε_{AC}, can be calculated from the amplitudes of reflected pulses by using Eq. (1):

$$\varepsilon_{AC} = \left(\frac{A_p + A_o}{A_p - A_o}\right)^2 \tag{1}$$

where

ε_{AC}	dielectric constant of surface the asphalt layer,
A_o	amplitude of the surface reflection, and
A_p	plitude of the incident signal. A_p can be measured by placing a copper plate under the antenna because copper is a perfect reflector of GPR signal and will therefore reflect all GPR wave energy back to the receiving antenna.

2.2. EM mixing models

Asphalt material is a mixture of aggregate, binder, air, and, possibly, water. The bulk dielectric constant, or effective dielectric constant, of a mixture, ε_{eff}, is a function of the dielectric constant and volumetric properties of its components. Multiple EM mixing models can be used to describe the relationship between the dielectric constant of a mixture and its components. A modified Bottcher model, shown in Eq. (2), is used to describe this relationship in asphalt mixtures (Al-Qadi et al., 2010; Leng, 2011; Leng et al., 2011, 2012).

$$\frac{\varepsilon_{AC} - \varepsilon_b}{\varepsilon_{AC} + u\varepsilon_b + 2(\varepsilon_{AC} - \varepsilon_b)} = V_{se}\frac{\varepsilon_s - \varepsilon_b}{\varepsilon_s + u\varepsilon_b + 2(\varepsilon_{AC} - \varepsilon_b)} + V_a\frac{\varepsilon_a - \varepsilon_b}{\varepsilon_a + u\varepsilon_b + 2(\varepsilon_{AC} - \varepsilon_b)} \tag{2}$$

where

ε_{AC}	effective dielectric constant of asphalt mixture,
ε_b	dielectric constant of asphalt binder,
ε_s	dielectric constant of aggregate,
ε_a	dielectric constant of air, which is 1.0,
V_{se}	effective volumetric fraction of aggregate,
V_a	volumetric fraction of air, or air void content, and
u	shape factor (Behari, 2005).

The volumetric properties of asphalt mixture are shown in Eqs. (3) and (4):

$$V_a = 1 - \frac{G_{mb}}{G_{mm}} \tag{3}$$