JOURNAL OF TRAFFIC AND TRANSPORTATION ENGINEERING (ENGLISH EDITION) 2015; 2 (1): 30–39

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Original Research Paper

Representative volume element of asphalt pavement for electromagnetic measurements

Terhi Pellinen [a,*], Eeva Huuskonen-Snicker [a], Pekka Eskelinen [b], Pablo Olmos Martinez [a]

[a] Department of Civil and Environmental Engineering, Aalto University, Aalto 00076, Finland
[b] Department of Electrical Engineering and Automation, Aalto University, Aalto 00076, Finland

ARTICLE INFO

Article history:
Available online 13 January 2015

Keywords:
Asphalt
Dielectric constant
Permittivity
Vector Network Analyzer
Bulk density

ABSTRACT

The motivation for this study was to investigate the representative volume element (RVE) needed to correlate the nondestructive electromagnetic (EM) measurements with the conventional destructive asphalt pavement quality control measurements. A large pavement rehabilitation contract was used as the test site for the experiment. Pavement cores were drilled from the same locations where the stationary and continuous Ground Penetrating Radar (GPR) measurements were obtained. Laboratory measurements included testing the bulk density of cores using two methods, the surface-saturated dry method and determining bulk density by dimensions. Also, Vector Network Analyzer (VNA) and the through specimen transmission configuration were employed at microwave frequencies to measure the reference dielectric constant of cores using two different footprint areas and therefore volume elements. The RVE for EM measurements turns out to be frequency dependent; therefore in addition to being dependent on asphalt mixture type and method of obtaining bulk density, it is dependent on the resolution of the EM method used. Then, although the average bulk property results agreed with theoretical formulations of higher core air void content giving a lower dielectric constant, for the individual cores there was no correlation for the VNA measurements because the volume element seizes deviated. Similarly, GPR technique was unable to capture the spatial variation of pavement air voids measured from the 150-mm drill cores. More research is needed to determine the usable RVE for asphalt.

1. Introduction

Good compaction is needed for asphalt pavements to achieve good durability and long service life of the road. A traditional method for controlling the air void content is to drill cores randomly over the length of the road. The number of cores to be drilled depends on the paving area. Once the cores are in the laboratory, the air void content is determined using the appropriate standard such as EN, ASTM or AASHTO.

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* Corresponding author. Tel.: +358 505553790.
E-mail addresses: terhi.pellinen@aalto.fi (T. Pellinen), Eeva.huuskonen-snicker@aalto.fi (E. Huuskonen-Snicker), Pekka.eskelinen@aalto.fi (P. Eskelinen), Pablo.olmos.martinez@aalto.fi (P. Olmos Martinez).

Peer review under responsibility of Periodical Offices of Chang'an University.
http://dx.doi.org/10.1016/j.jtte.2015.01.003

Another method has emerged in recent years, which is based on non-destructive technique of using ground penetrating radar (GPR). The GPR measures the dielectric value of the asphalt pavement, which is then correlated to the air void content. Ground penetrating radars typically used are impulse radars initially developed to map the ground and therefore, the frequencies they are operating are typically less than 2.2 GHz. The GPR transmits electromagnetic (EM) waves into the ground and records the echo characteristics, such as amplitude and time delay. To obtain dielectric material property, ε_r', the measured electromagnetic quantities, amplitude (A) and phase (φ) must be converted to ε_r' via radar electronics calibration. This is usually done with metal plate. Principles of reflectivity calibration are explained in detail for example in research of Scheer (1983). Then, to obtain a conventional material property such as the density of material (ρ), another calibration is needed to correlate the physical measurements and the EM measurements. This is illustrated in Fig. 1.

The maximum density of mixture (ρ_m) is then measured and the air void content is calculated as the ratio of the asphalt pavement density (ρ_p) to the maximum density (ρ_m), see Eq. (1). A common way of doing this calibration in Finland is to drill a core and then correlate the measured air void content to the measured ε_r' of the pavement (Roimela, 1998; Saarenketo, 2009). It has been also suggested that only one or two cores are needed to do this calibration (Saarenketo and Scullion, 2000). Leng et al. (2011) recommended using two to three cores. Poikajärvi et al. (2012) concluded that more attention should be placed where the calibration core samples are drilled and they suggested taking cores when the asphalt mixture, the working method, base treatment or environmental circumstances change. They also suggested that thermal changes may exist which have influence on the signal strength and these changes should be taken into account in dielectric value calculations.

$$V_a = \left(1 - \frac{\rho_p}{\rho_m}\right) \cdot 100\% \tag{1}$$

The propagation and attenuation of the electromagnetic field depend on the electrical and magnetic properties of the medium which are electrical conductivity σ, dielectric permittivity ε and magnetic permeability μ (Annan, 2003). This study focuses on the permittivity as magnetic properties for the aggregates used which can be neglected. Permittivity ε^* is a complex variable.

$$\varepsilon^* = \varepsilon_0 \varepsilon_r = \varepsilon_0 \left(\varepsilon_r' + j\varepsilon_r''\right) \tag{2}$$

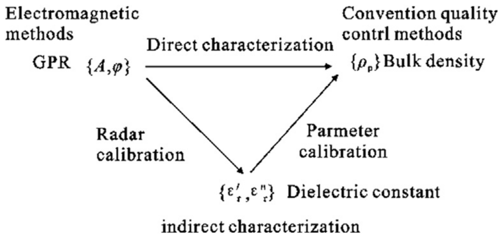

Fig. 1 – Schematic presentation of material characterization for EM measurements.

where ε_0 is the permittivity of free space, ε_r is relative permittivity of material, ε_r' is real part of relative permittivity and ε_r'' is imaginary part of relative permittivity. Real part of frequency dependent relative permittivity describes the stored energy and imaginary part accounts for energy losses.

The motivation for this study was to investigate the viability of using only one core for GPR calibration. Field experiments were conducted in the summer of 2013 in real conditions on highway Vt3 in Finland, near the City of Tampere. The test road had 2-lanes for one direction and road was paved with the Stone Mastic Asphalt mixture SMA 16. Road was overlaid with 40 mm thick new pavement layer. A total of 27 cores were obtained from the road and tested in the laboratory for the air void contents. To obtain a reference or a base line measurement, independent of the GPR, the in-situ GPR measurements were compared with the Vector Network Analyzer (VNA) measurements conducted in the laboratory of electrical engineering. The vector network analysis is a method of accurately characterizing signal deformations by measuring their effect on the amplitude and phase of swept-frequency test signals. The VNA measurements can then be considered giving the "true" permittivity values and therefore they give the baseline to evaluate the GPR measuring technique. The VNA used in this research was the model "Wiltron 360 Network Analyzer" and transmission through the sample was used. In this paper the phrase asphalt is used referring to the hot-mix asphalt or asphalt concrete mixture/pavement following the European convention.

2. Bulk properties versus RVE

2.1. *GRP measuring principle*

The nominal center frequency of the typical GPRs is usually less than 2.2 GHz and as the beam width is proportional to the antenna opening the GPR with 2.2 GHz covers ca. 300 mm × 300 mm area of pavement. The depth resolution depends also on the frequency and for 2.2 GHz the theoretical wavelength of the signal is 136 mm in the air. The total thickness of bound asphalt concrete layers can range from 50 to more than 200 mm depending on road classification and traffic volumes. At low volume roads where the asphalt concrete thickness is less than 120 mm, depth resolution may then reach down to unbound aggregate base layers. For thin asphalt layers, the dielectric constant of asphalt is obtained from the signal reflecting from the surface as is shown in Fig. 2. Depending on the attenuation of the signal, there is then the possibility that multiple depth reflections are recorded (Loulizi et al., 2003; Loizos and Plati, 2007; Lahouar and Al-Qadi, 2008). Therefore, the measured ε_r' is a volume "bulk property" for the asphalt as Fig. 2 illustrates.

When a core is drilled from the asphalt pavement, it represents a discrete point measurement. Then, depending on the homogeneity of the pavement, the antenna foot print of 300 mm × 300 mm may cover variable material properties. Therefore, a representative volume element (RVE) must be determined to quantify this variation for the assessment of paved road quality.