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Virtual Special Issue
Ground-Penetrating Radar and Complementary Non-Destructive Testing Techniques in Civil Engineering

Comparison of different radar technologies and frequencies for road pavement evaluation

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HIGHLIGHTS

- Study explores on real life situation on road trying to quantify the surface porosity of asphalt.
- Results shows importance of representative volume element.
- Results shows the sensitivity of measurements on aggregate permittivity variation.
- As an outcome, aggregate permittivity variation masks the porosity variation.

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ABSTRACT

Experimental asphalt pavement field measurements have been performed with a commercial Ground Penetrating Radar (GPR) system and with three dedicated, new prototype radars operating at 1–2 GHz, 12–18 GHz and 32 GHz frequency. The aim of these measurements is to find the surface or near-surface permittivity of worn asphalt and to investigate the suitability of various radar technologies for this task. Our experiments were supplemented by drill core samples extracted at selected interesting locations on a test road. As expected, there is hardly any correlation between the results of the four different radars along the same test track, and drill core results complicate the situation further. Taking 10 and 90 percentile cumulative probabilities, the commercial GPR data has the smallest ε_r' span from 5 to 5.6, the 1–2 GHz prototype system indicates ε_r' between 4.5 and 5.5, our 12–18 GHz system 4.5 to 6.5 and the 32 GHz fixed frequency reflectometer 2.5–4.5. Only the 32 GHz measurements show clearly different mean permittivity values for the visually different pavement surfaces. Test results, however, suggest that extracting air void variation from highly inhomogenous asphalt pavement needs stochastic approach instead of trying to do some deterministic calibrations with pavement cores.

1. Introduction

Non-destructive and non-contacting pavement quality analysis has been carried out in production use with Ground Penetrating Radar (GPR) systems for about 20 years. Some of the first practical implementations are documented in Maser and Scullion [1] Chen et al. [2]. Typical measurements have included studies of compaction ratio [3] and asphalt layer thickness. More recently, new methods for in situ asphalt mixture density prediction have been evaluated [4]. Most of these parameters are post-processed from radar pulse reflection amplitudes observed at permittivity discontinuities [5] and propagation time delays, often computed from raw data with sophisticated software packages. Measurements with contacting dielectric probes have also been tested at low VHF frequencies [6], but those methods are seldom suitable for long road surveys.

In a number of countries, including Finland, GPR road measurements have become routine. More recently, for example in Fauchard et al. [8], research has indicated concerns regarding the obtainable uncertainty of relative permittivity and depth resolution with GPR devices when employing them in applications for thin pavement surface layers. The GPR has been used, for instance

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in Finland, to gather quantitative data for quality control measurements to assess pavement compaction and density. Also, radar calibration procedures have aroused discussion, see for example Scheer [9] and Knott et al. [10].

Another important issue is the effect of pavement rock characteristics [11] on the permittivity of asphalt. The variation of the permittivity of rock aggregate in asphalt may mask the variation of porosity. This may prevent meaningful quality measurements. Asphalt is a granular composite material composed of aggregate, bitumen and air. Therefore, the permittivity of asphalt is the effective bulk permittivity of all these constituents. As such, the volume of air or porosity is hard to detect or measure, as it only constitutes less than ten percent of the total volume. Consequently, spatial resolution is crucial for obtaining meaningful results. Authors have studied this issue extensively [20,21,23–28] but a reasonably accurate model to predict the relative effective bulk permittivity of asphalt volume is yet to be developed. The need to develop such a model is thus the primary motivation for these measurements and the experiment. Even though we have used frequencies as high as 32 GHz and have selected the pavement test sites based on visual observations of surface conditions, the intent is not to gather information of the surface characteristics per se, but from the bulk volume of asphalt.

Interesting studies, mainly at the very high frequency of 94 GHz, have been made in Sarabandi et al. [12], where the authors have developed a theoretical model and performed reflectivity measurements of real asphalt, but mostly with grazing angles, which are applicable to automotive anti-collision radars. Results are thus not directly suitable for the problem in our experiments. However, the general problem of road layer structure and granularity of medium is identical.

The purpose of the measurements presented here was to evaluate the suitability and general performance of different radar technologies and frequency bands for road pavement quality assessment analysis, possibly even as a multi-radar configuration. The frequency band of 1–32 GHz has been chosen in order to investigate the effect of the frequency on the spatial resolution of the radar's performance. Studies on this issue [19,22] clearly indicate the importance of using higher frequencies to confine the radar pulse to the upper asphalt layers to obtain the density of the 40–50 mm thick surface layer. However, when using high frequencies, the radar is sensitive to the granularity of the material, which distorts measurement results in this particular case. Therefore, a compromise may be needed in choosing the best frequency range for the measurements.

2. Test road

The total length of our test road is 275 m divided into four consecutive visually different pavement sections, later labeled from A to D. Visual differences suggest changes in material composition, which in turn translate to differences in mechanical and electrical properties. The pavement of section A is more than 10 years old whereas section B was re-paved in 2014. Sections C and D are part of an old 1970s highway, but their pavement ages are unknown. No accurate mix design data of the constructional characteristics was available for this evaluation, but drill core samples were extracted during our campaign at selected points. Our measurement path was about 0.2 m to the right from the actual right wheel path and this distance was easily maintained constant with the help of the white edge road marking. All measurements were performed in warm, dry summer weather to minimize possible water-related erroneous results [13]. However, possible bound water effects [14] in the aggregate minerals could not be excluded. Only one radar device was used at a time to minimize the risk of radio frequency interference.

3. Radar equipment

Four different radar systems, having varying frequency ranges and operating principles, were used. Taking into account the known physical and electrical properties of asphalt pavement, it was clear from the very beginning that high microwave and millimeter wave frequencies would certainly behave differently to, say, typical L-band, but in this experiment we wanted to get initial real-life measurement data at this higher band and at the same time test if it is possible to create background data for some kind of sensor fusion. If feasible, such a process might help in improving the permittivity and thickness measurements of thin asphalt layers, tasks where current GPR systems have caused some concern. Standard commercial 2 GHz GPR data, obtained with SIR-30 system from GSSI Inc (USA) was selected as reference for the remaining three devices. Main GPR parameters were as follows: measurement time 20 ns, sweep count 1024 samples, sweep rate 500 scans/s, data width 32 bits.

This GPR has similar impulse characteristics to those normally used in Finland for road pavement analysis. The actual GPR measurement was performed simultaneously with our experiments by a company and only post-processed permittivity values were submitted to us.

Our own laboratory-built radars in this study are (a) a continuous-wave frequency sweeping (FMCW) 1–2 GHz system, partly similar to Zych [15], (b) a 12–18 GHz FM device described in detail in Huuskonen-Snicker et al. [16] and (c) a 32 GHz fixed frequency system. Both the 1–2 GHz and 12–18 GHz devices utilize inverse FFT to get the time domain reflection response of the pavement surface. After this, basic reflection coefficient calculus, Eq. (1) [5] is applied to get the air-asphalt interface permittivity at the correct time window, the location of which in our laboratory radars is currently defined manually from the raw IFFT plot.

$$\varepsilon_r' = \left[\frac{1 + A_r/A_0}{1 - A_r/A_0}\right]^2 \tag{1}$$

where

A_0 incident amplitude
A_r reflected amplitude
ε_r' permittivity of asphalt

An aluminum alloy sheet (its reflection coefficient assumed to be -1) and polyoxymethylene (POM) block (permittivity 2.85) serve as reference materials. The desired high attenuation in asphalt (about 20 dB/5 cm) at 32 GHz enables here direct reflectometer measurement without any time gating. Besides the frequency range, the main difference between 1 and 2 GHz and 12–18 GHz systems is in their detectors [17], which convert the reflected radio frequency energy into signals suitable for analog-to-digital conversion, which is followed by computer data acquisition. We use a comprehensive IQ-method (In phase – Quadrature phase) at 1–2 GHz but a cheaper and simpler amplitude/cosine-of-phase in the 12–18 GHz device.

In I/Q-detection, a sample of the momentary transmitted sine wave is fed to the local oscillator (LO) input ports of two identical balanced mixers. The first mixer gets its LO directly, but to the second it goes through a 90 degree phase shift. The received signal from the road goes from a two-way power splitter to the radio frequency (RF) ports of the same mixers. In this way, the strongly low-pass filtered intermediate frequency (IF) outputs of those mixers are two direct current (DC) voltages, the first being proportional to the real part of the received signal and the second to