Ground Penetrating Radar used for Detecting Deterioration and Voids & Determining Pavement Layer Thickness and Moisture Content

1. Ground Penetrating Radar Theory

High resolution, ground penetrating radar operates in a manner that is analogous to acoustic sounding. A short pulse, high resolution, ground penetrating radar emits precisely timed, very short radio frequency (RF) pulses of low power, repeated at a very high rate. The transmitted pulse is radiated downward by the radar antenna into the ground and a portion of the RF energy is reflected wherever there exists a change or discontinuity in the propagation medium. The remaining energy is coupled through the boundary. The amplitude of the reflected signal and its complement passing through a boundary depend on the difference between the relative dielectric constants of the materials at the boundary. RF reflections or radar target echoes are picked up by the antenna, coupled into the receiver and processed for display, recording and detection.

2. Deterioration Detection

Several types of deterioration are known to occur in PCC pavement, however, in continuously reinforced pavement (CRP), transverse cracking and the deterioration that is sometimes associated with this cracking is often prevalent. Unlike many other inspection methods, GPR detects deteriorated concrete not from the mechanical properties of the concrete but rather from changes in electrical properties as the concrete deteriorates. Based on this principle, GPR technology can be useful in evaluation of CRP, both exposed concrete pavement and those pavements with an asphalt riding surface. It is known that transverse cracking is common in CRP. However, with heavy traffic volume and exposure to environment, deterioration of concrete in the vicinity of the transverse cracks can occur. This deterioration is enhanced in the presence of water and chlorides and especially in climates where concrete freeze/thaw can occur. To GPR, this represents a discontinuity in the concrete medium from which part of the transmitted electromagnetic signal is reflected and is typically revealed by a change in reflectivity at the overlay to concrete interface.

3. Detection of Water Filled Voids

Voids result from various reasons, including settlement or movement in base materials or loss of bond between two layers. With GPR, voids can be characterized by the reflected energy resulting from the air gap, or thin moisture layer (in the case of a water filled void). The GPR response to a water filled void is similar to a highly saturated base layer and are detected in a similar manner. The water filled void is modeled as a two layer media with the second layer as water. Using the top-down calculation method water filled voids can be identified based on the known dielectric constant of water. A simulated waveform from a water filled void is shown in Figure (1).

![Simulated GPR Waveform from 6 inch Concrete Slab Over Base Material with Varying Moisture Level. Concrete permittivity is 9 and base dielectric varies as 12, 15, 18, 24, 50 and 80](image)

Figure 1.
GPR waveform showing the effect of variable moisture level in a concrete base material on signal amplitude.

4. Pavement Layer Thickness

Thickness of materials can be determined by measuring the time required for the radar wave to travel through the material (transit time), and knowledge of the velocity at which it travels, (propagation velocity). Echoes occurring at the top and bottom surfaces of a material layer provide a measure of the signal transit time through the material, and the dielectric constant of the material, which is based on reflected signal amplitude measurement, determines the wave velocity. With these measurements, GPR is able to measure the thickness of solid materials. This follows the basic
Pavement Layer Thickness
Detection of Moisture Content

equation for distance measurement as given in equation (1).

\[ x = v \times t \]  

(1)

where

\[ x = \text{distance} \]
\[ v = \text{velocity of radar wave in the medium} \]
\[ t = \text{two way transit time of radar wave to object} \]

Two way transit time is derived through a direct measurement of the radar signal which is measured in nanoseconds. This first involves identification of the echoes resulting from the interface corresponding to the top and bottom of the layer and measurement of the time difference. The velocity of the radar wave requires knowledge of the material dielectric constant (or electrical impedance) since velocity is inversely related to the square root of the dielectric constant. Pavement layer thickness, as measured by a ground penetrating radar is then given by equation (2).

\[ x = \frac{c \times t}{2 \times \sqrt{\varepsilon}} \]  

(2)

where

\[ x = \text{distance} \]
\[ c = \text{velocity of light} \]
\[ \varepsilon = \text{relative dielectric constant of material} \]

5. Moisture Determination

The moisture content of an underlying layer can be determined based upon its relative dielectric properties. With the introduction of water, (with a dielectric constant of 81) into a dry material the dielectric constant of the material necessarily increases in relation to the volume of water introduced. For instance, the relative dielectric constant of dry concrete material ranges of 6 to 9 depending on aggregate. When this concrete is water saturated the dielectric value can increase significantly to a range of 16 to 20. The volume of water retained in a material depends on its porosity and is also based on physical condition. While the porosity of the material may not be known it is expected that some water absorption will occur when water is present. Equation (3) is a simplified equation (assumes nonferromagnetic materials) which defines the reflection coefficient of an electromagnetic wave at a dielectric interface between two material layers. A graphical representation of reflection coefficient-vs-dielectric constant is shown in Figure (2). As the relative dielectric constant of the lower material increases it can be seen that the magnitude of the reflection coefficient increases. Materials with high moisture concentration produce larger radar reflections and can thereby be characterized by their reflectivity. This can be seen as an increase in the radar signal reflected from an interface.

\[ \rho = \frac{\sqrt{\varepsilon_{rn+1}} - \sqrt{\varepsilon_{rn}}}{\sqrt{\varepsilon_{rn+1}} + \sqrt{\varepsilon_{rn}}} = \frac{V_r}{V_i} \]  

(3)

where

\[ \rho = \text{reflection coefficient} \]
\[ \varepsilon_{rn+1} = \text{relative dielectric constant of lower material} \]
\[ \varepsilon_{rn} = \text{relative dielectric constant of upper material} \]
\[ V_r = \text{magnitude of reflected signal from interface} \]
\[ V_i = \text{magnitude of incident signal at interface} \]

In practice, areas of high moisture can be identified by calculation of the dielectric constant. Using a top-down calculation technique the dielectric constant of successively deeper layers are determined.