Technical Note 0301

Effect of Water and Temperature on Hot Mix Asphalt Density Measurement using Electromagnetic Sensing

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A number of electromagnetic sensors have been applied in various contexts related to Hot Mix Asphalt construction and characterization. Ground penetrating radar (GPR) is used to profile the thickness of existing pavements. Time domain reflectometry is used to measure soil and/or asphalt density by measurement of the electromagnetic propagation velocity in the medium. Other sensors, such as TransTech Systems Pavement Quality Indicator (PQI), assess density by measurement of the complex impedance of the asphalt.

The macroscopic interactions of electromagnetic fields with materials are described by Maxwell's equations. Solution of Maxwell's equations requires knowledge of three constitutive properties of the material: the magnetic permeability, the dielectric permittivity, and the conductivity. In general, these parameters are dependent upon material properties, material temperature, and frequency of the applied field. For asphalt, the permeability is nearly that of free space and the conductivity is nearly zero. As a result, the electromagnetic response of asphalt is determined primarily by dielectric properties. The constitutive relation describing the electromagnetic response of a dielectric material is

$$\vec{D} = \varepsilon_0 \vec{E} + \vec{P} \tag{1}$$

where D is the electric displacement vector, E is the applied electric field, P is the induced polarization and ε_0 is the permittivity of free space. For linear, isotropic materials, such as asphalt, the induced polarization is proportional to the applied field

$$\vec{P} = \chi \varepsilon_0 \vec{E} \tag{2}$$

where χ is called the electric susceptibility. Substituting this into Eq. 1 yields

$$\vec{D} = \varepsilon_0 (1 + \chi) \vec{E} = \varepsilon_r \varepsilon_0 \vec{E} \tag{3}$$

where ε_r is referred to as the relative permittivity or dielectric constant. As an example, air has a relative permittivity of = 1, distilled water has a relative permittivity of 80 at room temperature, asphalt is ~3 and granite is 3-5.

The polarization of a dielectric material due to an externally applied electric field may occur as a result of three molecular level dipole effects: (1) electronic polarization; (2) ionic polarization, and (3) orientational polarization. All three effects are in general functions of the frequency of the applied field, and the material temperature. The dielectric constant of a pure material as a function of frequency is described by Debye's equation.

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \tag{4}$$

where

$$\varepsilon_r' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + \left(f \big/ f_r \right)^2} \qquad (5)$$

and

$$\varepsilon_r'' = \frac{(\varepsilon_s - \varepsilon_\infty) f \big/ f_r}{1 + \left(f \big/ f_r \right)^2} \qquad (6)$$

where ε_s is the permittivity as f goes to 0, ε_∞ is the permittivity as the frequency goes to infinity, f_r is the relaxation frequency, and f is the applied frequency. The three parameters $\varepsilon_s, \varepsilon_\infty$ and f_r are properties of the material. The real part of the dielectric constant is a measure of how much energy from an external electric field is stored in the material and the imaginary part is a measure of how dissipative or lossy a material is to an external electric field.

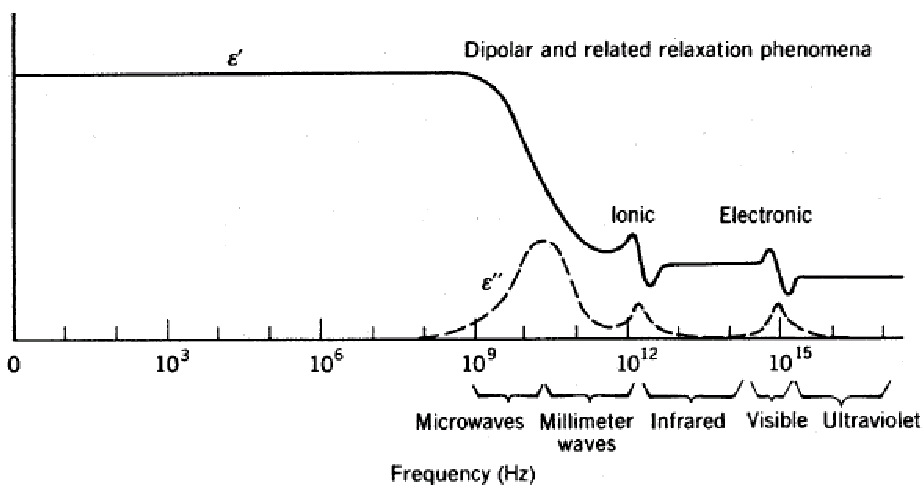

Figure 1. Typical Frequency Response of the Dielectric Constant of a Pure Material

Figure 1 shows the frequency response of the real and imaginary parts of the dielectric constant for a typical pure material (from [1]). Of note is that the permittivity of pure materials is constant from zero frequency (DC) up to over 1 GHz (10^9 Hz).

Dielectric Properties of Asphalt Constituents

Asphalt is typically characterized as a four-phase system consisting of asphalt cement, aggregate, air, and small amounts of water. The dielectric permittivity of air is approximately equal to 1.0 (i.e. no polarization in a free space). The conductivity of air is equal to zero. Solid particles in the aggregate are non-polar materials. Their dielectric polarization is only due to electronic and ionic polarization mechanisms, which have relaxation frequencies above 1 THz (10^{12} Hz). Therefore, they have a low value of dielectric permittivity (~5), and are nearly lossless, independent of frequency and temperature at frequencies less than 1 THz. The conductivity of asphalt cement is also equal to zero and the dielectric constant is ~2.8. For polar materials, such as water, the dipolar polarization adds to the electronic and ionic polarization, resulting in a much higher value of dielectric permittivity. With strongly polar molecules such as water, increasing temperature tends to depolarize the material due to increased molecular motion. The dielectric constant of water is found to strongly decrease with increasing temperature. For example, the dielectric constant of water is 78.5 at 25°C and ~48 at paving temperatures of ~150°C.

Dielectric Properties of Asphalt

Many researchers [2,3] have found empirically that the dielectric constant of a multiconstituent material matrix is proportional to the volume fractions and dielectric constants of the matrix constituents according to an empirically derived dielectric mixing equation

$$\varepsilon_{comp} = \left(\sum_{1}^{n} \nu_n \varepsilon_{rn}^{\alpha} \right)^{\alpha} \tag{7}$$

where the ε_{rn} are dielectric constants of the constituents and ν_n terms are their volume fractions. The α term is an empirically determined constant which is different for each matrix and which accounts for interfacial dielectric polarization effects. The value of α has been found to be equal to nearly 0.5 for many engineering materials, such as soil. An empirical dielectric mixing formula specific for asphalt has been determined by Subedi [4]. In this formula the interfacial quantities are encapsulated in cross terms

$$\varepsilon_{comp} = \left(\sum_{1}^{n} \nu_n \varepsilon_{rn}^{\alpha} \right)^{\alpha} + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \nu_i \nu_j \left(\left| \varepsilon_{ri} - \varepsilon_{rj} \right| \right) \tag{8}$$

Empirical results show agreement between this formula and the measured values for asphalt is within 3%.

The above equation was programmed into a spreadsheet to assess the sensitivity of the composite dielectric constant to the volume fraction of water and to temperature. A typical mix was used with 86% aggregate, 9% asphalt, 3% air, and 2% water. The dielectric constants used were air = 1, asphalt = 2.8, and aggregate = 4. A standard formula was used for the dielectric constant of water as a function of temperature

$$\varepsilon_w = 78.54(1 - 0.004579(T - 25)) + 0.0000119(T - 25)^2 \qquad (9)$$

where T is the temperature in °C.

The results predicted from the asphalt equation show that the temperature coefficient of the dielectric constant of a mix containing 2% water is –1% per 20°F for a typical paving temperature of 300°F. This corresponds to –1.5 pcf (pounds per cubic foot) per 20°F for the mix described. In practice the temperature compensation required has been found to be less than predicted using equations 8 and 9. This can be explained by noting that Eq. 9 is true for free water. In most engineering materials, such as asphalt, soil, or concrete, part of the water will exist as bound or adsorbed water while part may be free water. Adsorbed water, due to forces binding the water to the surface of the solid particles, will be less easily depolarized by increasing temperature. Therefore the change in permittivity per change in temperature will be less than for free water. However since it is common in practice to measure asphalt mats during or after rolling as well as after cooling. This represents a change of ~200°F. Over this temperature range, errors of 2 pcf will be observed without temperature compensation.

Reducing the water content from 2% to 1% (still at 300°F) results in a change in the dielectric constant by –16%. This change corresponds to –24 pcf. Therefore temperature and water content must be accounted for in the measurement of asphalt density where accuracies of the order of ± 1.5 pcf are specified.

Controlled studies conducted by Turner-Fairbank Highway Research Center [5] and others have confirmed the need for correction for asphalt temperature and water content when making density measurements with devices that depend on the dielectric properties of the material for the measurement.

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