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TRANSTECH SYSTEMS, INC.

PQI and SDG Technology Technical White Paper

Our flagship product, the PQI, is what put TransTech Systems on the map. The PQI is our NON-NUCLEAR pavement density gauge. Precise pavement density measurement almost instantly (3 seconds). The PQI is more accurate than the nuclear gauge but without the hassle of regulatory training and certification. There is no radiation threat with our product, which means after a day of work, just place it in your truck and you're done.

Technical White Paper on TransTech's PQI and SDG Technology

TransTech Systems is an instrument company that develops innovative and nondestructive evaluation products for the construction industry, all of which are based on our core platform technology. This technology utilizes an electromagnetic impedance-based approach, which is used in sensor system development (sensor design and measurement board development), signal processing and inverse model/algorithm development. The technology enables the use of single frequency measurements, as in the case of the Pavement Quality Indicator (PQI), and multifrequency sweep measurements (spectroscopy), which is how the Soil Density Gauge (SDG) operates, depending on the application. The basic technical premise is that, as you increase compaction by removing the amount of air within a volume of asphalt or soil with a roller, the bulk dielectric constant of the material will increase, since air has a dielectric constant of 1 and the other materials are in the 2-80 range (aggregate, binder, and water). For the PQI, as density increases, the measured bulk dielectric constant increases and a linear or non-linear correlation relationship is developed based upon coefficients developed in the lab for known asphalt stone sizes over an expected compaction range [1]. For the SDG, as density increases, the measured bulk dielectric constant increases and a correlation can be developed for various soil types over an expected compaction range that utilizes a proprietary real time analytical treatment of the data for determining the density and moisture contents [2].

The Pavement Quality Indicator (PQI)

The PQI was introduced over 20 years ago as a way to measure the density of joints made by one of TransTech's original products, the Notched Wedge Joint Maker. It became clear fairly quickly that a non-nuclear method for measuring asphalt density was an intriguing idea that was gaining momentum in the industry. The development of the PQI was funded internally as well as with funding from the NCHRP IDEA program, the U.S. Army Corps of Engineers and the New York State Energy Research and Development Authority. The device continues to be upgraded and a fourth generation Model 380 has been available since 2010 (Figure 1).

Figure 1. History of PQI Development

In general, as stated above, the technology used in the Pavement Quality Indicator (PQI) is electromagnetic impedance-based. The PQI (ASTM D7113-05, AASHTO T343-12) applies a constant voltage at a single frequency to an insulated, planar concentric ring sensor to take in-situ measurements of the pavement's dielectric properties (Figure 2). Changes in the pavement's density change the dielectric properties measured by the sensor. Using a parallel plate equation, which takes into account the electrode area and distance between electrodes, the

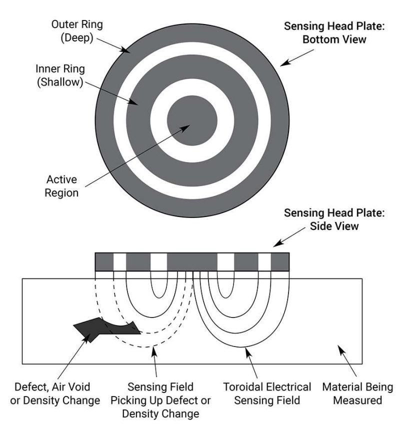

Figure 2. PQI Concentric Ring Sensor Geometry

dielectric constant is directly related to the measured capacitance. The same is true for the PQI sensor when using a modified coplanar waveguide model, except in this case, the PQI sensor's geometry and a hyperbolic sine function are utilized.

The PQI has two sensing electrodes that provide the average density at one of two fixed depths. Using the average dielectric properties in the measured volume, an inverse algorithm may utilize linear or non-linear regression analysis based upon coefficients developed in the lab for known asphalt stone sizes across varying field conditions, i.e., density ranges.

PQI Technical Background: A number of electromagnetic sensors have been applied in various contexts to determine the moisture content and/or density of engineering materials, such as asphalt or soil. For example, Time Domain Reflectometry (TDR) is used to measure soil density by measurement of the electromagnetic propagation velocity in the medium [3]. Other sensors, such as TransTech Systems' Pavement Quality Indicator (PQI), assess density by measurement of the complex impedance of the material and rely on Maxwell's fundamental equations.

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 fresh asphalt, the permeability is nearly that of free space and the conductivity is extremely low. For low conductivities it has been found that conductivity is independent of frequency out into the GHz range. 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

$$\vec{D} = \varepsilon_0 \vec{E} + \vec{P} \qquad (1)$$

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

$$\vec{P} = \chi \varepsilon_0 \vec{E} \qquad (2)$$

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

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

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, and typical aggregate solids are in the 3-5 range [4].

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.

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \qquad (4)$$

where

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

and

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

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 (permittivity) and the imaginary part is a measure of how dissipative a material is to an external electric field (conductivity).

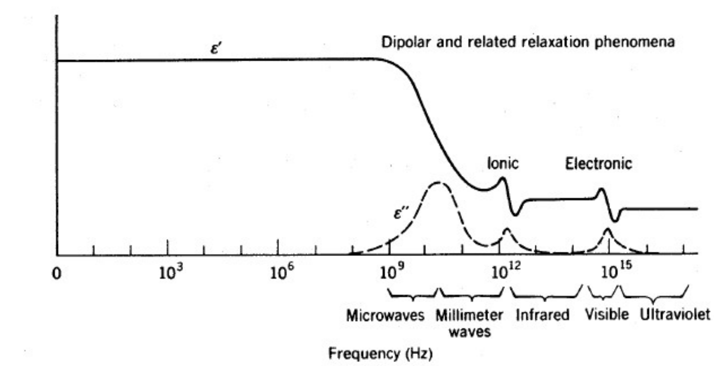

Figure 3: Typical Frequency Response of the Dielectric Constant of a Pure Material

Figure 3 shows the frequency response of the real and imaginary parts of the dielectric constant for a typical pure material. Of note is that the permittivity of pure materials is constant from zero frequency (DC) up to over 1 GHz (10^9 Hz) [4].

Dielectric Properties of Asphalt Concrete (AC): Asphalt concrete is a heterogeneous mixture consisting of four components; aggregate, binder, air, and small amounts of water. The dielectric property of each pure AC constituent can be described by the dielectric mechanisms shown earlier. At frequencies below the microwave region, the dielectric permittivity of the aggregate materials is almost independent of frequency. A mixture of non-polar constituents will exhibit a composite permittivity that is proportional to the volume fraction and dielectric constant of each component. Many researchers have shown that the dielectric constant of solid matrices, such as soil or AC, is found to be proportional to the volume fractions and dielectric constants of the matrix constituents according to an empirically derived dielectric mixing equation

$$k = \left(\theta \times k^{\alpha}{}_{w} + (1-\eta) \times k^{\alpha}{}_{s} + (\eta - \theta) \times k^{\alpha}{}_{a}\right)^{1/\alpha} \tag{7}$$

where the k_n are dielectric constants of the constituents and the multiplicative terms are the volume fractions of the constituents. The α term is an empirically determined constant which is different for each matrix and which accounts for interfacial polarization effects.

Typical values for the dielectric constants of the AC constituents are aggregate (3-5), binder (2.8), air (1), and water (80). Although water is not a part of the mix design for AC, it can be present in the form of water trapped in the aggregate or water remaining after drying the aggregate in the AC plant. It may also be present during paving due to water sprayed on roller drums. Water, if present, must be taken into account due to its very high dielectric constant compared to the other constituents. TransTech addresses this by utilizing a higher frequency than our original PQI and using a temperature and moisture correction in our proprietary algorithm.

The process of compaction displaces air in any volume with aggregate and binder. In accordance with the equation above, the measured dielectric constant will rise as the volume fractions of the materials with the higher dielectric constants are increasing.

One method of measuring the dielectric constant of a material is to place the material between two conducting metal plates to form an electrical capacitor. If no dissipative materials are present (e.g., conductive water), the total impedance will be equal to the capacitive impedance. Changes in AC density change the dielectric constant of the medium between the capacitor plates. The resultant measured capacitance is increased in proportion to the change in dielectric constant (*k*) according to the textbook equation for parallel plate capacitors

$$C = \frac{k \varepsilon_0 A}{d} \tag{8}$$

where C is the measured capacitance, A is the area of the plates, d is the plate separation, ε_0 is the permittivity of free space, and k is the dielectric constant.

The TransTech Systems Pavement Quality Indicator (PQI) operates by measurement of the complex permittivity of the AC at a frequency of 13.65MHz. As previously stated, the real part of the complex permittivity is the dielectric constant and the imaginary part is related to conductivity due to water containing dissolved ions. The real part is processed through calibration constants and a suitable mathematical algorithm to produce the density estimate. The imaginary part can be used to develop an indication to the operator that moisture may be present that may cause the density reading to be in error, allowing them to move the gauge to a different location free of water. [4].

The Soil Density Gauge (SDG)

While the Pavement Quality Indicator, PQI, and the Soil Density Gauge (ASTM D7830), SDG, appear very similar, there are a number of basic differences, as shown in Table 1. Other aspects of the two units are virtually identical as far as the hardware requirements. The remaining differences are in the software used to provide the user interface and the algorithms necessary to compute the output parameters.

Table 1. Comparison of the Major Differences between the PQI and SDG

Requirement	PQI – Asphalt Gauge	SDG – Soil Gauge
Control of Depth Measurement	Required to have control over the depth of measurement to match the depth of the new layer of asphalt. PQI has two depth ranges with two receiver sensors.	Required to have a single depth of measurement adequate to match the reading from a nuclear density gauge. SDG has a single receiver sensor.
Measurement Requirement	Required to measure changes in the impedance of an engineered material that acts like a pure capacitor in order to determine the density. Required to be insensitive to surface water from rollers.	Required to measure changes in the impedance of a natural material that has a complex response due to the presence of water in order to determine the wet density and moisture level. Required to measure water present within the soil.
Electronics Requirement	Required to operate only at a single frequency and to record data from two receiver sensors. Multiple frequency operation is possible but not necessary.	Required to operate over a range of frequencies to provide the impedance spectrum of the soil and to record data from one receiver sensor.
Contacting/Non-Contacting	Currently contacting but has been shown to be able to operate in a non-contacting mode.	Required to operate in a non-contacting mode as a means to compensate for variable surface effects.

The key difference is the SDG's ability to take a spectrographic reading of the impedance over a range of frequencies from 300kHz to 40MHz. The use of a multi-frequency sweep permits the SDG to separate the effects of the variations of density and moisture. TransTech utilizes a novel electromagnetic impedance-based technical approach in its line of density gauges to measure the dielectric constant of typical construction site soils. The basic technical premise is that, as you increase compaction by removing the amount of air within a volume of soil with a roller, the bulk dielectric constant of the aggregate and water will increase, since air has a dielectric constant of 1 and the other materials are in the 3-80 range. Therefore, as density increases, the measured bulk dielectric constant increases and a correlation can be developed for various soil types over an expected compaction range that utilizes a proprietary real time analytical treatment of the data for determining the moisture content. The development of the SDG was funded internally as well as with funding from the New York State Energy Research and Development Authority (NYSERDA), New York State Gas Association (Keyspan, ConEd, Questar), Brooklyn Union Gas, and the Department of Homeland Security Advanced Research Projects Agency.

A qualitative representation of the dielectric properties of moist soil is presented in Figure 4. The dielectric spectrum can be roughly divided into two parts, with the dividing frequency at about 20-50 MHz. The higher frequencies are dominated by the bound water relaxation and the lower frequencies are dominated by the Maxwell-Wagner (M-W) relaxation effect.

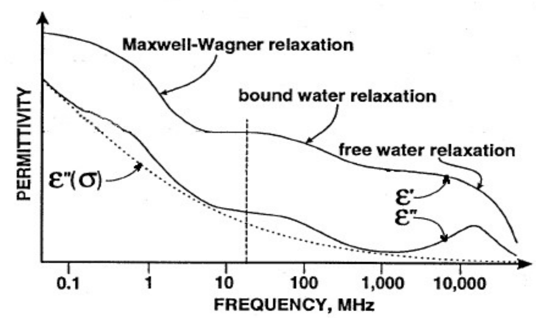

Figure 4. Dielectric Spectrum of Soil (adapted from Hilhorst, 1998)

During soil compaction, the volume fraction of the air is reduced, which results in an increase in the measured dielectric constant of the mixture, all other factors being equal. Thus, the measured real part of the permittivity is proportional to the density of the soil matrix at frequencies above the M-W region and below the water relaxation regions (~20-50 MHz). The real and imaginary parts of the measured permittivity vary in a complex way with frequency in the M-W frequency region primarily due to soil moisture, conductivity, the specific surface area of the soil solids, and the bound water fraction. The theoretical approach for utilizing a multifrequency sweep for the measurement of density and moisture of compacted engineering soils is described below.

Dielectric Mixing Equations: As described earlier for asphalt, the macroscopic interaction of electromagnetic fields with materials is 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 electrical conductivity. In general, these parameters are dependent upon material composition, temperature, and the frequency of the applied field. As the permeability of typical soils is nearly that of free space, the soil electromagnetic response is usually dominated by the dielectric properties.

Soil is a mixture of essentially three components: air, stone, and water, with water acting to help bind the stone matrix together. Some researchers have shown that the matrix bulk dielectric constant may be derived from the volume fractions and dielectric constants of the constituents according to the following empirically derived soil dielectric mixing equation, previously shown in Equation 7:

$$k = \left[\theta k_w{}^{\alpha} + (1-\eta)k_s{}^{\alpha} + (\eta-\theta)k_a{}^{\alpha}\right]^{1/\alpha}$$

Here, k is the bulk dielectric constant; k_w, k_s, k_a are the respective dielectric constants of water, stone, and air; θ is the volume fraction of water; η is the porosity (so that $1-\eta$ is the volume fraction of stone, and $\eta-\theta$ is the volume fraction of air); and α is an empirically determined constant, different for each soil matrix [5,6]. For sandy type soil matrices, $\alpha = 0.46$ has been found to be typical [6]. Typical values for the component permittivity are: $k_s = 3-5$, $k_w = 80$, and $k_a = 1$. As compaction increases, porosity decreases; the k_s term drives k upward, while the k_a term drives downward, but because $k_s > k_a$, the net effect is an increase in k (regardless of the value of α , and even if $\alpha < 0$). The mathematics just confirms the obvious: when you squeeze out the component with the lowest dielectric constant, the bulk dielectric constant goes up. As shown previously, asphalt, too, is a mixture of essentially three components: air, stone, and bituminous binder. The following sections make apparent the essential differences between soil and asphalt.

The Challenge of Soil: For asphalt, the contractor specifies, and rather closely controls, the volume fractions of the constituents. In the asphalt mixing equation, therefore, with k being the measurement, the only unknown is the porosity η . A single measurement at a single frequency (13.65MHz in the current model of the PQI) is sufficient to determine the porosity or, equivalently, the density.

For soil, on the other hand, both η and the volumetric moisture content, θ , are unknown. Obviously, at least one other measurement and one other equation are required to solve for the two unknowns. To find this second equation, we exploit the fact that the dielectric "constant" is, in fact, a function of the applied electric field frequency.

The Maxwell-Wagner (M-W) Effect: In soil, there are three primary mechanisms that lend richness to the dielectric spectrum: the free water relaxation, the bound water relaxation, and the M-W relaxation (see Figure 4). Here, ε' is the permittivity, ε'' is the total conductivity divided by the frequency, and the dotted envelope is the static conductivity divided by the frequency. It has been shown [5,6,7,8,9] that the mixing equation should hold in the frequency range between the M-W and bound water relaxations.

Data Extraction Methodologies: TransTech and other researchers have shown that individual soil measurements can be extremely noisy due to variable surface variations. To address this, TransTech utilizes a parametric approach made possible by the standoff design that was implemented for the SDG after related work on a non-contacting PQI device in a NYSERDA funded program. Since the electromagnetic response of soil with the original non-contacting SDG prototype could not be estimated in advance, several controlled compactions were completed, varying the moisture level and density level separately. Then, working with the spectrographic soil responses of the collected compaction data, the form of the soil response was estimated with a second order equation. The equation's parameters (i.e., coefficients) that best fit the data were identified. Subsequently, the parameters were further interpreted, such that statistically significant patterns were revealed expressing the soil's density and moisture properties. Using the identified patterns, a system model was developed to calculate the soil's wet density and moisture content. During the development of the empirical soil model, it was found that the model was sensitive to the specific surface area of the material being measured. Once the material's specific surface area was accounted for, in six subsequent test compactions, there was a

119% increase in accuracy when using the SDG's new wet density calculation as compared to the Nuclear Density Gauge's wet density calculation, which was considered the standard at the time [10].

Impedance Spectroscopy Background: Impedance spectroscopy has been used many times for the evaluation of material characteristics. In general, the parameters used to solve Maxwell's equations are dependent upon material composition and physical properties, temperature, and frequency of the applied field. In the following discussion, the characteristics of soils will be discussed.

The determination of a material characteristic where the material contains water is a difficult problem. Typically, for many soils and other materials of interest in construction, the permeability is nearly that of free space and the conductivity is low (2-10 mS/cm). As a result, the electromagnetic response of soil is primarily determined by its dielectric properties. Soil is a porous medium consisting of a heterogeneous mixture of pore fluids, air and soil particles of different mineralogy, size, shape and orientation. The heterogeneity of soil combined with significant interfacial effects between the highly polar water molecules and the soil solids surface results in a complex electrical response for which good phenomenological theories are scarce.

There are three primary polarization effects in soil: bound water polarization, double layer polarization, and the M-W [5] effect (Figure 4). The bound water polarization results from the fact that water can be electrostatically bound to the soil matrix. The degree of binding varies from unbound or free water at a great distance (> 10 molecular diameters) from the matrix surface, to heavily bound, or adsorbed, water. If water becomes bound to the soil matrix, it is not capable of doing as much work and hence has lost energy. The relaxation frequency and the apparent dielectric constant of bound water are significantly less than that of free water [5]. Double layer polarization is due to separation of cations and anions in an electric double layer around plate-like clay particles. It is a surface phenomenon that is dominant at frequencies < 100 kHz [5]. Double layer polarization is mostly observed in soils containing a large fraction of clay. The M-W effect is the most important phenomenon that affects the low radio frequency dielectric spectrum of soils (0.2-30 MHz). The M-W effect is a macroscopic phenomenon that depends on the differences in dielectric properties of the soil constituents. It is a result of the distribution of conducting and non-conducting areas in the soil matrix. This interfacial effect is dominant at frequencies less than ~30 MHz, below the frequencies where bound and free water relaxations play a dominant role [5].

TransTech research has shown that typical well-graded sandy soils suitable for engineering fill exhibit a single M-W relaxation in the 1-10 MHz range [11]. Above this frequency range, the dielectric response is empirically described by mixing equations in which the matrix bulk dielectric constant is proportional to the sum of the products of the volume fractions and dielectric constants of the constituents [12]. At frequencies below the M-W relaxation, the apparent permittivity may rise more than an order of magnitude from its value in the mixing region [11]. In addition, the conductivity is dispersive, falling with frequency, as shown in Figure 4.

In many granular materials with bound and/or free water, the M-W effect may be used to aid in the determination of the important engineering characteristics of the material. The changes due to the reduction of the air in the mix and the relaxation characteristics of water can be used in impedance spectroscopy to determine the density and moisture content of the soil, as is the case with the TransTech Soil Density Gauge.

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