New Technique To Measure Moisture in Hot-Mix Asphalt Concrete Nondestructively

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A new technique was developed to measure the moisture content in hot-mix asphalt concrete. The technique involves measuring the dielectric properties of the hot-mix asphalt concrete using electromagnetic waves in the microwave range of 12.4 to 18.0 GHz. Using the dielectric property measurements, the moisture content can be calculated. This study used piedmont gravel and limestone aggregates in dense-graded and open-graded cases. One type of asphalt cement was studied exclusively because three types of asphalt were found to have almost the same dielectric properties. Asphalt content, surface smoothness, and specimen thickness were also found to have no effect on the measured dielectric properties. The study considered the different void ratios that had noticeable effects on the microwave reflection measurements. However, the presence of water in the mixes overshadowed the effects of all other factors on the dielectric properties of the mix. Regression models were developed to predict the volumetric moisture content. The study suggested a model that was found to be a function of the dielectric properties of dry and wet hot-mix asphalt concrete. Therefore, in practice, several cores are essential to obtain the in situ dry dielectric properties of hot-mix asphalt concrete.

The strength of hot-mix asphalt concrete is drawn from the bonding between the asphalt cement and the aggregate. The existence of moisture in asphalt concrete causes major damage to the asphalt cement–aggregate bonding and therefore reduces the overall strength of asphalt concrete pavements. This phenomenon is referred to as "stripping." The presence of excess moisture affects both resilient modulus and fatigue life; in general, it reduces the pavement life.

As part of the research to prevent the weakening of asphalt concrete pavements caused by the existence of moisture, this study attempted to measure moisture content using electromagnetic waves at the microwave frequency range. Microwave wavelengths are typically 10^5 times larger than optical wavelengths. Indeed, microwaves behave much like light waves in that they travel in the same manner and according to the same physical laws; they are reflected by metallic objects, are absorbed by some dielectric materials, are transmitted without significant absorption through other dielectric materials, and change directions when traveling from one dielectric material into another. Because microwaves can penetrate many nonmetals, information can be obtained about material composition, density, state of cure, and moisture content. This information can be obtained from the amplitude and phase measurements of wave transmitted and/or reflected by the specimen.

The microwave was used in this study as a nondestructive testing (NDT) technique to detect the moisture content in asphalt concrete pavements without contact. The water molecule possesses a permanent dipole moment; that is, its electrical properties might be simulated to first order as arising from a fixed positive charge and fixed negative charge, separated by a certain distance. The molecule also possesses a polarizability as a result of an additional dipole, which is induced by an electric field and is proportional to its magnitude. Although the composition of the asphalt concrete can influence its dielectric properties, water dipoles have the greatest influence on these properties. The changes in the asphalt concrete dielectric properties can be monitored indirectly through the ability of microwaves to detect changes in complex dielectric constant.

The dielectric properties of asphalt concrete depend on the proportion and state of the water component in the mixture, as well as the polarization and conductivity of the other component or components (*1*). The water molecule, at microwave frequencies, is unique in having an extremely high dielectric constant and loss tangent. Water will absorb several thousand times more microwave energy than a similar volume of almost any perfectly dry material. Therefore, microwaves can be used to monitor the moisture content of many materials instantaneously and continuously.

The use of electromagnetic waves in pavement NDT started in the 1960s. Over the past two decades, extensive studies on the microwave signature of soil moisture have been reported (*2–4*). The capabilities of microwave remote sensing in detecting moisture in soils have been investigated through experimental studies since the early 1970s. As a result of these investigations, the role of microwave scattering became well recognized. However, most of the studies were performed on thin soil specimens using conductors.

Electromagnetic waves have also been used in rigid pavements, using pulse radar. The use of short-pulse radar for subsurface exploration has received considerable attention, especially during the past decade. Short-pulse radar has been used in a variety of subsurface applications, including measurement of pavement thickness, void detection, reinforcement detection, and delamination. The transmitted wave form of ground-penetration radar is usually a very narrow pulse, 1 ns and 1 GHz central frequency. Although short-pulse radar represents a major change in the application of new tech-

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nology to evaluate rigid pavement distress, its application is still under investigation because of current limitations. This method depends largely on the user's interpretation. Also, the imaginary part of the complex dielectric constant is neglected in the evaluation process, which might undergo a significant change if the pavement is wet. However, Clemena used electromagnetic waves to detect the water content of fresh concrete mixes using both reflection and transmission methods (*5*). Although the transmission method gave more accurate and more precise results than the reflection method, the transmission method is unfeasible and impractical for field applications (*1*).

The use of electromagnetic waves for NDT of asphalt concrete pavements has not been well investigated. Few studies have been made on the dielectric properties of asphalt cement (*6*), and many studies have been made on the dielectric behavior of aggregates (*1,7*). Only very limited investigations have been conducted regarding the dielectric properties of asphalt concrete (*8–10*).

The first radar in the swept frequency mode was built by Lundien in 1970–1971, using a frequency range of 0.5 to 8.0 GHz (*11*). The results obtained from 2.0 to 8.0 GHz were found to be 200 to 300 percent out of calibration compared with the data in the range of 0.5 to 2.0 GHz. Although the antennas used were huge, very high, and unfocused, the research in the laboratory and field represented a new era in using electromagnetic waves as an NDT technique in asphalt concrete.

THEORY OF ELECTROMAGNETIC WAVES

The dielectric constant of a material is a measure of the extent to which the electric charge distribution in the material can be distorted by applying an electrical field. Based on their dielectric constants materials are classified as lossless, complex, or lossy. The pavement materials are considered to be poor conductors or dielectric. Therefore, the penetration of this material (which is considered low-loss material) is possible. The complex dielectric constant is usually presented as

$$\varepsilon^* = \varepsilon_0 (\varepsilon' - j\varepsilon'') \tag{1}$$

where

ε^* = complex dielectric constant,
ε_0 = vacuum dielectric constant (8.84×10^{-12} farad/m),
ε' = real part of $(\varepsilon^*/\varepsilon_0)$ associated with the ability of dielectric material to store energy,
ε'' = imaginary part of $(\varepsilon^*/\varepsilon_0)$ associated with the dielectric losses that occur in the material, and
$j = (-1)^{1/2}$.

In practice, the normalized complex dielectric constant (ε_r) is used; it is called the relative dielectric constant, or simply the dielectric constant, and is defined by

$$\varepsilon_r = \varepsilon^*/\varepsilon_0 = \varepsilon'(1 = j\tan\delta) \tag{2}$$

where $\tan\delta$ is the loss tangent ($\varepsilon''/\varepsilon'$).

In this study, the dielectric properties of asphalt concrete were calculated from the measured microwave reflections. The microwaves used were in the Ku band (12.4 to 18.0 GHz). A uniform plane wave is normally incident on a specimen backed by a metal plate. The metal plate is used because of its complete reflection. Therefore, a finite specimen theory can be used (*10*). The complex reflection coefficient S_{11} is related to the complex relative dielectric constant. Because the asphalt concrete material is nonmagnetic, the following equation can be obtained:

$$S_{11} = \frac{[jZ_s \tan(\beta_d) - Z_0]}{[jZ_s \tan(\beta_d) + Z_0]} \tag{3}$$

where

Z_s = impedance in specimen = $Z_0/(\varepsilon^*)^{1/2}$,
Z_o = impedance in vacuum,
d = specimen thickness, and
β = phase constant.

Because $Z_s/Z_o = 1/(\varepsilon^*)^{1/2}$, the following equation can be developed:

$$S_{11} = \frac{[j \tan(\beta d) - (\varepsilon^*)^{1/2}]}{[j \tan(\beta d) + (\varepsilon^*)^{1/2}]} \tag{4}$$

ε^* is found iteratively from Equation 4. The iterative procedure is based on finding the zeros of an error function from the measured and calculated values of the complex reflection coefficient:

$$E_r = |S_{11}^m - S_{11}^c| \tag{5}$$

where S_{11}^m equals the measured values of the complex reflection coefficient, and S_{11}^c equals the calculated values of the complex reflection coefficient.

A program was developed in this study to find the roots of a complex function. The program required a good initial estimate of the dielectric constant, which is a function of light speed, the frequencies corresponding to two successive minimums from the reflection coefficient-frequency relationship, and the specimen thickness. The initial estimate of the loss factor depends on successive local minimums and maximums of the reflection coefficients, the obtained real dielectric constant, and the specimen depth.

When water exists in the specimens, the material has a high loss factor and becomes difficult to measure using this method. Therefore, an infinite theory may be used, in which the specimen is assumed to be a lossy material or very long (*10*). In this case, the reflection coefficient (S_{11}) is related to the complex dielectric constant according to the following relationship:

$$\varepsilon^* = \left(\frac{1 - S_{11}}{1 + S_{11}}\right)^2 \tag{6}$$

EXPERIMENTAL SYSTEM

The system used in this study consisted of an HP8510B network analyzer, synthesized sweeper, and focused antenna as shown in Figure 1. The HP8510B network analyzer is a high-

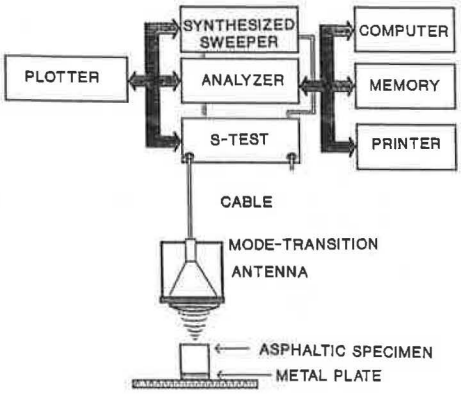

FIGURE 1 Schematic diagram of measurement system used in study.

performance vector receiver that gives accurate and repeat able measurements of S_{11}. Measurement by the HP8510B network analyzer is actually made in the frequency domain and transformed mathematically into the time domain by calculating the inverse Fourier transform. The frequency domain reflection measurement is a composition of the responses of all of the discontinuities present in the material tested. The source is phase-locked at each measurement frequency under the control of the HP8510B network analyzer. The synthesized sweeper generates the microwave signals in a sweep mode at 801 frequency points. The antenna consists of a conical feed horn and two back-to-back planoconvex dielectric lenses mounted in a conical horn antenna. The combination of lenses produces a plane wave with an approximate spot size of one free-space wavelength at a focal distance of 30.45 cm. The system used 0.01 watt power.

The difficulties usually encountered in measuring the dielectric properties in free space are the suppression of unwanted reflections, the launching of a plane wave in a limited space, and the diffraction from the edges of the specimen. A free-space calibration was adopted to overcome these limitations. The calibration of the measurement system shown in Figure 1 was performed in two steps. First, the rectangular wave guide calibration was conducted between the analyzer and the mode of transition. Then the other calibration was performed on the reflection coefficient data obtained from the metal plate placed at the focus of the antenna (free-space S_{11} calibration). Time domain response was used to apply gating on the transformed frequency domain. Taking a Fourier transform of a gated time domain response (from the top and bottom of the specimen), as shown in Figure 2, gives the reflection data obtained from the specimen only. The correct reflection coefficient, obtained after the calibration, is the ratio of uncalibrated reflections obtained after time domain gating from the metal-backed specimen and the metal plate.

A standard material (0.384-cm-thick glass plate) with known response was used to verify the calibration procedure. Figures 3 and 4 show the variation of the calculated and measured values of $|S_{11}|$ and ϕ (the real and phase of reflection coefficient) for metal-backed glass. The calculated values were obtained by using $\varepsilon^* = 4.38 - j0.02365$. It was found that the measurement accuracy of $|S_{11}|$ and ϕ is ± 0.2 dB and ± 6 degrees, respectively (dB $= -20 \text{ Log } |S_{11}|$). After performing the calibration, the maximum error in $|S_{11}|$ and ϕ for the dry asphalt concrete specimen was found to be ± 1 percent and ± 14 percent, respectively; for the wet specimen, it was found to be ± 5.7 and ± 20 percent, respectively. This error is acceptable considering that the ratio of the loss factor of the wet specimen to the loss factor of the dry specimen is 4:7.

TEST MATERIALS

The test materials used are part of the group of materials under investigation by the Strategic Highway Research Pro-

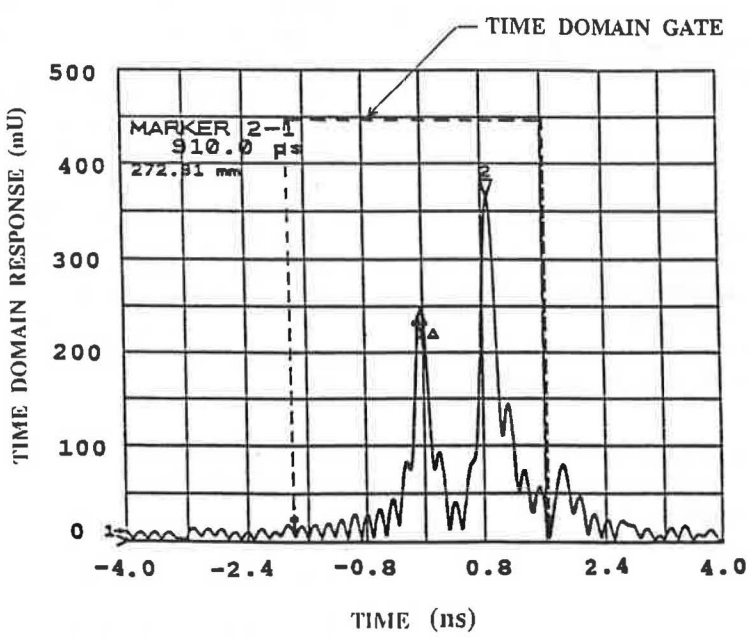

FIGURE 2 Typical time domain response of asphalt concrete specimen backed by metal plate.

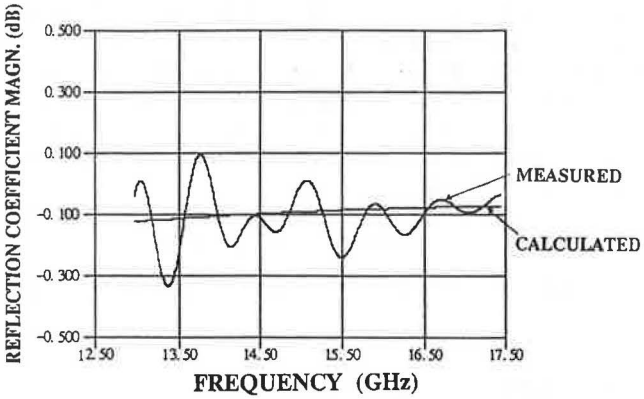

FIGURE 3 Calculated and measured values of $|S_{11}|$ in decibels for 0.384-cm-thick glass plate.

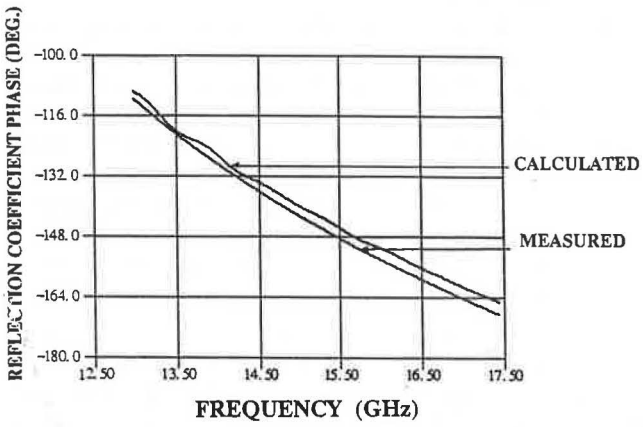

FIGURE 4 Calcualted and measured phase values of S_{11} in degress for 0.384-cm-thick glass plate.

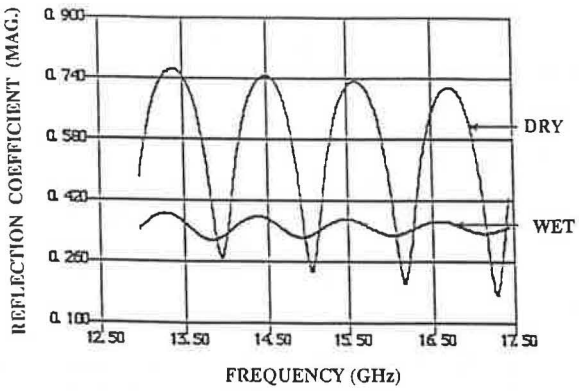

FIGURE 5 Typical reflection coefficient–frequency relation for dry and wet asphalt concrete specimens.

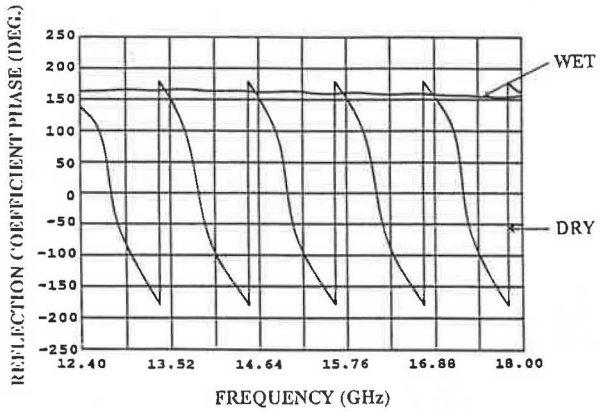

FIGURE 6 Typical phase-frequency relation for dry and wet asphalt concrete specimens.

gram. Two kinds of aggregates were used: low-absorption aggregates (limestone) and high-absorption aggregates (piedmont gravel). Each type of aggregate was used in two gradation forms, dense-graded and open-graded. The dielectric properties of three types of asphalt—Conoco AR4000, Witco AR4000, and Shamrock AC-20—were measured. However, because the measured dielectric properties of these types of asphalt cements were almost the same, only Conoco AR4000 was used in the study. Asphalt concrete specimens were prepared using a kneading compactor for different air void contents, thicknesses, asphalt contents, aggregates, and aggregate gradations.

EXPERIMENTAL RESULTS AND DISCUSSION

The laboratory rest results were obtained at 801 frequency points, each representing an average of 128 measurements. The overall measurements were taken over 30 sec for each test. The measurements consisted of the reflection coefficient and phase as a function of frequency. Figure 5 shows a typical reflection coefficient-frequency relation for dry and wet asphalt concrete specimens; Figure 6 shows a typical phase-frequency relation for dry and wet asphalt concrete specimens. The dielectric constants were calculated over a frequency range of 12.96 to 17.44 GHz. From experience, it is known that the greatest possibility of error occurs at the beginning and end of the frequency band measurements.

The dielectric constants (real and imaginary parts) were calculated over 641 frequency points for each specimen. It was found that the dielectric properties did not vary significantly over the frequency band used. Therefore, the effect of frequency on the calculated dielectric properties was assumed negligible for both dry and wet specimens. Thus, an average dielectric constant and loss factor were used for the specific frequency band. The maximum coefficient of variation obtained was 5 percent.

The real relative dielectric constants of the three types of asphalt cement—Conoco AR4000, Witco AR4000, and Shamrock AC-20—were found to be 2.65, 2.68, and 2.67, respectively. The loss tangents for the three types were found to be 0.0104, 0.0094, and 0.0086, respectively. These results are different from the results obtained for asphalt cement by the Air Force Materials Laboratory (AFML), which showed that the magnitude of the dielectric constant was 2.46 at frequencies of 1, 3, and 8.5 GHz (*6*). The loss tangent results are also different from those found by AFML (which were between 0.0017 and 0.0019). However, the results obtained in this study are in agreement with the results obtained by the Colorado Department of Highways, where the dielectric

constant magnitude was 2.6; no information was given about the loss tangent (*12*). These results indicate that the asphalt cement type does not affect the dielectric constant magnitude of the asphalt concrete mixture and might have a minor effect on the loss factor. Also, the asphalt content of the mixture was found to have no effect on the measured dielectric properties of the mix. This conclusion was reached by measuring the dielectric properties of six specimens having the same characteristics but with different asphalt cement contents. The three asphalt cement contents tested were 4.5, 5.0, and 5.5 percent.

The dielectric properties of aggregates were studied for particle sizes less than 75 μm. In this case, the wavelength of the microwaves was larger than the particle size. The magnitude of the dielectric constants was found to be 4.23 for limestone and 3.20 for piedmont gravel. However, the loss tangent was found to be 0.0318 for limestone and 0.0346 for piedmont gravel.

The specimen surface roughness was found to have no effect on the dielectric properties obtained. Many specimens were tested on both the bottom face and the top face, which was leveled by 1,000 psi compression force after compaction. Specimen thickness was also tested and showed an insignificant effect on the measured dielectric properties of the mixture. Three thicknesses were tested for open-graded limestone asphalt concrete mix: 6.35, 10.16, and 15.24 cm.

After the initial study, it was decided that only the aggregate type and gradation and the air void content have significant effects on the dielectric properties of the asphalt concrete mixture. Therefore, each specimen, with different aggregates, gradation, and air void content, was exposed to three stages of microwave reflection measurements. In the first stage, the specimen was dry. In the second stage, the specimen was vacuum-saturated for 20 min at a vacuum pressure of 25 psi and soaked in water for 2 hr. In the third stage of microwave measurements, the specimen was vacuum-saturated for 90 min at a vacuum pressure of 25 psi and soaked overnight in water. All vacuum-saturated and microwave measurements were performed at 23°C. The amount of water in the specimen was measured by the weight differential method.

The dielectric properties of water were measured at the center of the frequency band used, 15.2 GHz. The water in the asphalt mixture was assumed free and its dielectric properties were determined using the Cole-Cole equation (*1*). The water dielectric constant was 63.34, and the loss tangent was 29.66.

A statistical regression study was performed to correlate the moisture content measured by the microwave technique with the amount of water determined by the weight differential method. The independent variables were the thickness of the specimen, the specimen's air void content, the type of aggregate, the aggregate gradation, the specimen surface smoothness, the dielectric constant magnitude, the loss factor, the difference in the dielectric constant magnitude between the dry and wet specimen, and the difference in loss factor between the dry and wet specimen. The dependent variable was the measured volumetric moisture content. The type of aggregate, aggregate gradation, and surface smoothness were expressed as binary (0 or 1).

The correlation method was used to measure the associations between the variables, and R-squared values were obtained by constructing regression analysis for all possible combinations of the independent variables. The R-squared results show that the difference in the dielectric constant magnitude between dry and wet measurements for a given specimen is the most important factor affecting the R^2-value. If all the independent variables are included in a statistical model, the model is expressed as

$$Y = 0.217 + 0.002A + 0.122B - 0.442C + 8.378E - 0.017F + 0.794G + 0.098H + 6.735I + 1.090J \quad (7)$$

where

Y = volumetric moisture content,
A = specimen thickness,
B = specimen air void content,
C = dielectric constant magnitude,
E = loss factor × 10^4,
F = surface smoothness: 0 for relative rough and 1 for relative smooth,
G = aggregate type: 0 for limestone and 1 for piedmont gravel,
H = gradation type: 0 for open-graded and 1 for dense-graded,
I = difference in dielectric constant magnitude between dry and wet specimens, and
J = difference in loss factor between dry and wet specimens.

The R^2-value for the above model was 95.3 percent and the root mean square error (root MSE) was 0.417. The results of this model are shown in Figure 7. Although this model has good correlation, it is difficult to obtain in situ information about some of the independent variables, such as the air void content. Also, the study showed that the existence of water overshadowed all other effects. Therefore, the following model was developed as a function of the difference of dielectric properties between the dry and wet specimens:

$$Y = 0.620 + 6.136I + 6.873J \quad (8)$$

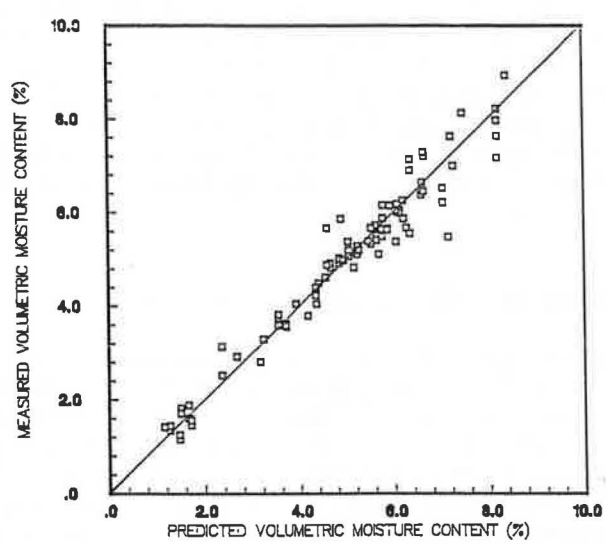

FIGURE 7 Measured versus predicted volumetric moisture content using Equation 7.

R^2 for the above model is 83.2 percent, and the root MSE is 0.758 (Figure 8). This model can be used to estimate the in situ moisture content of asphalt concrete pavement. It requires the measurement of the dry dielectric properties of a few cores from the test site. It is believed that the model shown in Equation 8 is simple and that it is feasible to obtain its parameters. Also, this model is feasible for field application.

FINDINGS AND CONCLUSIONS

This study resulted in the following findings and conclusions:

1. The reflection coefficient and phase amplitude are good indicators of water presence in asphalt concrete mixtures.
2. The information obtained using the free-space setup in the reflection method can be used to calculate the dielectric properties of the asphalt materials.
3. The three types of asphalt cement tested in this study—Conoco AR4000, Witco AR4000, and Shamrock AC-20—have almost the same dielectric properties. However, limestone was found to have a higher dielectric constant magnitude than piedmont gravel and almost the same loss tangent.
4. The difference in dielectric properties between dry and wet asphalt mixtures was found to correlate very well to the volumetric moisture content.
5. The volumetric moisture content in an asphalt concrete mixture can be predicted with an R^2-value of 96.2 percent and a root MSE of 0.560.

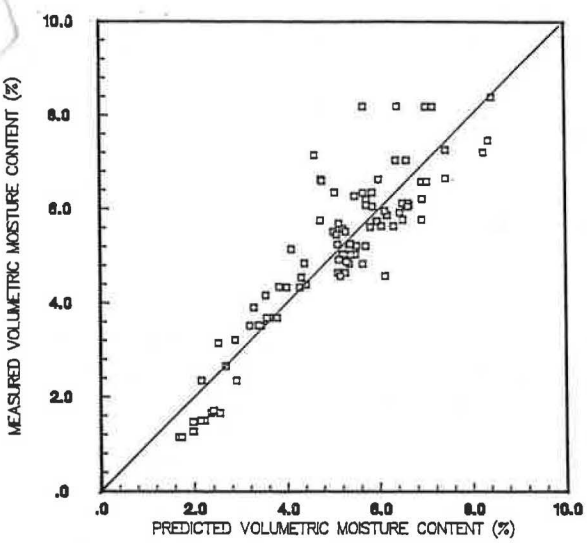

FIGURE 8 Measured versus predicted volumetric moisture content using Equation 8.

6. Because of difficulties encountered in measuring the air void content in the field, a statistical model was developed in which the volumetric moisture content is a function of dry and wet asphalt mixture dielectric properties. The developed model has an R^2-value of 83.2 percent and a root MSE of 0.758.

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