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Title of Design: In-place Hot Mix Asphalt Density Estimation Using Ground Penetrating Radar for Airport Pavement Quality Control and Assurance Activities

Design Challenge addressed: Airport Operation and Maintenance

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In-place Hot Mix Asphalt Density Estimation Using Ground Penetrating Radar for Airport Pavement Quality Control and Assurance Activities

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Executive Summary

Title: In-place Hot Mix Asphalt Density Estimation Using Ground Penetrating Radar for Airport Pavement Quality Control and Assurance Activities

Summary: In-place airport pavement system characteristics need to be quantified for quality control, to effectively assess condition, and to monitor performance. Hot mix asphalt (HMA) density is one of the most important parameters to monitor. This proposal introduces an innovative approach of using Ground Penetrating Radar (GPR) to measure in-place HMA density accurately, continuously, and rapidly. Through a GPR survey, the dielectric constant, an electromagnetic (EM) property, of the HMA layer can be accurately determined. Since the dielectric constant of HMA is a function of the dielectric and volumetric properties of its components (i.e. air, binder, and aggregate), it is possible to predict the HMA density based on its GPR-measured dielectric constant. In this study, three mathematical models using HMA dielectric constant to predict its density were developed based on EM mixing theory. To evaluate these models, testing was conducted on laboratory HMA slabs. The best model was then selected and validated using the GPR data from a composite pavement with HMA surface. Cores extracted from the HMA pavement indicated that the selected model provided reasonably accurate HMA density. In addition, GPR was shown to be a cost-effective method compared to other in-place HMA density measurement methods.

Participants: Zhen Leng and Jongeun Baek, graduate students, conducted this design project under the guidance of Prof. Imad Al-Qadi and Prof. Samer Lahouar at University of Illinois at Urbana-Champaign

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1. Problem Statement and Background

1.1 Problem Statement

In-place airport pavement system characteristics need to be quantified for quality control (QC), to effectively assess condition, and to monitor performance. For hot mix asphalt (HMA) pavements, the layer mass density is one of the most important parameters to monitor. According to the FAA (2007), sampling, testing, and inspection at a sufficient rate are conducted in a QC program to monitor the HMA's density in airport pavements. Insufficient density of an in-place HMA pavement is the most frequently cited construction-related performance problem. Density that is either too high or too low can lead to premature pavement failure (Killingsworth, 2004). Lower percentages of in-place air voids can result in rutting and shoving, while higher percentages allow water and air to penetrate into a pavement, leading to an increased potential for water damage, oxidation, raveling, and cracking.

The acceptance of pavement quality is determined using specified number of samples. An uncertainty or risk exists in the measurement as well as the decision because the population of the random samples tested is only a small fraction of all materials for the evaluation. Therefore, a test method that can cover a larger area in a reliable and rapid way is desired to enhance the confidence level of the data.

1.2 In-place HMA Density Measurement Methods

Traditionally, two techniques have been used to estimate in-place HMA density: laboratory tests on pavement cores (Figure 1a) and in-situ nuclear gauge measurements (Figure 1b). The first technique uses a destructive procedure, in which cores are extracted from a pavement to directly measure the thicknesses and the volumetric properties of pavement layers. Although this method provides accurate density measurements, it is time consuming and provides limited information because cores are typically taken every 1000ft. On the other hand, the nuclear gauge is a nondestructive technique that can be used to provide reasonably accurate estimates of the HMA layer density. However, this technique also has some drawbacks. First, it provides limited information about the layer density, since nuclear measurements are usually taken with high spatial spacing. Second, nuclear gauge operation requires special licensing because it uses radioactive material. Hence, it can be used only by authorized personnel.

Recently, electromagnetic (EM) density gauges (Figure 1c) have entered the market as an alternative to the nuclear density gauges and the coring process. These nonnuclear devices use EM signals to measure in-place density. The EM density gauges have the advantages of completely eliminating the licenses, training, specialized storage, and risks associated with devices that use a radioactive source (Romero, 2002). However, similar to the traditional methods, the nonnuclear density gauges are not able to provide continuous information of the entire pavement either.

(a) Coring (b) Nuclear gauge (c) Non-nuclear EM gauge

Figure 1. Available methods for density measurements for HMA airport pavements.

A fourth technique that can be used to nondestructively estimate the density of HMA layers is Ground Penetrating Radar (GPR), the performance of which will be investigated in this research. The motivation for using GPR is that it is rapid, cost effective, and can provide more information about the internal pavement structure (layer thicknesses and subsurface distress) in addition to the HMA density.

1.3 Ground Penetrating Radar Application on Pavements

Ground penetrating radar (GPR) is a special type of radar designed to look into the ground by penetrating the surface. Among various types of GPR systems, a pulsed (or impulse) GPR system is the most commercially available and commonly used to evaluate transportation infrastructure (Al-Qadi, 1999). The principle of the pulsed systems is based on transmitting a narrow EM pulse and analyzing the reflected pulses from interfaces where there is a contrast in the dielectric properties. The most common uses of GPR data are to measure pavement layer thicknesses, to identify large voids, to detect the presence of excess water in a structure, to locate underground utilities, and to investigate significant delamination between pavement layers (FAA, 2004).

Depending on the way antennae are deployed, GPR systems are classified as air-coupled (or launched), or ground-coupled systems (Lahouar, 2003). In air-coupled systems, the antennae are typically mounted 6 to 20in. above the surface (Figure 2a). These systems produce a clean radar signal and allow for highway speed surveys (up to 60mph). The drawback of these systems is the low depth of penetration into the pavement structure, since part of the EM energy, sent by the antenna, is reflected back by the pavement surface. In contrast, a ground-coupled GPR antenna is in full contact with the ground (Figure 2b), which gives a deeper penetration at the same frequency but limits the speed of the survey. For HMA thickness and density measurements, the air-coupled system is usually preferred due to its high survey speed and better accuracy.

(a) Air-coupled antennae

(b) Ground-coupled antennae

Figure 2. Typical types of GPR antennae.

The most important material property used in GPR surveys is the dielectric constant of the medium. The dielectric constant of a medium, ε_r, determines the EM velocity within the medium, v, based on the following equation:

$$v = \frac{c}{\sqrt{\varepsilon_r}} \tag{1}$$

where, c is the speed of light in free space (3×10^8 m/s= 670,616,629mph). For a layered structure, such as an airport pavement, the dielectric constant of an HMA surface, $\varepsilon_{r, HMA}$, can be estimated using the following equation (Lahouar, 2003):

$$\varepsilon_{r,HMA} = \left(\frac{1 + A_o / A_p}{1 - A_o / A_p} \right)^2 \tag{2}$$

where, A_p is the amplitude the incident GPR wave obtained by collecting data over a copper plate placed on the surface of the pavement; A_o is the amplitude of the surface reflection. Then, the thickness of the HMA layer can be calculated as follows:

$$d_{HMA} = \frac{ct_{HMA}}{2\sqrt{\varepsilon_{r,HMA}}} \tag{3}$$

where, t_{HMA} is the two-way travel time of the GPR signal within the HMA layer.

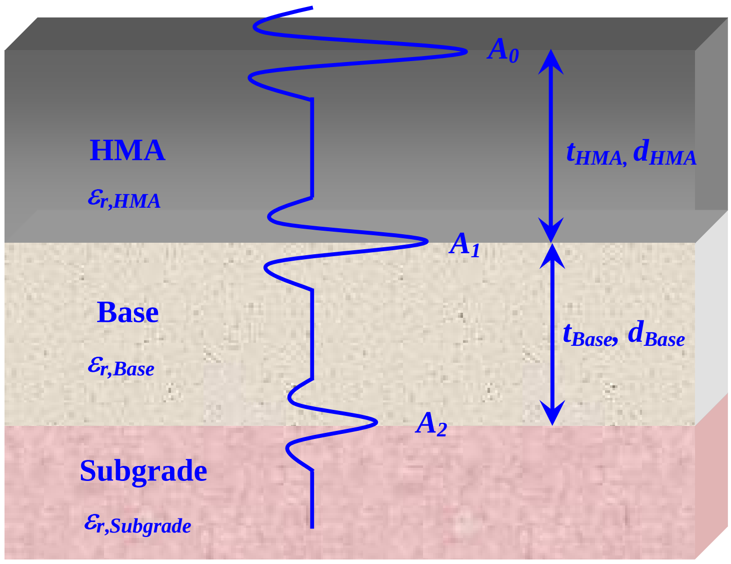

Figure 3. Typical GPR signal for an HMA pavement system.

1.4 Objective and Challenge

Considering the limitations of the current methods for in-situ HMA density measurement, the objective of this study is to investigate the feasibility of using GPR to measure the HMA density for airport pavement accurately, continuously, and rapidly.

As described in the last section, the dielectric constant of the HMA layer can be accurately determined using an air-coupled GPR system. Then, if an accurate relationship could be established between the dielectric constant and density of the HMA, it is feasible to estimate HMA density using GPR. Hence, the challenge of this study is to develop the best mathematical model which is able to predict the HMA density of airport pavements based on its dielectric constant measured by GPR.

2. Summary of Literature Review

While GPR has been successfully used in a variety of areas in pavement engineering, its use for measuring HMA density remains minimal. In this section, the most essential studies in this area are summarized.

Lytton (1995) developed a computer program to determine the density and water content of various layers within a multilayer pavement system using conventional GPR (U.S. Patent No. 5384715). In this approach, digitized images were obtained based on a reflected radar signal from the multilayer pavement system. The program, named system identification and analysis of subsurface radar signals (SIDARS), takes advantage of the fact that each pavement layer itself is composed of three types of materials: solids, fluids, and gases. Thus, the dielectric constant of a pavement layer is a function of the layer's solid, fluid, and gas dielectric constants. A wave propagation model of the pavement system is employed in SIDARS to generate a synthetic reflected radar signal. Initial values for a layer's solids, fluid, and gas concentrations are adjusted through an iterative process to minimize the mean-squared-error between the measured reflected and calculated synthetic radar signals. By calibrating the model embedded in the software to ground truth data obtained from cores, very accurate measurements of the volume and weight compositions of the layer can be calculated. As illustrated by Wells et al. (2001), all of the density measurements were made with the accuracy that is needed for quality assurance in the construction of new and rehabilitated pavements.

Saarenketo (1997) is one of the first researchers in Europe who used GPR to measure HMA pavement density. It was also assumed that the dielectric constant of an HMA layer is a function of the dielectric constants of its components such as asphalt, aggregate, air, and possibly water. Changes in their proportions (e.g. in void contents) can be measured when overall dielectric constants of the pavement are recorded. The dielectric constant usually ranges from 2.6 to 2.8 for asphalt; from 4.5 to 6.5 for absolutely dry, crushed aggregate; and is 1.0 for air. Water was found not to affect the dielectric constant measurements of new HMA. Laboratory tests were performed to prove the correlation between dielectric constant and the dry density in HMA samples. According to the long-term studies on applying GPR in pavement QC, an exponential relationship between the surface dielectric constant and void content was built as follows:

$$void(\%) = a \cdot e^{-b \cdot \varepsilon_a} \tag{4}$$

where, ε_a represents the surface dielectric measured in field; and coefficients a and b are calibration constants dependent on mixture types. GPR data collected from various roads proved that the drop in dielectric value indicates density problems, and GPR has tremendous potential to assist in monitoring the localized problem (Saarenketo 2000).

Silvast (2001) measured air void contents of the runway at the Helsinki-Vantaa airport in Finland using GPR. The purpose of this project was to test the use of GPR for runway pavement QC. The GPR survey was conducted at speeds of 30 to 45mph for approximately three hours on a pavement area of 3000ft in length and 200ft in width containing eight parallel lanes. The dielectric constant of the pavement was calculated using a surface reflection technique. Air void contents were calibrated based on dielectric constant values of calibration samples taken from three lanes. During data processing, the air void content was calculated with five-meter mean values. This study concluded that GPR technology presents a functioning pavement QC method for runways. The speed and large coverage were the main advantages of GPR compared to traditional methods. In addition, GPR enabled the monitoring of changes in pavement quality and pavement structure over time.

Two non-destructive testing methods, infrared imaging and GPR were applied in Texas to evaluate the density uniformity of HMA overlays (Sebesta et al. 2002). Data were collected from Texas DOT overlay projects on US-79, IH-10, and US-290 during the summer of 2001. By using the exponential equation proposed by the Finnish researchers, the relationship between the surface dielectric constants and air voids were achieved through a regression analysis. Then, the air void content profile was predicted for the whole pavement. The GPR was concluded to be a much better tool for investigation than the infrared devices if density changes are the primary heterogeneities in the new HMA surface. The researchers also recommended the maximum values of dielectric constant reductions to meet the Texas DOT density profile specification: 0.8 for coarse-graded mixes and 0.4 for dense-graded mixes.

3. Problem Solving Approach

HMA is a composite material composed of asphalt binder, aggregates, air, and possible water. The density of HMA is dependent on the specific gravities and volumetric fractions of its components. Similarly, the dielectric constant of the HMA is a function of the dielectric and volumetric properties of its components. Various EM mixing models exist to predict a mixture's dielectric constant based on the dielectric constants and volume fractions of its components (Sihvola 1999). Most of these models hypothesize that a mixture is composed of a background material with inclusions in different sizes and shapes.

In this study, models that include HMA bulk specific gravity (which equals the HMA density divided by the density of water at 4^{o}C) and dielectric constant were developed based on these EM mixing formulae, and their performances of predicting HMA density/bulk specific gravity were evaluated using laboratory and field testing data as follows:

(1) HMA bulk specific gravity model development. Through literature reviews, three EM mixing models were selected: the complex refractive index model (CRIM), the Rayleigh mixing model, and the Böttcher mixing model. These mixing models are formulae between the dielectric constant of a homogeneous mixture and the dielectric and volumetric properties of its components. The specific gravity models, which predict the HMA bulk specific gravity based on its dielectric constant and other known volumetric properties, such as asphalt binder content, were developed based on the EM mixing models using the volumetric relationships among different components (air, asphalt binder, and aggregate).

(2) HMA bulk specific gravity model evaluation using laboratory-prepared HMA specimens. HMA slabs (2ft×2ft×2in) were prepared with the same job mix fomulae but different densities. The dielectric constants of these HMA slabs were measured using GPR and their bulk specific gravities were measured according to the ASSHTO standard test method (AASHTO, 2001). Based on the collected data, the three EM mixing models used in the previous step were evaluated, and the best specific gravity model was selected.

(3) HMA bulk specific gravity model validation using a testing site. GPR data was collected from an HMA test pavement located in the pavement facility at the University of Illinois. The bulk specific gravity profile of the HMA surface was created using the selected model in the previous step. A couple of cores were extracted from the field and their bulk specific gravities were measured to validate the accuracy of the specific gravity prediction model.

4. Description of the Technical Aspects

4.1 Specific gravity model derivation

The three major compositions of HMA are aggregates, asphalt binder, and air are shown in Figure 4. Volumetric and mass contribution of each component on the entire mixture is represented by V and M, respectively; specific gravity and dielectric constant of each component is G and ε, respectively. The three EM models assumed that background material is asphalt binder and all inclusions have spherical shapes.

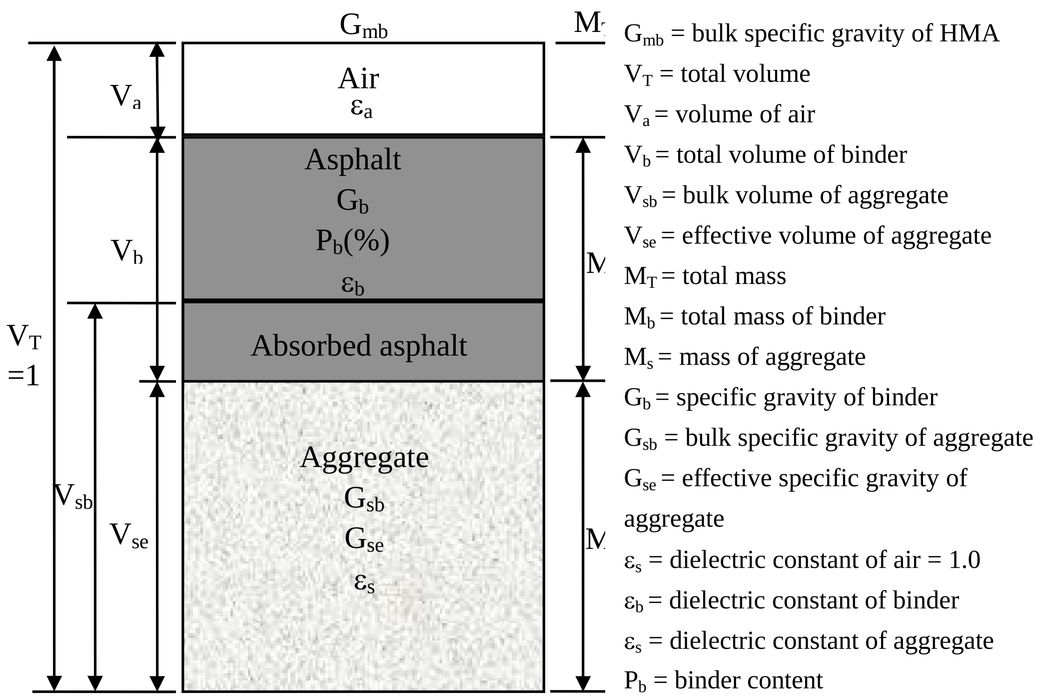

Figure 4. HMA volume and mass composition.

4.1.1. Complex refractive index model (CRIM)

The dielectric constant of a homogenous mixture can be estimated, based on the CRIM mixture theory, according to Eq. (5).

$$(\varepsilon_{HMA})^{1/\alpha} = V_a(\varepsilon_a)^{1/\alpha} + V_{sb}(\varepsilon_s)^{1/\alpha} + V_b(\varepsilon_b)^{1/\alpha}\text{, with } \varepsilon_a\text{=1} \tag{5}$$

From the volumetric properties of HMA, the following relations are found:

$$V_a = 1 - V_b - V_{se} \tag{6}$$

$$G_b = \frac{M_b}{V_b.1} \tag{7}$$

$$G_{sb} = \frac{M_s}{V_{sb}.1} \tag{8}$$

$$G_{se} = \frac{M_s}{V_{se}.1} \tag{9}$$

$$G_{mb} = \frac{M_T}{V_T.1} = \frac{M_b + M_s}{V_T} = M_b + M_s \tag{10}$$

$$P_b = \frac{M_b}{M_T} = \frac{V_b G_b}{V_T G_{mb}} \Rightarrow V_b = P_b \frac{G_{mb}}{G_b} \tag{11}$$

Substituting Eq. 6 in Eq. 5 gives:

$$(\varepsilon_{HMA})^{1/\alpha} = 1 + V_b\left((\varepsilon_b)^{1/\alpha} - 1\right) + V_{sb}(\varepsilon_s)^{1/\alpha} - V_{se} \tag{12}$$

Combining Eq. 8 and Eq. 9 gives:

$$V_{se} = \frac{G_{sb}}{G_{se}} V_{sb} \tag{13}$$

Thus, Eq. 9 becomes:

$$(\varepsilon_{HMA})^{1/\alpha} = 1 + V_b\left((\varepsilon_b)^{1/\alpha} - 1\right) + V_{sb}\left((\varepsilon_s)^{1/\alpha} - \frac{G_{sb}}{G_{se}}\right) \tag{14}$$

Substituting Eqs. 7 and 8 in Eq. 10 gives:

$$G_{mb} = M_b + M_s = G_b V_b + G_{sb} V_{sb} \tag{15}$$

Therefore,

$$V_{sb} = \frac{G_{mb} - G_b V_b}{G_{sb}} \tag{16}$$

Substituting Eq. 11 in Eq. 16 gives:

$$V_{sb} = \frac{G_{mb}}{G_{sb}}(1 - P_b) \tag{17}$$

Substituting Eqs. 11 and 17 into Eq. 14 gives the following relation:

$$(\varepsilon_{HMA})^{1/\alpha} = 1 + P_b \frac{G_{mb}}{G_b}\left((\varepsilon_b)^{1/\alpha} - 1\right) + \frac{G_{mb}}{G_{sb}}(1 - P_b)\left((\varepsilon_s)^{1/\alpha} - \frac{G_{sb}}{G_{se}}\right) \tag{18}$$

Reorganizing Eq. 18 gives:

$$(\varepsilon_{HMA})^{1/\alpha} = 1 + G_{mb}\left[\frac{P_b}{G_b}\left((\varepsilon_b)^{1/\alpha} - 1\right) + \frac{(1 - P_b)}{G_{sb}}\left((\varepsilon_s)^{1/\alpha} - \frac{G_{sb}}{G_{se}}\right)\right] \tag{19}$$

Thus the expression of G_{mb} can be found as:

$$G_{mb} = \frac{(\varepsilon_{HMA})^{1/\alpha} - 1}{\left[\frac{P_b}{G_b}\left((\varepsilon_b)^{1/\alpha} - 1\right) + \frac{(1 - P_b)}{G_{sb}}\left((\varepsilon_s)^{1/\alpha} - \frac{G_{sb}}{G_{se}}\right)\right]} \tag{20}$$

Substituting Eqs. 11, 13, and 17 into Eq. 6 gives the air voids content as:

$$AV = V_a = 1 - G_{mb}\left[\frac{P_b}{G_b} + \frac{(1 - P_b)}{G_{se}}\right] \tag{21}$$

Finally, knowing that:

$$AV = 1 - \frac{G_{mb}}{G_{mm}} \tag{22}$$

where G_{mm} is the maximum theoretical specific gravity of HMA, the expression of G_{mm} can be determined from Eqs. 21 and 22 as:

$$G_{mm} = \frac{1}{\frac{P_b}{G_b} + \frac{(1-P_b)}{G_{se}}} \quad (23)$$

Thus, Eq. 20 is simplified as follows:

$$\boxed{G_{mb} = \frac{(\varepsilon_{HMA})^{1/\alpha} - 1}{\frac{P_b}{G_b}(\varepsilon_b)^{1/\alpha} + \frac{(1-P_b)}{G_{sb}}(\varepsilon_s)^{1/\alpha} - \frac{1}{G_{mm}}}} \quad (24)$$

For α=2, Eq. 24 is rewritten as:

$$\boxed{G_{mb} = \frac{\sqrt{\varepsilon_{HMA}} - 1}{\frac{P_b}{G_b}\sqrt{\varepsilon_b} + \frac{(1-P_b)}{G_{sb}}\sqrt{\varepsilon_s} - \frac{1}{G_{mm}}}} \quad (25)$$

4.1.2 Rayleigh mixing formula

With the Rayleigh mixing formula, the effective dielectric constant, ε_{eff}, of a mixture composed of a background material (dielectric constant ε_b) with N inclusions of different dielectric constants is given by the following equation:

$$\frac{\varepsilon_{eff} - \varepsilon_b}{\varepsilon_{eff} + 2\varepsilon_b} = \sum_{i=1}^{N} \frac{n_i \alpha_i}{3\varepsilon_b} \quad (26)$$

where n_i and α_i are respectively the number of inclusions and the polarizability factor of material i. The polarizability α_i of a spherical inclusion of radius a_i is given by:

$$\alpha_i = 4\pi a_i^3 \varepsilon_b \frac{\varepsilon_i - \varepsilon_b}{\varepsilon_i + 2\varepsilon_b} \quad (27)$$

where ε_i is the dielectric constant of inclusion i. Thus, the dielectric constant of the mixture is given by the following:

$$\frac{\varepsilon_{eff} - \varepsilon_b}{\varepsilon_{eff} + 2\varepsilon_b} = \sum_{i=1}^{N} \frac{4\pi a_i^3 n_i}{3} \frac{\varepsilon_i - \varepsilon_b}{\varepsilon_i + 2\varepsilon_b} \quad (28)$$

Since the volume of n_i spheres of radius a_i is:

$$V_i = \frac{4\pi a_i^3 n_i}{3}\,, \tag{29}$$

Eq. 28 is rewritten as:

$$\frac{\varepsilon_{eff} - \varepsilon_b}{\varepsilon_{eff} + 2\varepsilon_b} = \sum_{i=1}^{N} V_i \frac{\varepsilon_i - \varepsilon_b}{\varepsilon_i + 2\varepsilon_b} \tag{30}$$

where V_i is the fractional volume of inclusions i if the total material volume V_T is considered equal to one.

To apply the Rayleigh mixing formula, we assume that the HMA is composed of an asphalt binder (dielectric constant ε_b) as the background material and spherical shapes of aggregates and air as inclusions. From Eq. 27, the HMA dielectric constant is given by the following equation:

$$\frac{\varepsilon_{HMA} - \varepsilon_b}{\varepsilon_{HMA} + 2\varepsilon_b} = V_{sb} \frac{\varepsilon_s - \varepsilon_b}{\varepsilon_s + 2\varepsilon_b} + V_a \frac{\varepsilon_a - \varepsilon_b}{\varepsilon_a + 2\varepsilon_b} \tag{31}$$

where all the parameters are as defined in Figure 4 and ε_a=1.

Let:

$$C = \frac{\varepsilon_s - \varepsilon_b}{\varepsilon_s + 2\varepsilon_b} \tag{32}$$

and

$$D = \frac{1 - \varepsilon_b}{1 + 2\varepsilon_b} \tag{33}$$

Substituting Eqs. 16, 21, 32, and 33 in Eq. 31 gives:

$$\frac{\varepsilon_{HMA}-\varepsilon_b}{\varepsilon_{HMA}+2\varepsilon_b}=\frac{G_{mb}}{G_{sb}}(1-P_b)C+\left[1-G_{mb}\left(\frac{P_b}{G_b}+\frac{(1-P_b)}{G_{se}}\right)\right]D \tag{34}$$

Solving this equation for G_{mb}, we find the following expression:

$$\boxed{G_{mb}=\frac{\dfrac{\varepsilon_{HMA}-\varepsilon_b}{\varepsilon_{HMA}+2\varepsilon_b}-D}{\dfrac{(1-P_b)C}{G_{sb}}-\dfrac{D}{G_{mm}}}} \tag{35}$$

4.1.3 Böttcher mixing formula

The Böttcher mixing formula is derived in the same way as the Rayleigh mixing formula. The dielectric constant of HMA in this case is given:

$$\frac{\varepsilon_{HMA}-\varepsilon_b}{3\varepsilon_{HMA}}=V_{sb}\frac{\varepsilon_s-\varepsilon_b}{\varepsilon_s+2\varepsilon_{HMA}}+V_a\frac{\varepsilon_a-\varepsilon_b}{\varepsilon_a+2\varepsilon_{HMA}} \tag{36}$$

where all the parameters are as defined in Figure 4 and ε_a=1.

Let:

$$f_1(\varepsilon_{HMA})=\frac{\varepsilon_s-\varepsilon_b}{\varepsilon_s+2\varepsilon_{HMA}} \tag{37}$$

and

$$f_2(\varepsilon_{HMA})=\frac{1-\varepsilon_b}{1+2\varepsilon_{HMA}} \tag{38}$$

Substituting Eqs. 16, 21, 37, and 38 in Eq. 36 gives:

$$\frac{\varepsilon_{HMA}-\varepsilon_b}{3\varepsilon_{HMA}}=\frac{G_{mb}}{G_{sb}}(1-P_b)f_1(\varepsilon_{HMA})+\left[1-G_{mb}\left(\frac{P_b}{G_b}+\frac{(1-P_b)}{G_{se}}\right)\right]f_2(\varepsilon_{HMA}) \tag{39}$$

Solving this equation for G_{mb}, we find the following expression:

$$G_{mb} = \frac{\dfrac{\varepsilon_{HMA} - \varepsilon_b}{3\varepsilon_{HMA}} - f_2(\varepsilon_{HMA})}{\dfrac{(1-P_b)}{G_{sb}} f_1(\varepsilon_{HMA}) - \dfrac{f_2(\varepsilon_{HMA})}{G_{mm}}} \tag{40}$$

4.1.4 Specific Gravity Results

Figures 5 and 6 show respectively the variations of G_{mb} and air voids, AV, as a function of ε_{HMA} for the three mixture theories using the following parameters: ε_s = 6, ε_b = 3, P_b = 5%, G_b = 1.015, G_{sb} = 2.705, G_{mm} = 2.521, and α = 2. According to Figure 5, the three models give approximately the same results for the specific gravity G_{mb} (e.g. ε_{HMA} = 5.2, G_{mb} = 2.334 from the CRIM, G_{mb} = 2.396 from the Rayleigh model, and G_{mb} = 2.363 from the Böttcher model). The air voids are also comparable for the three models as shown in Figure 6 (e.g. ε_{HMA} = 5.2 and AV = 7% from the CRIM model, AV = 5% from the Rayleigh model, and AV = 6% from the Böttcher model).

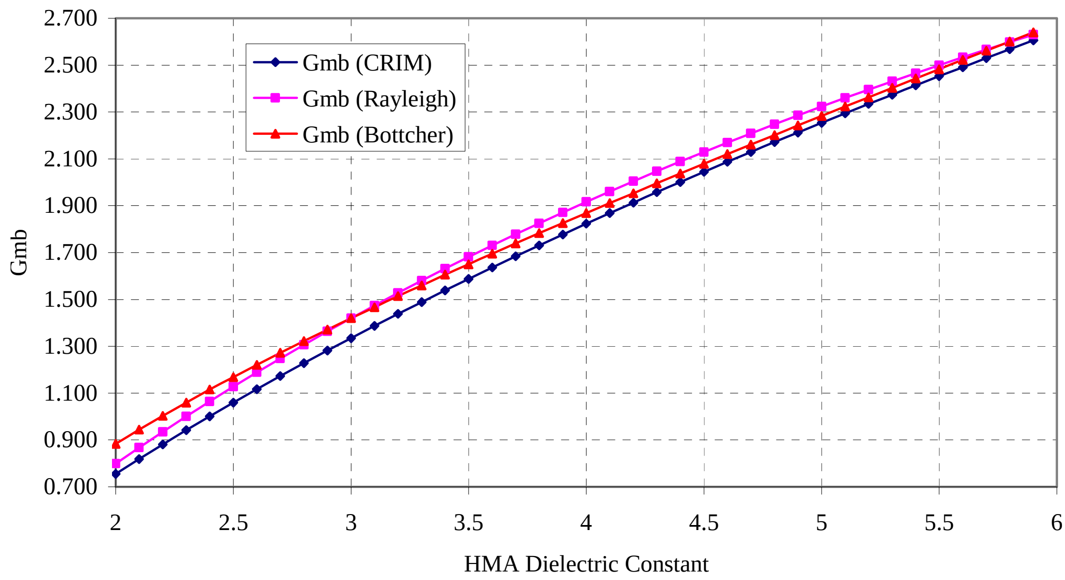

Figure 5. G_{mb} variations as a function of ε_{HMA}.

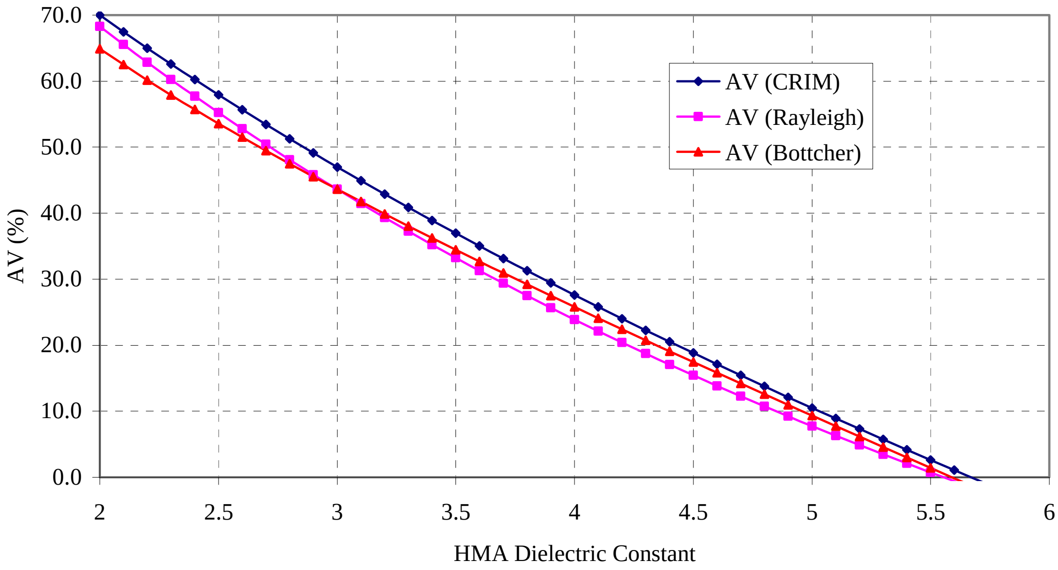

Figure 6. Air voids variations as a function of $\varepsilon_{HMA.}$

Figure 7 shows the specific gravity sensitivity of the three theories with respect to dielectric constant errors. The error on the specific gravity is at most equal to the error on the dielectric constant (e.g. the ε_{HMA} error of 10%, the G_{mb} error is respectively 8.8% for the CRIM model, 7.6% for the Rayleigh model, and 8.7% for the Böttcher model). For the three models, the Rayleigh model has the lowest sensitivity to dielectric constant errors.

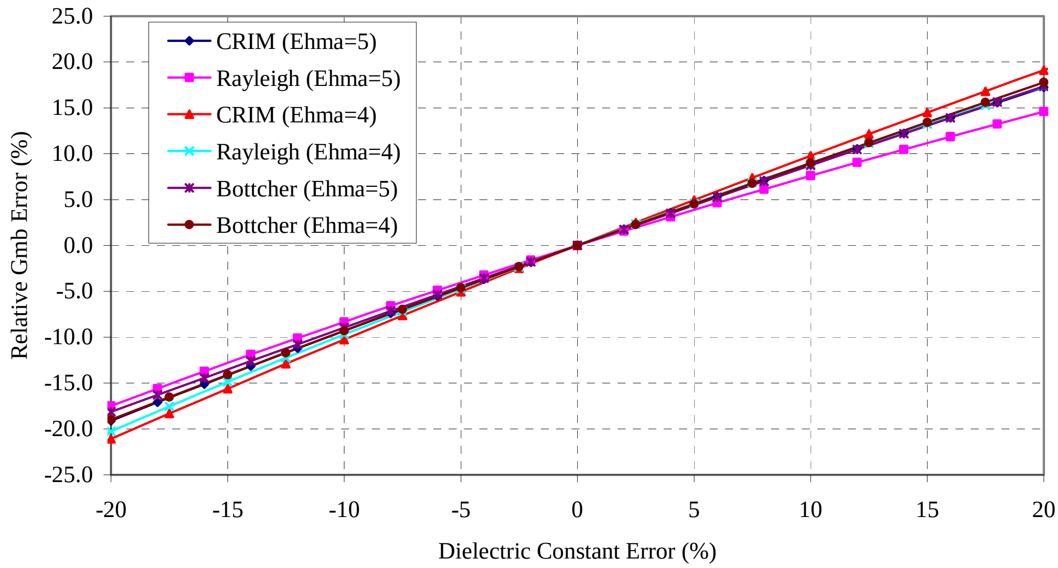

Figure 7. Relative G_{mb} error as a function of ε_{HMA} error.

4.2 Model evaluation using laboratory testing

Laboratory tests were conducted to evaluate the three specific gravity models. In these tests, six 2ft×2ft×3in HMA slabs were manufactured with different compaction levels and then were probed by GPR to estimate their dielectric constants. The specific gravity of these slabs was then estimated by direct measurements on cores and then correlated to the GPR results.

4.2.1 Slab preparation

The HMA slabs were made of limestone aggregates with an asphalt binder content of 5%. The gradation of this mixture is presented in Table 1. As shown in Figure 8, preheated HMA was placed in a 2ft×2ft wooden mold and then compacted with a small roller compactor. To achieve different density levels, specified quantities of HMA were poured in the mold. Then all slabs were compacted to a final design thickness of 3in. After cooling down overnight, the slabs were removed from the mold to be probed by GPR.

Table 1. Gradation of the aggregate used for slab preparation.

Sieve Size	Passing Ratio (%)
1/2"	100.0
3/8"	97.0
# 4	56.3
# 8	34.5
# 16	22.7
# 30	15.0
# 50	8.9
#100	6.3
#200	5.1

(a) HMA fill-in

(b) Compaction

Figure 8. Laboratory slab preparation.

4.2.2 GPR data collection

GPR data were collected from different slabs using a 2.0GHz air-coupled antenna and the SIR20 GPR system manufactured by GSSI. As shown in Figure 9, the antenna was placed on Styrofoam sheets on the slab to insure the air-coupling of the antenna where Styrofoam has a dielectric constant close to that of air (ε_a = 1).

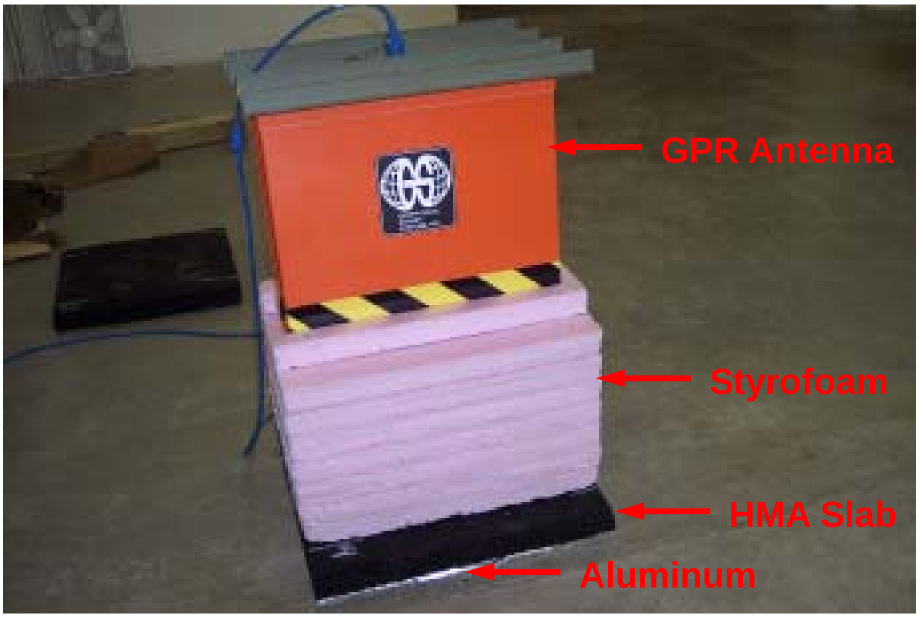

Figure 9. GPR data collection from the slabs.

Figure 10 shows a typical single-scan GPR data collected on one of the HMA slabs. In order to detect the reflection at the bottom of the slab, an aluminum plate, a perfect EM reflector, was placed underneath it. With this method, the reflections from the surface and bottom of the slab were easily detected as seen in Figure 10. From the GPR data, the dielectric constant of each slab was estimated from the reflection amplitude at the surface using Eq. 2. The dielectric constants of the different slabs are presented in Table 2.

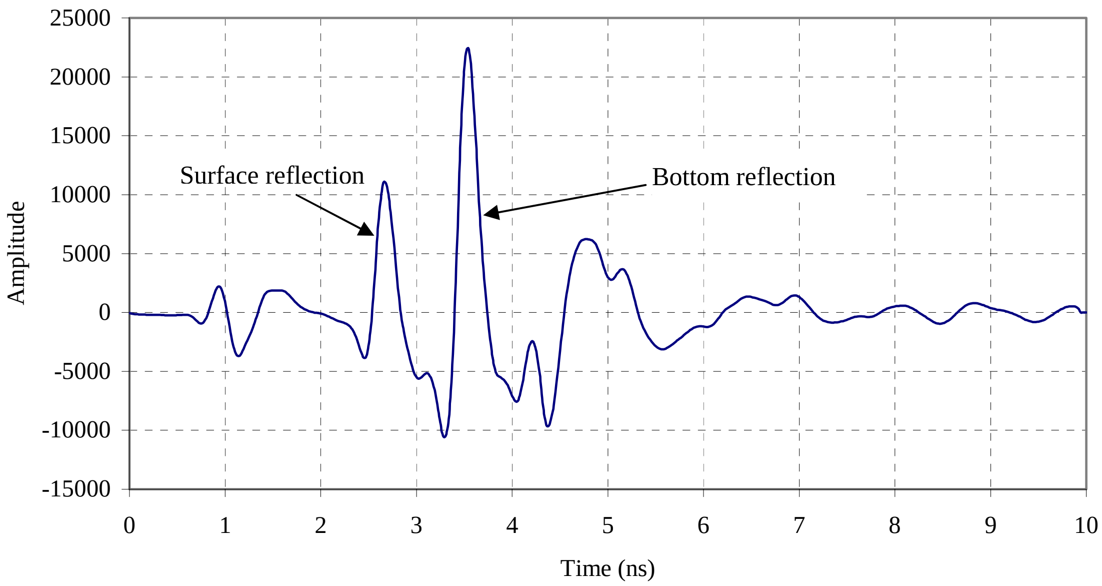

Figure 10. Typical GPR scan collected on a HMA slab.

Table 2. Summary of HMA dielectric constants estimated from GPR data.

Slab #	A_0	A_0/A_P	ε_{HMA}
1	11032	0.391178	5.22
2	10916	0.387065	5.12
3	10890	0.386143	5.10
4	11965	0.428976	6.26
5	11204	0.401692	5.49
6	11346	0.406783	5.62

4.2.3 Laboratory HMA density measurements

After collecting GPR data from all the slabs, two cores were taken from each slab to directly measure the specific gravity (G_{mb}), the maximum theoretical specific gravity (G_{mm}), and the air-voids content according to the AASHTO standards (2001). The results of these tests are presented in Table 3.

Table 3. Specific gravity for the different HMA slabs.

Slab #	Dry Sample Weight (g)	Submerged Weight (g)	SSD Weight (g)	$\boldsymbol{G_{mb}}$	G_{mm}	Air Voids (%)
1	912.2	518.7	948.4	**2.122**	2.526	16.0
2	1041.1	597.9	1090.9	**2.111**	2.526	16.4
3	892.4	508.4	927.6	**2.128**	2.526	15.7
4	1013.7	579	1024.6	**2.274**	2.526	9.9
5	990.4	564.1	999.6	**2.274**	2.526	10.0
6	833.6	476.2	856	**2.194**	2.526	13.1

4.2.4 Preliminary modal validation

Using the results of Table 2 and Table 3, the HMA specific gravity variation as a function of the dielectric constant variation are presented in Figure 11. This figure also shows the fitting results of the three models to the measured data using a non linear least squares fitting algorithm due to the complexity of the models. In this case, two variables were assumed constants (G_{sb} = 2.610 and G_b = 1.015), and the remaining four parameters were determined from the curve fitting.

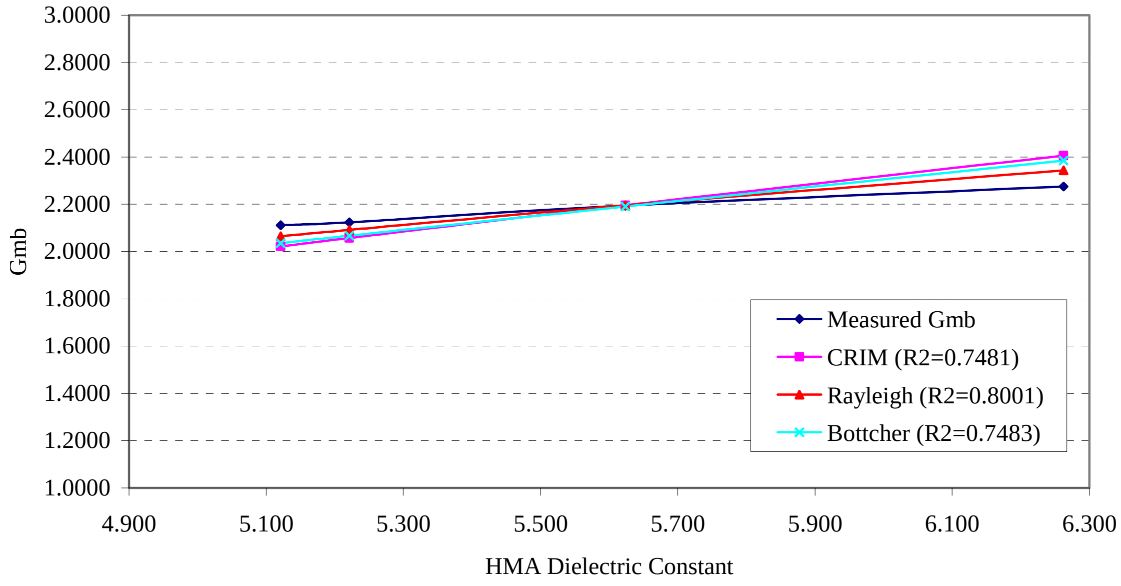

Figure 11. Measured and fitted G_{mb} variation as a function of ε_{HMA}..

The results of the curve fitting procedure for the three models are presented in Table 4. Based on these results, the dielectric constant estimation by the Rayleigh model gives better G_{mb} results (higher R^2 value and lower root mean square error) than the other two models for this particular mix. Therefore, its performance was further validated by using the field collected GPR data. Based on the preliminary results, the specific gravity and air voids content of the HMA could be predicted from the dielectric constant of the HMA estimated from GPR data if a proper model is used.

Table 4. Statistical analysis results for the proposed models.

Model	R^{2*}	RMSE*	ε_s	ε_b	P_b(%)	G_{mm}
CRIM	0.7481	0.0857	6.38	3.21	5.1	2.602
Rayleigh	0.8001	0.0443	7.44	2.00	4.1	2.276
Böttcher	0.7483	0.0727	8.33	7	6.0	3.026

* R^2 is the coefficient of determination and RMSE is root mean square error.

4.3 Model validation using a testing site

Laboratory testing results indicated that the specific gravity model based on the Rayleigh mixing formula gives better G_{mb} results (higher R^2 value and lower root mean square error) than the other two models. In order to evaluate the performance of this model for predicting in-place HMA density, a field GPR survey was conducted on a composite pavement located at the University of Illinois. This composite pavement consists of an HMA overlay on a continuously reinforced concrete (CRCP) pavement. The HMA overlay is 2.25in thick and approximately 250ft long. The aggregate used in the HMA is limestone and the asphalt binder is PG64-22 at 4.6%. The gradation of the HMA is shown in Table 5. The same 2.0GHz air-coupled antennae were used for GPR data collection (Figure 12). The survey speed was about 20mph, which means it only took around 10s to survey the whole 250-ft long pavement section.

Table 5. Gradation of the aggregate used in HMA overlay.

Sieve Size	Passing Ratio (%)
1"	100
3/4"	98
1/2"	76
3/8"	66
# 4	39
# 8	23
# 16	16
# 30	10
# 50	7
#100	6
#200	4.5

Figure 12. HMA pavement survey using a 2.0GHz air-coupled antenna.

Figure 13 shows the GPR image data for the surveyed composite pavement. Based on the collected GPR data, the dielectric constant profile of the HMA surface was calculated using Eq. (2) as shown in Figure 14. The dielectric constant values of the HMA surface are relatively constant throughout the whole pavement section. All dielectric constant values are within the range from 7.0 to 7.5. It indicates that the HMA density is also relatively uniform for the entire section.

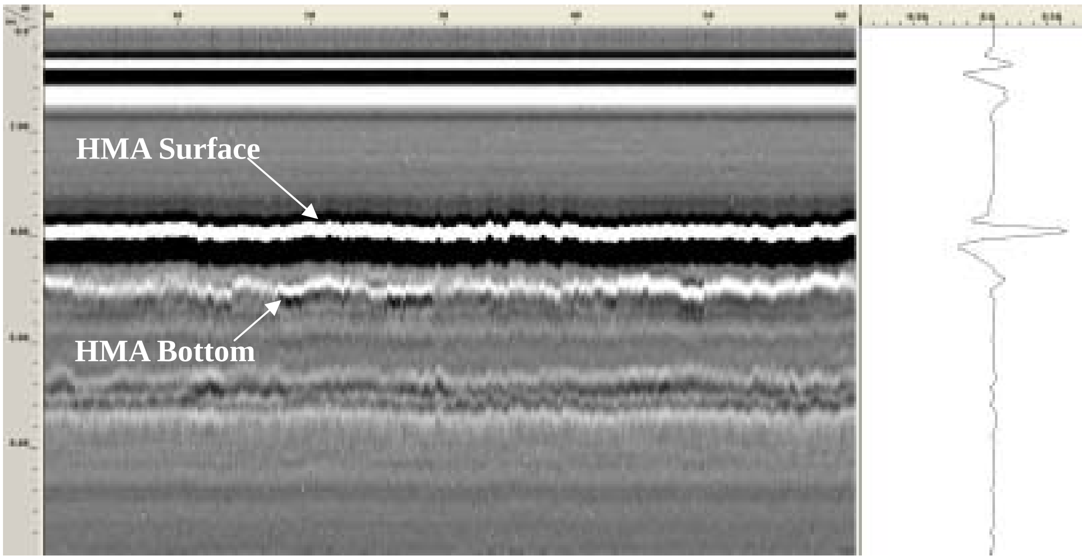

Figure 13. GPR image from the composite pavement with HMA surface.

After the dielectric constant profile of the HMA surface was obtained, the bulk specific gravity profile of the HMA surface was calculated using the specific gravity model based on the Rayleigh mix formula (Eq. (35)). The following parameters were used in the model: ε_b = 3 (as a typical value), P_b = 4.6% (as measured), G_b = 1.015 (as a typical value), G_{sb} = 2.70 (as a typical value), G_{mm} = 2.488 (as measured). Now only one parameter, $\varepsilon_{s,}$ is unknown on the right hand side of Eq. 35. Since the dielectric constant of limestone, ε_s, is within a relatively wide range from 7.5 to 9.2 (Johnson & Pile, 2002), one HMA core was extracted from the field and its bulk specific gravity was measured in the lab to get a good estimate of this value. Based on the measured G_{mb} from the HMA core, ε_s was determined as 8.78. Then the bulk specific gravity profile of the HMA surface was calculated and presented in Figure 14.

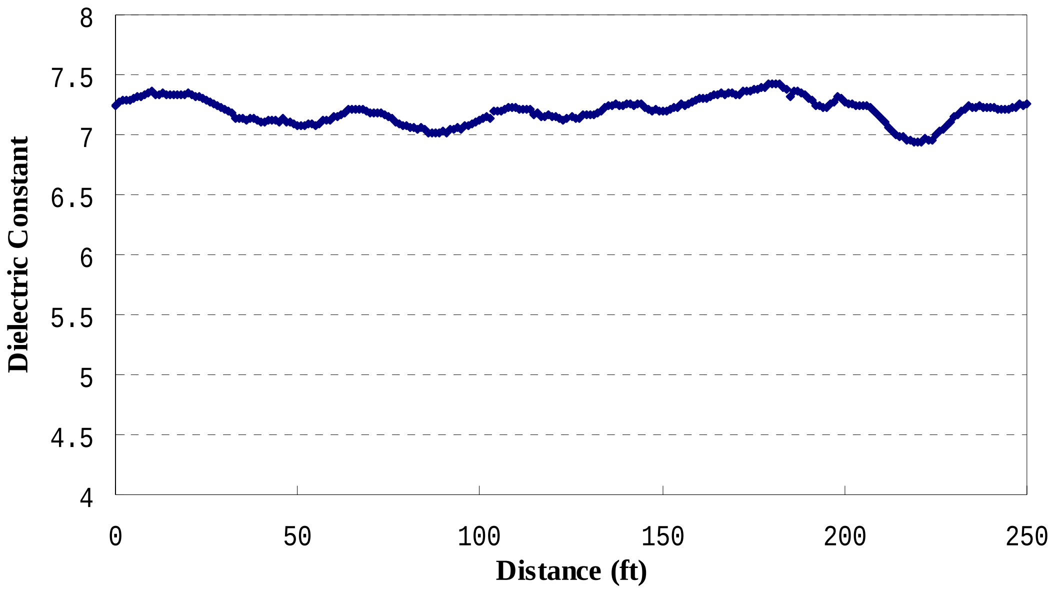

Figure 14. Dielectric constant profile of the HMA surface.

To validate the specific gravity model, four more field cores were taken at the same location where the GPR test was conducted. The measured bulk specific gravities of these HMA cores are also shown in Figure 14 (marked as a square shape) and Table 6. The predicted HMA bulk specific gravity values show quite reasonable agreements with the measured values from the cores. Table 6 also shows the relative errors of the bulk specific gravity prediction at these four coring locations. The small relative error indicates that the estimations by the bulk specific model based on the Rayleigh formula are reasonably accurate after calibration with the pavement core.

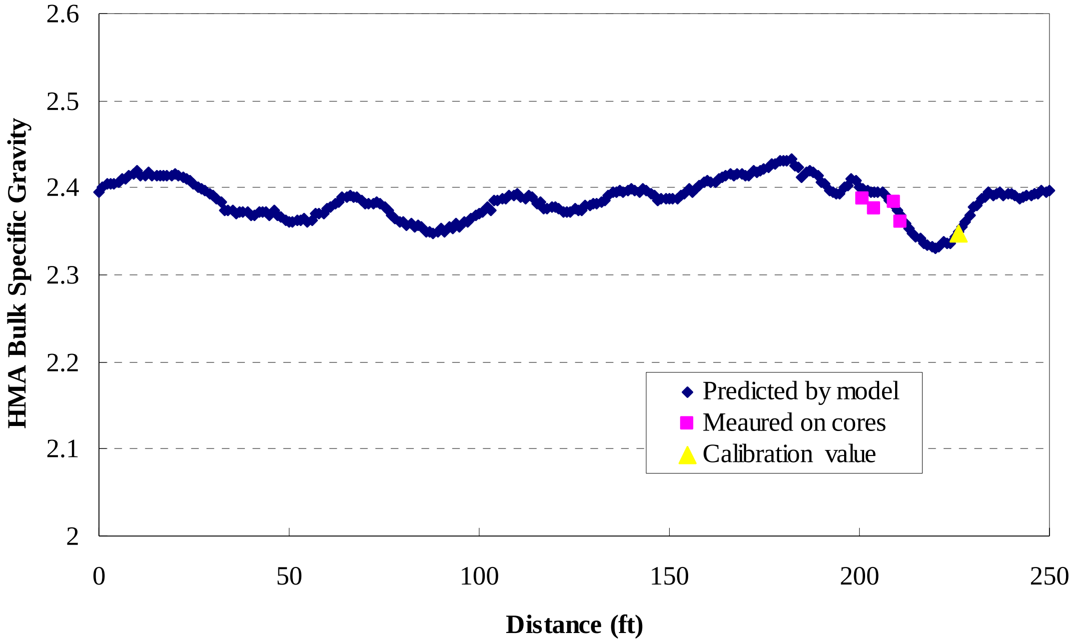

Figure 14. Bulk specific gravity profile of the HMA surface.

Table 5. Relative errors in bulk specific gravity prediction.

Core #	1	2	3	4	5*
G_{mb} measured on cores	2.398	2.395	2.380	2.368	2.350
G_{mb} predicted by the Rayleigh model	2.388	2.375	2.384	2.362	2.350
Relative error (%)	4.3	5.1	3.6	4.6	0.0

* Core #5 was used for calibration

4.4 Summary

Based on the EM mixing theory, three HMA bulk specific gravity models were developed in this study. The best model was then selected through laboratory testing and validated by the field data. The ability of using GPR to measure in-place HMA density was investigated. The following summarizes the findings:

- Estimated HMA dielectric constant from GPR data can yield to determining its density and air void when appropriate model is used. For the case presented in this proposal, the relative errors of the predicted HMA bulk specific gravities based on the Rayleigh mixing formula are less than 6% after the model was calibrated by a field core.

- When GPR is used for in-place HMA pavement density measurement, the density profile of the entire pavement can be obtained. This significantly improves the reliability of the in-situ pavement density measurement considering all the other in-place density measurement methods can only provide density data at discrete sampling locations.

- GPR density measurement is fast. For example, for the 250-ft pavement section surveyed in this study, it only took around 10 seconds to collect the GPR data.

However, it should be noted that in this study, only one type of aggregate, limestone, was evaluated, and all materials were tested under dry condition. In future research, more variables, such as different aggregate types and moisture effect, should be included in the model, and the accuracy of the model should be validated by more data collected from in-service airport pavements. Only in this way, the accuracy of the HMA specific gravity models can be assured and this new approach for in-place HMA density measurement can be implemented in practice.

5. Cost Effectiveness Evaluation

For QC for new airport pavement construction, the main statistical inputs are mean, standard deviation, and the coefficient of variation which is a percentage of mean to standard deviation. When the coefficient of variation is less than 20%, the data is normally acceptable (FAA, 2004a). Since most pavement measurements are assumed to be distributed normally, the probability of failure events can be simply computed mean and standard deviation. However, this assumption can be failed due to an uncertainty of the measurements when the population of the random samples tested with typical density measurement methods is only a small fraction of all materials evaluated. If the proposed GPR system is used to estimate the HMA density, more density data can be obtained in a wider region. In turn, a more reliable or higher confidential density evaluation can be achieved. Also, contractors are paid for the construction of an HMA layer based on a pay factor. The pay factor is determined with the percentage of material within specification limits (PWL), which is computed with the sample average and standard deviation of the number of sublots. Hence, although it is hard to do direct quantification for the benefit of the higher reliability of the data, it is clear that the proposed GPR system can yield more reliable data and moreover, contribute on un-biased payment to contractors and agencies.

6. Safety Risk Assessment

The existing FAA safety management system guidance was examined regarding the usage of GPR. According to Introduction to Safety Management Systems for Airport Operators (FAA, 2007) and FAA Safety Management System Manual (FAA, 2004), no inherent risks were found to ensure safe operations in that HMA pavements should be constructed during a period when no aircraft operation is requested.

If some aircraft traffic is operated during the pavement construction, the radio frequency interference can occur since GPR is an ultra wide band (UWB) device. Also, the FAA Technical Center conducted operational tests on an available GPR to provide a qualitative assessment of the effects on aeronautical systems operating below 960MHz (Badinelli et al. 2004). The tested GPR exceeded the new Federal Communications Commission (FCC) requirements meaning that severe interference can occur to the air traffic control (ATC). Thus, the FAA recommended that "the FCC require that GPRs be shielded so that emissions other than those required for proper operation of the equipment, are suppressed." Therefore, it is required to test the effects of the usage of the 2.0GHz GPR antenna on the ATC.

7. Description of Interactions with Airport Operators and Industry Experts

The results presented herein are based partly on an ongoing project sponsored by the Federal Aviation Administration (FAA) through the Center of Excellence for Airport Technology (CEAT). The authors would like to acknowledge the support of Albert Larkin and David Brill of FAA.

In order to obtain the advice from airport operators and industry experts on this new method for in-place HMA density measurement, a technical survey was sent to several experts in airport pavement design, maintenance, and management. Three responses to the questionnaire were received, and the experts' contact information is listed in Table 7.

Table 7. List of experts responding to the questionnaire.

Name	Title	Company/ Organization	Phone	Email
David Peshkin	Vice President	Applied Pavement Technology, Inc.	(217)398-3977	dpeshkin@appliedpavement.com
Matthew Wenham	Managing Engineer	C&S Engineers	(216) 619-5449	mwenham@cscos.com
William Trudeau	Quality Assurance Manager	O'Hare Modernization Program	(312)656-1913	william.trudeau@cityofchicago.org

The questions in the survey are contained in Appendix G. The following summarizes the findings from the questionnaire:

- Coring and nuclear gauge are the most commonly used methods for in-place HMA density measurement. None of the experts who responded to the survey have experience using non-nuclear density gauge or GPR for HMA density measurement.

- Regarding the number of data points needed to ensure uniform HMA density and thickness measurement, two experts answered that the FAA specifications should be followed, and one expert thinks the data points should be as many as possible.

- All experts are more or less familiar with ground penetrating radar (GPR). However, none of them have knowledge about using GPR for in-place HMA density for airport pavement.

- All experts showed interest in an innovative technique which is capable of accurately predicting HMA density and thickness in a continuous and non-destructive way.

- The feedback from the questionnaire indicates that the industry is strongly interested in an innovative method which can provide continuous in-place HMA density data for airport pavements, and using GPR to measure in-place HMA density is new to the industry.

8. Description of the Projected Impacts of Team's Design and Findings

This study proposes a rapid, continuous, and accurate non-destructive test method to predict in-place HMA bulk specific gravity/density of airport pavements using GPR and mathematical models. The projected impacts of the team's design and findings mainly include the following:

1. The airport pavement quality control and assurance activities can be conducted in a more reliable way, since continuous HMA density profile will be provided from GPR data instead of only limited data at discrete sampling locations. Checking the uniformity of the HMA density for airport pavements will become feasible.

2. The in-place density measurement for HMA airport pavement can be conducted rapidly at a speed of up to 60mph, which will cause minor or no interruption to the normal airport operation.

3. GPR data can provide more information on the internal airport pavement structure (such as layer thicknesses and subsurface distress) in addition to the HMA density.

4. In-place HMA density of airport pavement can be quantified in a more cost-effective way.

5. The GPR method will completely eliminate the licenses, specialized storage, and risks associated with nuclear gauge devices that use a radioactive source, while also being nondestructive.

6. Various GPR equipments and softwares are commercially available. Therefore, the proposed approach can be easily implemented to measure the in-place HMA density for airport

QC/QA activities after further field validations. The only additional thing needed is to incorporate the developed models into the GPR data processing and analysis softwares.

List of Appendices

A. List of complete contact information

B. Description of the university

C. Description of non-university partners

D. Sign-off from for faculty advisor and department chair

E. Evaluation of the educational experience provided by the project

F. Reference list with full citations

G. Other support materials - Questionnaires

Appendix A. List of Complete Contact Information

1. Faculty Advisor #1

- Name: Imad L. Al-Qadi
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- Phone: 217-265-0427, Fax: 217-333-1924
- Email: alqadi@illinois.edu

2. Faculty Advisor #2

- Name: Samer Lahouar
- Affiliates: Visiting Scholar at University of Illinois at Urbana-Champaign from Institut Supérieur des Sciences Appliquées et de Technologie de Sousse, Tunisia
- Address: 1611 Titan Dr. Rantoul, IL 61866
- Phone : 217-893-0705, Fax: 217-893-0601
- Email : Samer.Lahouar@issatso.rnu.tn

3. Student #1

- Name: Zhen Leng
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- Phone: 217-893-0705, Fax: 217-893-0601
- Email: zleng2@illinois.edu

4. Student #2

- Name: Jongeun Baek
- Affiliates: Graduate Research Assistant
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- Phone: 217-893-0705, Fax: 217-893-0601
- Email: baek2@illinois.edu

Appendix B. Description of the University

The University of Illinois, founded in 1867, currently consists of 16 colleges and instructional units and 37 campus libraries. The main campus is located in Urbana and Champaign in central Illinois, and about 30,000 undergraduate and 11,000 graduate students are enrolled. The University of Illinois operates an impressive array of academic, educational and research programs for innovative achievements with excellence in many key areas. In addition, with remarkable new discoveries and innovative achievement in its research projects, the university has served the state, the nation and the world. By creating knowledge and applying knowledge for crucial societal needs and developments, it has enriched and improved the lives of people in the world.

The University of Illinois is recognized as one of the leading universities in America by producing outstanding alumni and consistently receiving high rankings in university and college evaluations. Twenty-two Nobel prizes and thirteen Pulitzer prizes were endowed to its alumni and faculties. According to U.S News & World Report on America’s Best colleges, it is ranked as the number 8 public university and the number 38 national university. Especially, the schools of engineering are nationally ranked as the 5^{th} in both undergraduate and graduate programs. Among the engineering schools, the department of civil and environmental engineering has been recognized as the best program in America.

Appendix C. Description of Non-University Partners

The results presented in this proposal are based partly on an ongoing project sponsored by the Federal Aviation Administration (FAA) through the Center of Excellence for Airport Technology (CEAT). The pavement section evaluated in this study is used in a project sponsored by the Illinois Department of Transportation (IDOT).

Appendix D. Sign-Off from for Faculty Advisor and Department Chair

FAA Design Competition for Universities Design Submission Form

Note: This form should be included as Appendix D in the submitted PDF of the design package. The original with signatures must be sent along with the required print copy of the design.

University ____ University of Illinois at Urbana-Champaign ____
List other partnering universities if appropriate ____

____

Design Developed by: ☐ Individual Student ■ Student Team

If Individual Student

Name ____
Permanent Mailing Address ____

____

Permanent Phone Number ____ Email ____

If Student Team:

Student Team Lead ____ Zhen Leng ____
Permanent Mailing Address ____ 1611 Titan Dr., Rantoul, IL 61866 ____

____

Permanent Phone Number ____ (217)419-6683 ____ Email zleng2@illinois.edu

Competition Design Challenge Addressed:
Airport Operation and Maintenance: non-destructive evaluation methodologies

I certify that I served as the Faculty Advisor for the work presented in this Design submission and that the work was done by the student participant(s).

Signed ____ *Date* ____
Name ____ Imad L. Al-Qadi ____
University/College ____ University of Illinois at Urbana-Champaign ____
Department(s) ____ Department of Civil and Environmental Engineering ____
Street Address ____ 205 N. Mathew MC-250 ____
City ____ Urbana ____ State ____ IL ____ Zip Code ____ 61801
Telephone ____ (217) 265-0427 ____ Fax ____ (217) 333-1924 ____

Appendix E. Evaluation of the Educational Experience Provided by the Project

E.1. Faculty advisor: Imad L. Al-Qadi

For faculty members:

l. Describe the value of the educational experience for your student(s) participating in this competition submission.

- I'm conducting the evaluation on behalf of the faculty advisors. This project allows Zhen and Baek to work together as a team. They were able to work on developing models and use advanced technologies for new application. They took this further and implemented their findings after being preliminarily validated. One of the most important parts of any research project is evaluating its potential applicability compared to exiting techniques and its cost effectiveness. They have done that appropriately and compared the GPR to existing techniques and identified its cost effectiveness as well as other advantages that this technique has.

2. Was the learning experience appropriate to the course level or context in which the competition was undertaken?

- Yes. The students did learn advanced technology and its implementation, but also they learned how to be team players and use engineering value.

3. What challenges did the students face and overcome?

- Developing a model for hot-mix asphalt that allows the calculation of bulk dielectric constant from the volumetric and dielectric constant of its components was a real challenge.

4. Would you use this Competition as an educational vehicle in the future? Why or why not?

- Yes, I have and will continue to do so for the reasons mentioned in #1.

5. Are there changes to the Competition that you would suggest for future years?

- No. It is good for students; especially when they work as a team.

E.2 Student #1: Zhen Leng

For the students, the evaluation should minimally address the following questions:

1. Did the FAA Airport Design Competition provide a meaningful learning experience for you? Why or why not?

Yes, it surely did. Going over the resource listed in the FAA Competition Design website extended my knowledge from highway pavement to airport pavement, and from ground-penetrating radar to other non-destructive testing methods for pavement; Cooperating with Jongeum as a team under Prof. Al-Qad's guidance and communicate with airport industry experts increased my ability of communication; completing this technical report increased my ability of presenting technical work in a clear way.

2. What challenges did you and/or your team encounter in undertaking the Competition?

How did you overcome them?

The biggest challenge I had was that the GPR is an electromagnetic device, and as a student majoring in civil engineering, I didn't have strong background on the working mechanism of the electromagnetic device and the corresponding data analysis techniques. In order to overcome this challenge, I have registered for or sat in several classes in electrical engineering, such as Digital Signal Analysis and Electromagnetic Field. In addition, I have searched and read many papers and books related to this topic. My advisor, who's an expert on GPR application, also gave me tremendous advice. After all these efforts, I have become confident and comfortable using the GPR as a nondestructive method for evaluating transportation structures, such as highways, airports, and railroads.

3. Describe the process you or your team used for developing your hypothesis.

First of all, we were very clear that the in-place HMA density is a critical parameter for airport *pavement performance, but we also noticed that the current methods for in-place HMA density measurement have many drawbacks. At the same time, we had the experience of accurately measuring the pavement thickness using GPR technology. When looking at the GPR data collected on HMA pavement, we found that the dielectric constant of HMA was affected by its density or air void. For the same mixture, the larger the air void, the smaller dielectric constant was measured by GPR. Then we looked into the background knowledge about the mixture's dielectric constant and found that the dielectric constant of a mixture is dependent on the dielectric and volumetric properties of its components. Since the dielectric constant of HMA pavement can be measured by GPR in an accurate, continuous and rapid way, we were encouraged to work on developing models between the dielectric constant and density of HMA.*

4. Was participation by industry in the project appropriate, meaningful and useful? Why or why not?

Yes. The industry experts have provided valuable information on the current methods commonly used for in-place HMA density measurement for airport pavement and how they judge these methods. Through sending out the questionnaire, we also introduced the industry experts to a promising new method of using GPR to measure the in-place HMA density for airport pavements continuously and nondestructively.

5. What did you learn? Did this project help you with skills and knowledge you need to be successful for entry in the workforce or to pursue further study? Why or why not?

By working on an interdisciplinary topic in this competition, I learned how to effectively combine the knowledge of electrical engineering and civil engineering to develop an innovative method *for airport pavement QC/QA. I also learned that the cost-effectiveness is always an important issue for engineering problems and the engineering research should be oriented by industry need. Beyond the technical aspects, I learned how to plan and organize a project as a group leader as well as how to cooperate and communicate with others as a group member. All these experiences will be extremely helpful when I enter the workforce.*

E.3 Student #2: Jongeun Baek

For the students, the evaluation should minimally address the following questions:

1. Did the FAA Airport Design Competition provide a meaningful learning experience for you? Why or why not?

- Yes, it was another valuable opportunity for me to understand airport pavement construction better, especially on quality control (QC) and quality assurance (QA) programs. At the end of the completion of this competition, I could get an idea on other innovative approaches. Moreover, the corporation with others for this work was the most invaluable experience that I can't achieve from books.

2. What challenges did you and/or your team encounter in undertaking the Competition? How did you overcome them?

- The most challenging issue that I have experienced was to understand typical circumstances airport pavements faced on since most of works I have been involved in were related to roads. In order to apply the proposed NDT approach to airports, I had to specify the own characteristics on airport pavements first. In this point, I can't overemphasize the usefulness of the FAA's

documentations such as Advisory Circular. Throughout the documentations, I could catch up with most of problems and solutions to be considered in this proposal.

3. Describe the process you or your team used for developing your hypothesis.

- The idea of this proposal, estimating density of a hot mix asphalt (HMA) layer using ground penetrating radar (GPR), needs lots of mechanical and physical understandings and knowledge for HMA materials and electromagnetic (EM) pulse. Zhen, a team leader, already took several classes for those matters and has been doing a couple of projects and I was involved in a couple of projects in which GPR was used. However, those experiences and knowledge were not enough for us to solve the particular problem unless we shared our own ones with each other.

4. Was participation by industry in the project appropriate, meaningful and useful? Why or why not?

- Yes, it was definitely a good chance to hear what happens in our real life from airport experts though it was not smooth to get responses from them through questionnaires. We found that there are some needs for efficient and reliable QC and QA programs for airport pavement construction. It could encourage us to move forward with full of confidence on this concern.

5. What did you learn? Did this project help you with skills and knowledge you need to be successful for entry in the workforce or to pursue further study? Why or why not?

- I recognized that the payment for the construction is made based on end-product-quality such as a density level. Before the participation, I didn't have any interest on those kinds of practical and financial procedure, but now I realized that I have to study a "real" design procedure considering cost and QC matters before getting into the workforce.

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Appendix G. Other Support Materials

G.1 Questionnaire to airport experts

FAA Design Competition Questionnaire

Your participation in this survey is greatly appreciated. This survey will be used ONLY for the "FAA Design Competition for Universities 2008-2009 Academic Year." Our design team's objective is to develop "a fast and reliable nondestructive test (NDT) method to estimate in-situ hot-mix asphalt (HMA) density of airfield pavements using ground penetration radar (GPR)." In order to accomplish the goal, we need to collect information on the current methods airports use for quality control (QC) and quality assurance (QA) for flexible pavement density. Please answer the following questions:

1. Please provide basic information about your airport (if applicable):
   Name:
   Location:
   ** If possible, please attach an information sheet on the traffic at your airport (type of airplanes and frequency).*

2. Your airport's runways are (if applicable): A. Flexible; B. Rigid; C. Composite
   Your airport's taxiways are (if applicable): A. Flexible; B. Rigid; C. Composite
   Your airport's aprons are (if applicable): A. Flexible; B. Rigid; C. Composite

3. Which of the following methods have you used to determine the HMA density of newly constructed as well as existing pavements? (Circle all that apply.)
   A. Coring;
   B. Nuclear gauge;
   C. Non-nuclear electromagnetic gauge;
   D. Ground penetrating radar

4. In your opinion, how many data points are needed to ensure the uniformity of HMA density and thickness measurement for a 1000ft-long section?
   A. 20; B. 50; C. 200; D. As many as possible

5. If a nondestructive technique is capable of accurately predicting HMA density and thickness in a continuous way, will it be of interest to your organization?

6. Are you familiar with ground penetrating radar?

7. In your opinion, will ground penetrating radar work for predicting HMA density?

8. If you have any other comments regarding this topic in addition to the above questions, please provide your input here:

Please return your questionnaire and possible questions to Jongeun Baek at baek2@illinois.edu or Zhen Leng at zleng2@illinois.edu. Thank you!

G.2 Survey response #1

FAA Design Competition Questionnaire

Your participation in this survey is greatly appreciated. This survey will be used ONLY for the "FAA Design Competition for Universities 2008-2009 Academic Year." Our design team's objective is to develop "a fast and reliable nondestructive test (NDT) method to estimate in-situ hot-mix asphalt (HMA) density of airfield pavements using ground penetration radar (GPR)." In order to accomplish the goal, we need to collect information on the current methods airports use for quality control (QC) and quality assurance (QA) for flexible pavement density. Please answer the following questions:

1. Please provide basic information about your airport (if applicable): N/A
   Name:
   Location:
   ** If possible, please attach an information sheet on the traffic at your airport (type of airplanes and frequency).*

2. Your airport's runways are (if applicable): A. Flexible; B. Rigid; C. Composite N/A
   Your airport's taxiways are (if applicable): A. Flexible; B. Rigid; C. Composite N/A
   Your airport's aprons are (if applicable): A. Flexible; B. Rigid; C. Composite N/A

3. Which of the following methods have you used to determine the HMA density of newly constructed as well as existing pavements? (Circle all that apply.)
   A. Coring;
   B. Nuclear gauge;
   C. Non-nuclear electromagnetic gauge;
   D. Ground penetrating radar

4. In your opinion, how many data points are needed to ensure the uniformity of HMA density and thickness measurement for a 1000ft-long section?
   A. 20; B. 50; C. 200; D. As many as possible
   I don't know the number, but it should correspond with that required by the FAA in their P-401 specification.

5. If a nondestructive technique is capable of accurately predicting HMA density and thickness in a continuous way, will it be of interest to your organization?
   This would be interesting for several reasons, including the availability of more data, the quicker availability of data, and the ability to identify localized areas of poor density or insufficient thickness.

6. Are you familiar with ground penetrating radar?
   Yes.

7. In your opinion, will ground penetrating radar work for predicting HMA density?
   I have no opinion on this. Would it need to be calibrated to actual densities (as must be done to use it for thicknesses)?

8. If you have any other comments regarding this topic in addition to the above questions, please provide your input here:

Please return your questionnaire and possible questions to Jongeun Baek at baek2@illinois.edu or Zhen Leng at zleng2@illinois.edu. Thank you!

G.3 Survey response #2

FAA Design Competition Questionnaire

Your participation in this survey is greatly appreciated. This survey will be used ONLY for the "FAA Design Competition for Universities 2008-2009 Academic Year." Our design team's objective is to develop "a fast and reliable nondestructive test (NDT) method to estimate in-situ hot-mix asphalt (HMA) density of airfield pavements using ground penetration radar (GPR)." In order to accomplish the goal, we need to collect information on the current methods airports use for quality control (QC) and quality assurance (QA) for flexible pavement density. Please answer the following questions:

1. Please provide basic information about your airport:
   Name:
   Location:
   ** If possible, please attach an information sheet on the traffic at your airport (type of airplanes and frequency).*
   I'm a consultant to provide service to many airports

2. Your airport's runways are A. Flexible; B. Rigid; C: Composite

Your airport's taxiways are: A. Flexible; B. Rigid; C: Composite
Your airport's aprons are: A. Flexible; B. Rigid; C: Composite
Variety. Usually large airports have more rigid (PCC) pavement. Also, aprons are more frequently rigid.

3. Which of the following methods have you used to determine the HMA density of newly constructed as well as existing pavements? (Circle all that apply.)
   A. Coring;
   B. Nuclear gauge;
   C. Non-nuclear electromagnetic gauge;
   D. Ground penetrating radar

4. In your opinion, how many data points are needed to ensure the uniformity of HMA density and thickness measurement for a 1000ft-long section?
   A. 20; B. 50; C. 200; D. As many as possible
   20 or less. More dependent on production capacity. FAA method is 4 sublots per lot. Lot is one day's production or 2000tons. This usually equals to about 1500'*100'*2" thickness.

5. If a nondestructive technique is capable of accurately predicting HMA density and thickness in a continuous way, will it be of interest to your organization?
   Yes.

6. Are you familiar with ground penetrating radar?
   Somewhat.

7. In your opinion, will ground penetrating radar work for predicting HMA density?
   I don't know.

8. If you have any other comments regarding this topic in addition to the above questions, please provide your input here:

Please return your questionnaire and possible questions to Jongeun Baek at baek2@illinois.edu or Zhen Leng at zleng2@illinois.edu. Thank you!

G.4 Survey response #3

FAA Design Competition Questionnaire

Your participation in this survey is greatly appreciated. This survey will be used ONLY for the "FAA

Design Competition for Universities 2008-2009 Academic Year." Our design team's objective is to develop "a fast and reliable nondestructive test (NDT) method to estimate in-situ hot-mix asphalt (HMA) density of airfield pavements using ground penetration radar (GPR)." In order to accomplish the goal, we need to collect information on the current methods airports use for quality control (QC) and quality assurance (QA) for flexible pavement density. Please answer the following questions:

1. Please provide basic information about your airport:
   Name: O'Hare
   Location: Chicago
   ** If possible, please attach an information sheet on the traffic at your airport (type of airplanes and frequency).*

2. Your airport's runways are A. Flexible; B. Rigid; C: Composite
   Your airport's taxiways are: A. Flexible; B. Rigid; C: Composite
   Your airport's aprons are: A. Flexible; B. Rigid; C: Composite

3. Which of the following methods have you used to determine the HMA density of newly constructed as well as existing pavements? (Circle all that apply.)

   A. Coring;
   B. Nuclear gauge;
   C. Non-nuclear electromagnetic gauge;
   D. Ground penetrating radar

4. In your opinion, how many data points are needed to ensure the uniformity of HMA density and thickness measurement for a 1000ft-long section?
   A. 20; B. 50; C. 200; D. As many as possible
   Quality control should constantly be checked.

5. If a nondestructive technique is capable of accurately predicting HMA density and thickness in a continuous way, will it be of interest to your organization?
   The nuclear gauge is NDE for density. Surely does thickness.

6. Are you familiar with ground penetrating radar?
   Yes.

7. In your opinion, will ground penetrating radar work for predicting HMA density?
   Not yet.

8. If you have any other comments regarding this topic in addition to the above questions, please provide your input here:

Please return your questionnaire and possible questions to Jongeun Baek at baek2@illinois.edu or Zhen Leng at zleng2@illinois.edu. Thank you!