A Nuclear Density Gauge for Thin Overlays of Asphalt Concrete

ALI REGIMAND

The principle of operation of a new thin layer backscatter density gauge is presented in this paper. Field and laboratory data are used to verify the accuracy of this gauge for directly measuring the density of a thin overlay of material applied over an underlying base material. This instrument requires only a good estimate of the overlay thickness to measure the overlay density. The bottom density is algebraically eliminated from the gauge equations, enabling the top density to be calculated using an internal microprocessor. This gauge will be helpful in the road construction industry for measurement of thin overlay density of asphaltic concrete.

In recent years, thin sections of asphaltic concretes have been used for maintenance and repair of Interstate and other primary and secondary roads. The inability of conventional backscatter nuclear density gauges to measure density of a specific thickness has increased the need for a portable, fast, and nondestructive method for measuring thin sections of asphaltic concretes and high-density portland cement concretes.

Conventional nuclear backscatter density gauges using a gamma radiation source and a suitable detection system such as Geiger-Müller tubes are designed to measure primarily the scattered radiation. The unscattered radiation is minimized by the use of appropriate shielding material between the source and the detector. When source energies of less than 1.1 Mev are used, the gamma ray scattering is governed by two interactions, photoelectric effect and Compton scattering.

At zero density, the count rate is zero because there is no material to cause scattering into the detector. As the density increases, so does the number of gamma rays scattered into the detector. The count rate reaches a maximum when the rate of scattering is matched by the rate at which the gammas are absorbed. The count rate continues to decrease and asymptotically approaches zero as the density is further increased. Most commercial backscatter gauges are designed for operation on the negative slope portion of the count rate.

All conventional backscatter gauges assume the measuring medium is uniform over the sample volume. However, problems arise when the measurement volume consists of two layers with different densities, as is often the case when a thin overlay of 1.0 to 2.5 in. is applied on top of an existing road.

In this paper, the theory behind the new portable Troxler 4640 thin-layer gauge is explained and laboratory results and field data are reported. The gauge consists of a multidetection system and an 8-mCi Cesium^{137} source of radiation. All calculations are performed in a gauge microprocessor, and no preparation or measurements are required prior to the asphalt overlay application.

Troxler Electronic Laboratories, Inc., Research Triangle Park, N.C. 27709.

GAUGE THEORY

Overlay thickness, top density, and the density of the bottom material determine the amount of the backscatter radiation reaching the detection system in the thin-layer gauge. These counts are results of scattering in either the top-layer material or the bottom-layer material or the combination of the two layers (Figure 1).

When one considers the problem of measuring thin overlays of 1.0 to 2.5 in., the gauge bulk density reading D_G is essentially a function of three unknown variables: the density of the top layer D_T, the density of underlying base D_B, and the thickness X of the top layer. D_G may be expressed by the general function

$$D_G = f(D_T, X, D_B)$$

and one specific form of this function is

$$D_G = (D_B - D_T)K + D_T \tag{1}$$

where K is the constant defining the effect of the top-layer material on the gauge and is a function of the gauge geometry. K can be experimentally determined by using materials of known density as D_B and D_T. From Equation 1,

$$K = (D_G - D_T / (D_B - D_T) \tag{2}$$

where D_G is the bulk density measured using a particular gauge geometry.

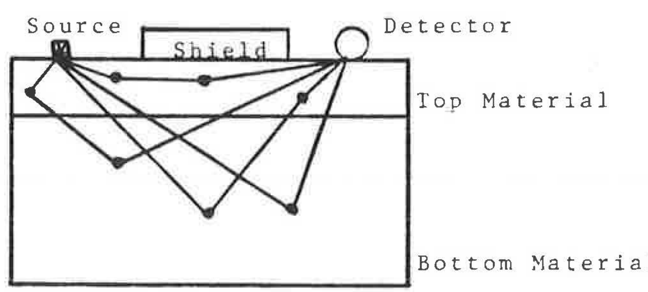

FIGURE 1 Typical radiation paths for a backscatter gauge.

The geometrical relationship between the radiation source and detector has a significant impact on what is seen by the detector. The geometrical relationship can often be controlled by collimating the radiation source or collimating the detector. One simple way of changing the geometrical relationship is by changing the distance between the source and the detector. By decreasing the distance from source to detector, the reading of the gauge is more heavily weighted towards the density of the material close to the surface of the gauge. Conversely, by increasing the distance from source to detector, bulk density of material up to 4.5 in. thick can be measured. Using this phenomenon, one can place two detectors at different distances from the source to make separate and distinct radiation measurements. The two independent systems reflect physical characteristics of the same material, but are weighed more heavily towards different depth strata within the material.

When the two systems are used to measure the density of the material, which is possibly composed of two different layers, the bulk density for each system may be written as

$$D_{G1} = (D_B - D_T)K_1 + D_T \quad (3)$$

$$D_{G2} = (D_B - D_T)K_2 + D_T \quad (4)$$

Eliminating D_B and then solving the resulting equation for D_T yield

$$D_T = (K_2\, D_{G1} - K_1\, D_{G2})/(K_2 - K_1) \quad (5)$$

It can be seen from Equation 5 that if the constants K_1 and K_2 are determined, D_T could be calculated using the two separate and independent gauge density readings D_{G1} and D_{G2}.

In order to calculate K_1 and K_2, calibration is needed for the two systems for a given range of densities to yield bulk density readings D_{G1} and D_{G2} using the following standard gauge equations:

$$CR_1 = A_1[\exp(-B_1\, D_{G1})] - C_1 \quad (6)$$

$$CR_2 = A_2[\exp(-B_2\, D_{G2})] - C_2 \quad (7)$$

where CR_1 and CR_2 are the ratios of the measure counts to a reference standard count. This ratio is used to correct for decay of the radiation source over the useful life of the gauge.

The constants A_1, B_1, C_1 and A_2, B_2, C_2 are gauge constants and are functions of the gauge geometries. If Equation 6 is evaluated at three different densities, that is, by running the gauge on three blocks of known density in the range of 100 to 170 lb/ft^3, the resulting three equations can be solved simultaneously for A_1, B_1, and C_1. Similarly, Equation 7 and the second gauge geometry yield values for A_2, B_2, and C_2. The results of such an exercise on solid blocks of magnesium, magnesium-aluminum laminate, and aluminum are shown in Table 1.

Using three blocks of known densities in the range of 100 to 170 lb/ft^3, parameters in Equations 6 and 7 can be calculated.

From Equations 6 and 7 then,

$$D_{G1} = (1/B_1)\ \ln(A_1/CR_1 + C_1) \quad (8)$$

$$D_{G2} = (1/B_2)\ \ln(A_2/CR_2 + C_2) \quad (9)$$

where D_{G1} and D_{G2} are now the bulk densities measured by Systems 1 and 2, respectively (Figure 2). Equations 8 and 9 now can be used to calculate D_{G1} and D_{G2} from gauge count ratios CR_1 and CR_2.

The next step is to establish equations for K_1 and K_2 as a function of top-layer thickness using various thicknesses of metal blocks of two different densities that lie within the useful range of the densities encountered in the field applications. The two metals used for calibrating this gauge are magnesium (density 111.3 lb/ft^3) and aluminum (density 169.6 lb/ft^3). These densities have to be normalized to account for asphalt. Because the nuclear gauge responds to the electron density of the medium, the mass densities of the metals must be modified to values that are asphalt-equivalent values. The electron density of a material is proportional to Z/A, where Z is the atomic number of the material and A is the atomic weight. Each system will yield two sets of K values: one set, K_{11} and K_{21}, when thin layers of magnesium are measured on top of an "infinite" aluminum block; and a second set, K_{12} and K_{22}, when thin layers of aluminum are counted on top of an "infinite" magnesium block.

To establish values of K_{11}, 1.4-in.-thick magnesium sheets are added one at a time to the top of a 14-in.-thick aluminum block and the gauge is read after each addition. Equation 8 is used to calculate D_{G1}, and Equation 2 is then used to calculate K_{11}. The process is then repeated with aluminum sheets stacked on a 14-in.-thick magnesium block to establish K_{12}. The resulting values for Systems 1 and 2 are shown in Tables 2 and 3, respectively.

TABLE 1 COUNTING DATA (DIVIDED BY 32) FOR SOLID BLOCKS OF MAGNESIUM, MAGNESIUM-ALUMINUM, AND ALUMINUM WITH PARAMETERS *A*, *B*, AND *C* FOR EACH SYSTEM

Reference Standard Count = 4247

	MAG	MAG/ALUM	ALUM	A	B	C
System 1	6228	5217	4263	-7.71115	-0.00102	-10.09443
System 2	4689	3297	2463	5.72494	0.01671	- 0.19120

TABLE 2 SYSTEM 1 COUNTING DATA (DIVIDED BY 32) AND *K* VALUES CALCULATED FROM EQUATION 2

Thickness (ins)	Mag on Alum	Alum on Mag	K_{11}	K_{12}
1.00	5823	4610	0.21042	0.17284
1.25	5941	4483	0.14935	0.10940
1.50	6080	4361	0.07716	0.04865
1.75	6090	4317	0.07196	0.02679
2.00	6150	4264	0.04071	0.00050

TABLE 3 SYSTEM 2 COUNTING DATA (DIVIDED BY 32) AND *K* VALUES CALCULATED FROM EQUATION 2

Thickness (ins)	Mag on Alum	Alum on Mag	K_{21}	K_{22}
1.00	3530	3147	0.41604	0.40604
1.25	3706	2985	0.34254	0.32182
1.50	3906	2799	0.26426	0.21700
1.75	4002	2733	0.22847	0.17743
2.00	4129	2632	0.18274	0.11416

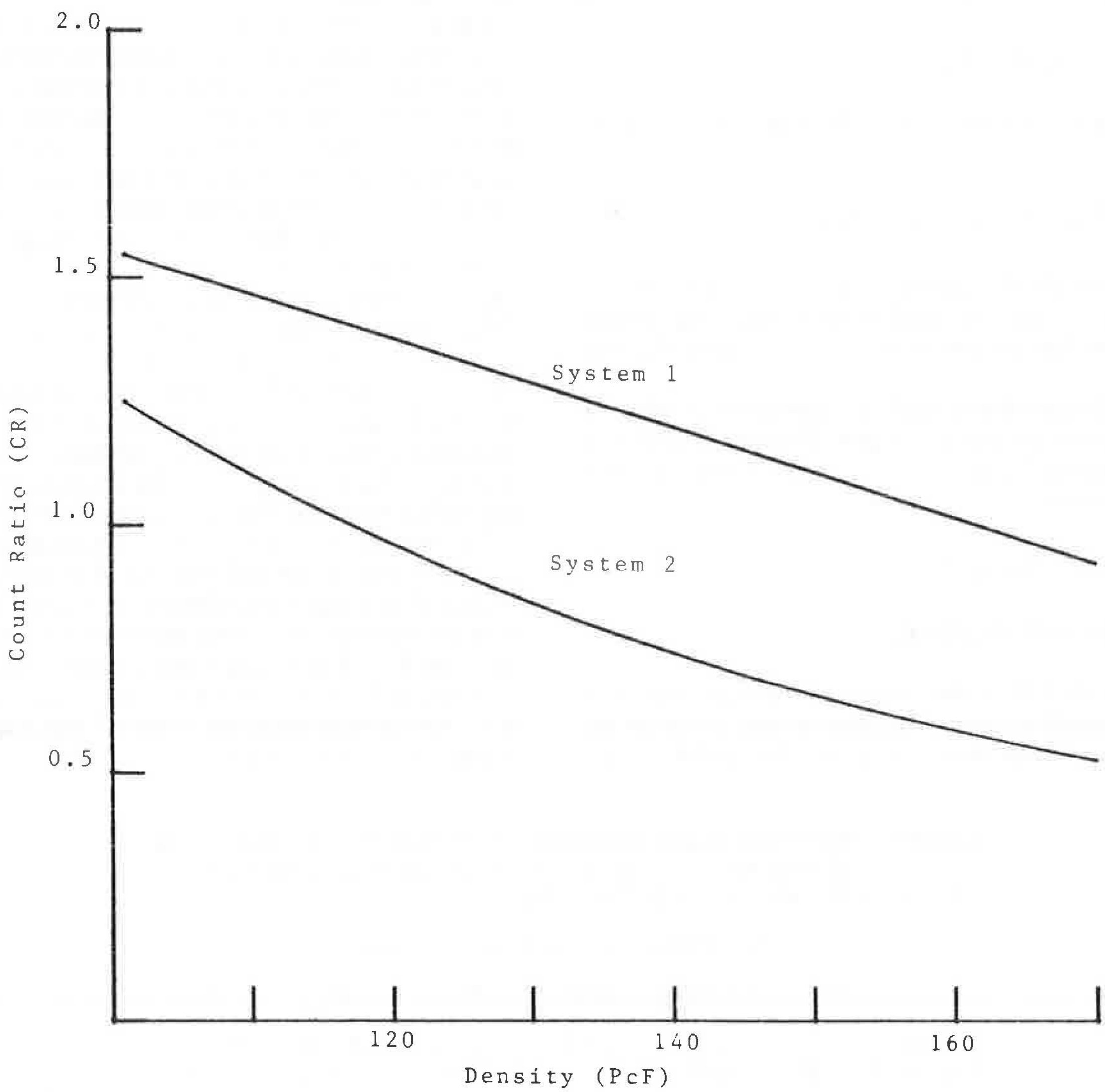

FIGURE 2 Backscatter density calibration curve for Systems 1 and 2.

The next step is to use a suitable least squares routine to establish equations for K_{11}, K_{12}, K_{21}, and K_{22}, as functions of layer thickness. The curves take the form

$$K_{ij}^* = H_{ij}[\exp(-G_{ij}X)] - F_{ij}$$

$$i = 1, 2; j = 1, 2 \qquad (10)$$

where K_{ij}^* is the predicted value for K_{ij}; and H_{ij}, G_{ij}, and F_{ij} ($i = 1, 2; j = 1, 2$) are fitted constant parameters. The least squares fit produces four equations for K_{11}^*, K_{12}^*, K_{21}^*, and K_{22}^*. The assumption is made that the top- and base-layer densities D_T and D_B in a field application are somewhere between these two extreme metal densities. The arithmetic mean of K_{11}^* and K_{12}^* in this case can be used as a value for K_1, and the mean of K_{21}^* and K_{22}^* will yield a value K_2 for the range of thicknesses used in the field.

If these approximated values of K_1 and K_2 are calculated at several top-layer thicknesses, they can also be fitted to an equation similar to Equation 10. This procedure will produce a fitted value for K_1 and K_2 for a given top-layer thickness X, thus

$$K_1 = A_{11}[\exp(-A_{12}X)] - A_{13} \qquad (11)$$

$$K_2 = A_{21}[\exp(-A_{22}X)] - A_{23} \qquad (12)$$

where A_{11}, A_{12}, A_{13}, A_{21}, A_{22}, and A_{23} are fitted constant parameters. Tables 4 and 5 show the K values for Systems 1 and 2, respectively.

Figures 2 and 3 show that K_1 and K_2 curves are not unduly sensitive to thickness X in the range of interest, and if one can supply a good estimate of the top-layer thickness, one can calculate K_1 and K_2 from Equations 11 and 12 and ultimately a D_T value from Equation 5. Later in this paper, the effect of the thickness on thin-layer density measurement is shown.

THIN-LAYER GAUGE TESTING

The thin-layer gauge consists of a multidetection system that measures densities of thin layers of asphalt. Top-layer density is calculated automatically in kg/m^3 or lb/ft^3 by the gauge microprocessor. The thin-layer gauge was tested in four states: North Carolina, Tennessee, Virginia, and Maryland. The variables included in the evaluation were thin-layer asphalt thicknesses and asphalt mixes with varying aggregate sizes. When possible, measurements were taken before and after cores were extracted. All readings were compared with the generally accepted water displacement method of testing core samples. Core results given in the data are values measured by contractors and state inspectors. Errors associated with sampling and water displacement measurement of the cores are not discussed here but individuals in this practice are familiar with these sources of error.

Laboratory testing consisted of measurements on thin layers of metallic materials of known density. In this study, the density error resulting from varying thicknesses was investigated to demonstrate the independence of the thin-layer measurement from the bottom density.

ANALYSIS OF DATA

The purpose of the testing was to compare the thin-layer gauge density readings with water displacement core results. Several different mixes were tested in North Carolina, and a variety of different mixes were tested in Virginia, Maryland, and Tennessee. The top-layer thicknesses keyed into the gauge for the measurements were the job thicknesses given by contractors or the inspectors at the different jobs. Even though some cores subsequently showed thicknesses different from the values used in the gauge, no adjustment was made to the data. Using the exact thicknesses might have produced slightly better results; nevertheless, the job-specified thickness would be the only available value at the time of measurement.

Importance of Estimate of Top-Layer Thickness

Tests were conducted in the laboratory to determine errors resulting from the incorrect estimation of the thickness of the top layer. Tests showed that the error in gauge density reading decreased exponentially as the selected thickness increased. To demonstrate this effect, a 1.25-in.-thick, 110.0-lb/ft^3 block of magnesium was measured on top of solid laminated magnesium-aluminum block of 137 lb/ft^3 and then on a solid aluminum block of 157.5 lb/ft^3. Different assumed thicknesses (1.25 to 2.55 in.) were then keyed into the gauge and the density D_T of the top layer was calculated. Tables 6 and 7 show the results: ΔX is the difference between the 1.25-in. thickness and the one used to calculate the density and ΔD is the error in D_T, that is, the difference in density readings between the density reading with the true thickness (1.25 in.) keyed in and the density reading with the assumed thickness keyed in. In the extreme case of a 1.25-in. magnesium block on the solid aluminum block (Table 6), where the two materials differ in density by approximately 47 lb/ft^3, the density error for a 0.2-in. error in the top-layer thickness estimate is 1.7 lb/ft^3. A 0.2-in. error in thickness estimate for a 2.35-in. layer would yield an error in the density of only 0.6 lb/ft^3 (117.6-118.2 lb/ft^3). In Table 7 where the two materials differ in density by 27 lb/ft^3, the error in the calculated top-layer density produced by an error in estimating the top-layer thickness is significantly smaller. A 0.2-in. error at a true thickness of 1.25 in. results in an error of 1.0 lb/ft^3 in the top-layer density. At a true thickness of 2.35 in., the result is an error of 0.4 lb/ft^3. The interesting thing to notice in Table 7 is that ΔD is only 3.8 lb/ft^3 for the range of thicknesses between 1.25 and 2.55 in., and a change of 104 percent in the correct thickness only changed the density readings by 3.4 percent.

The effect of thickness on the density reading is a function of the difference between the top-layer density and the bottom-layer density, as shown in Tables 6 and 7. In the field application, the difference between top- and bottom-layer densities is generally less than 15 lb/ft^3; in many asphalt-on-

TABLE 4 *K* VALUES FOR SYSTEM 1

Thickness (ins)	K_{11}*	K_{12}*	K_1	Fitted K_1
1.00	0.21261	0.17418	0.19339	0.19339
1.25	0.13959	0.10399	0.12179	0.12180
1.50	0.09253	0.05601	0.07427	0.07426
1.75	0.06221	0.02321	0.04271	0.04270
2.00	0.04267	0.00080	0.02173	0.02174

TABLE 5 *K* VALUES FOR SYSTEM 2

Thickness (ins)	K_{21}*	K_{22}*	K_2	Fitted K_2
1.00	0.41752	0.40872	0.41312	0.41312
1.25	0.33656	0.31124	0.32390	0.32391
1.50	0.27299	0.23221	0.25260	0.25260
1.75	0.22308	0.16812	0.19560	0.19560
2.00	0.18390	0.11616	0.15003	0.15003

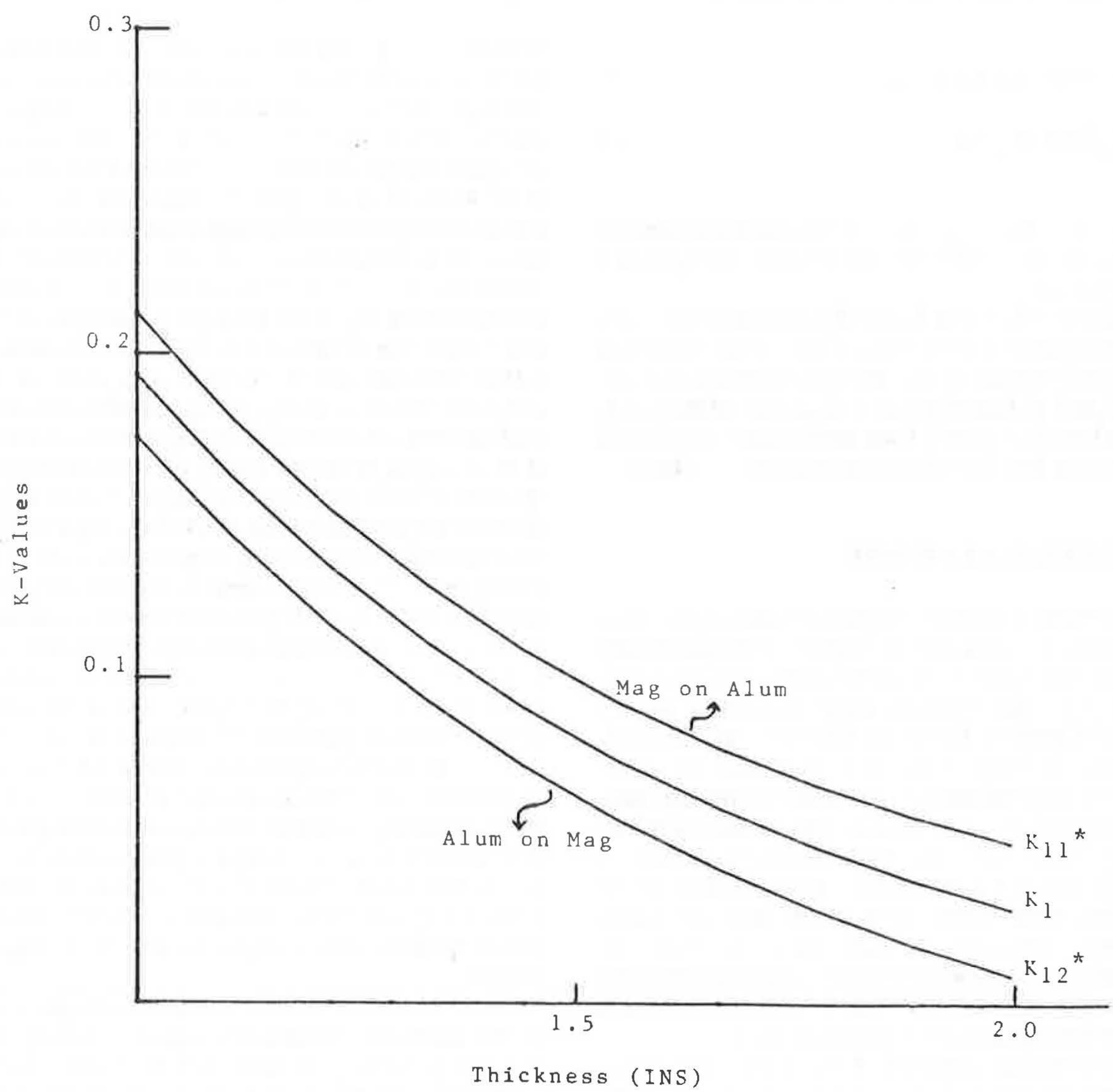

FIGURE 3 System 1: Fitted *K* values for thicknesses between 1 and 2 in.

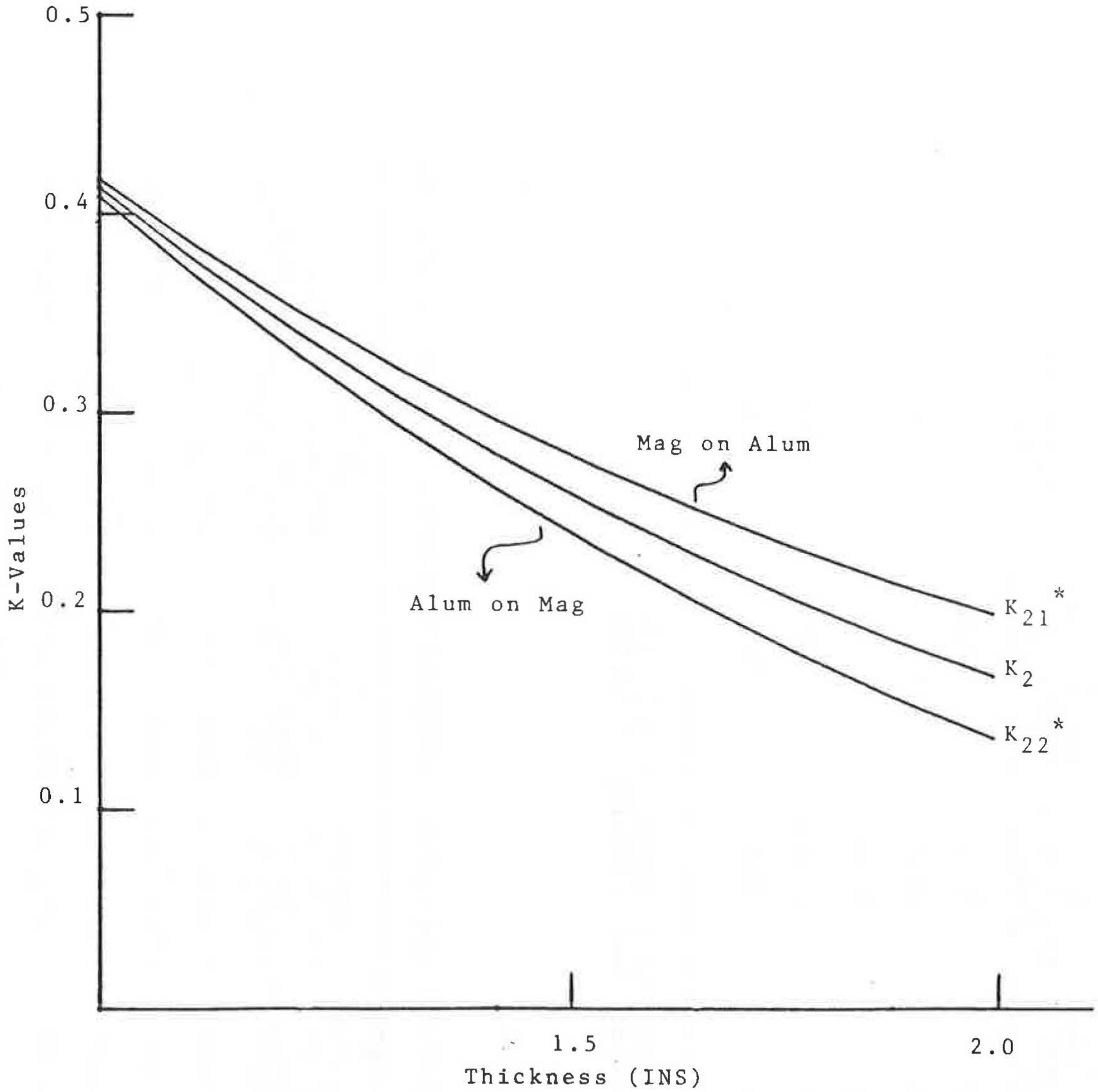

FIGURE 4 System 2: Fitted *K* values for thicknesses between 1 and 2 in.

TABLE 6 BULK DENSITIES FOR 1.25-IN. MAGNESIUM ON SOLID ALUMINUM BLOCK

Thickness (inches)	D_T Calculated Density (PcF)	ΔX (inches)	ΔD (PcF)
1.25	111.5	0.00	0.0
1.35	112.4	0.10	0.9
1.45	113.2	0.20	1.7
1.55	113.9	0.30	2.4
1.65	114.6	0.40	3.1
1.75	115.1	0.50	3.6
1.85	115.6	0.60	4.1
1.95	116.1	0.70	4.6
2.05	116.5	0.80	5.0
2.15	116.9	0.90	5.4
2.25	117.3	1.00	5.8
2.35	117.6	1.10	6.1
2.45	117.9	1.20	6.4
2.55	118.2	1.30	6.7

TABLE 7 BULK DENSITIES FOR 1.25-IN. MAGNESIUM ON SOLID MAGNESIUM-ALUMINUM BLOCK

Thickness (inches)	D_T Calculated Density (PcF)	ΔX (inches)	ΔD (PcF)
1.25	110.6	0.00	0.0
1.35	111.1	0.10	0.5
1.45	111.6	0.20	1.0
1.55	112.0	0.30	1.4
1.65	112.3	0.40	1.7
1.75	112.6	0.50	2.0
1.85	112.9	0.60	2.3
1.95	113.2	0.70	2.6
2.05	113.4	0.80	2.8
2.15	113.6	0.90	3.0
2.25	113.8	1.00	3.2
2.35	114.0	1.10	3.4
2.45	114.2	1.20	3.6
2.55	114.4	1.30	3.8

TABLE 8 THIN-LAYER AND BULK DENSITY READINGS (LB/FT^3) FOR 1.25 IN. OF ALUMINUM AND MAGNESIUM ON TOP OF SOLID MATERIALS OF DIFFERENT DENSITY

Bottom Layer Material	D_T Thinlayer Gauge Aluminum Density (pcf)	D_G Bulk Density (pcf)	D_T Thinlayer Gauge Magnesium Density (pcf)	D_G Bulk Density (pcf)
Magnesium	159.0	141.0	110.5	110.2
Magnesium/Alum	158.0	149.9	110.0	123.0
Asphalt	158.5	150.0	111.0	123.4
Concrete	157.5	151.3	110.6	126.0
Aluminum	157.5	157.3	111.3	132.0

Normalized Magnesium Density: 110.0 PcF
Normalized Aluminum Density: 157.5 PcF

TABLE 9 THIN-LAYER GAUGE DENSITY AND BULK DENSITY GAUGE COMPARISON TO WATER-DISPLACED ASPHALT CORE DENSITIES

Location	No. of Samples	X Thinlayer Thickness (inches)	Average Core Density (pcf)	D_T, Average Thinlayer Gauge Density (PcF)	D_G, Average Bulk Density (PcF)	% Difference Thinlayer	% Difference Bulk
B.W.I. Airport - FAA, Mix	8	2.50	151.7 $\pm$ 0.62	150.4 $\pm$ 0.94	151.7 $\pm$ 0.44	- 0.9	0.0
Memphis, TN 411 E Mix	10	1.00	141.7 $\pm$ 1.25	143.6 $\pm$ 1.62	145.5 $\pm$ 1.12	+ 1.3	+ 2.7
Wake Forest, NC I.2 Mix	15	1.50	137.3 $\pm$ 0.87	136.1 $\pm$ 1.25	134.8 $\pm$ 1.19	- 0.9	- 1.8
Fort Meade, MD	7	1.25	144.8 $\pm$ 4.43	143.6 $\pm$ 2.87	143.6 $\pm$ 2.93	- 0.8	- 0.8
Raleigh, NC I.1 Mix	10	1.00	135.5 $\pm$ 3.06	137.3 $\pm$ 2.87	138.6 $\pm$ 1.87	+ 1.3	+ 2.3
Route 157, VA S.5 Mix	6	1.50	138.0 $\pm$ 0.75	138.0 $\pm$ 0.75	139.2 $\pm$ 2.25	0.0	+ 0.9

asphalt resurface roads the final difference after compaction may be less than 7 lb/ft^3 and a good estimate (± 0.20 in.) of the job thickness will produce acceptable density readings in the field.

Effect of Bottom-Layer Material on Top-Layer Density Value

A true thin-layer gauge should only measure the top-layer density. This measurement should be independent of the bottom-layer density and composition. To show the effect of bottom density on the thin-layer gauge, a 1.25-in.-thick block of magnesium and a 1.25-in.-thick block of aluminum were each measured on top of magnesium, magnesium-aluminum-laminated block, aluminum, concrete, and asphalt. The latter blocks ranged in density from 110 to 160 lb/ft^3. One 4-min reading was taken with each of the two thin-layer blocks on top of the five bottom materials of different densities.

Table 8 shows that all the thin-layer density readings D_T established by the gauge are within 1.5 percent of the true density of the thin-layer block, regardless of the bottom material density and composition. At the same time, the bulk density measurements D_G in Table 8 show the effect of the bottom density on the bulk density gauges presently used for density measurements.

Field Results

Field data are summarized in Table 9. Averages and standard deviations for all data are presented. The gauge density corresponding to each core was the average of four 1-min readings around the core. The data in the tables are averages of several cores with several corresponding gauge readings. Job thicknesses are also shown in Table 9. For comparison of thin-layer density values with what present gauges would read on the same jobs, bulk density readings are also presented.

The main aspects considered in testing the thin-layer gauge was the correlation between the water displaced core readings and the corresponding gauge readings for different mixes.

The difference column shown on Table 9 indicates that in all cases regardless of the thickness, asphalt mix, and composition, the gauge readings were within ± 1.5 percent of the core readings. Four out of six mixes gave percentage differences of less than ± 1 percent. On some of the jobs, bulk density values are close to thin-layer gauge density readings because of the fact that, as the thickness increases, at greater than 1.5 in., the majority of the gamma interactions are taking place in the top 1.5 in. and the effect of the bottom material is small. Also, if the bottom-material density is close to the top-material density, as was the case in the Wake Forest data, the bottom layer does not affect the readings. In this case, all measurements are the same as thin-layer density gauge readings. However, as thickness gets smaller, at less than 1.5 in., the effect from the bottom layer increases; if the bottom-layer density is different from the top-material density, as in the Tennessee E mix data, the errors in the bulk density readings become significant.

CONCLUSIONS

Nuclear density gauges have been used on asphalt paving projects for a number of years, but because of their design, they could only measure certain jobs and with modification of the data. The thin-layer gauge has been designed primarily to measure thin layers of asphaltic concrete, that is, top layers between 1 and 2.5 in., without any data manipulation or modification. The tests done using this gauge showed its top-layer density determination to have little dependence on the bottom-layer density; thus, the only parameter required for top-density measurement is the top-layer thickness. In the field, four 1-min readings around a core gave good results compared with the density established in the laboratory; on the five projects tested, the average difference between cores and the gauge was always less than 1.5 percent.

These initial results indicate that the thin-layer gauge should be a useful tool for thin-layer density measurement and should reduce the number of cores necessary. In the majority of jobs, the immediate results obtainable with the gauge will help the contractors adjust their rolling pattern before an excessive time lapse between placing the pavement and completing the final run.

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