Laboratory Density Measurements of Bituminous Mixes by Gamma-Ray Probe

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An experimental study that evaluated the feasibility of applying a twin-probe gamma-ray gauge for density measurements of cylindrical bituminous specimens is described. Major considerations related to the operational features of the gauge and the characteristics of the composite structure of bituminous mixtures are highlighted. Three bituminous mix types—namely, sand asphalt, dense-graded mix, and open-graded mix—were included. The measurement precision and accuracy characteristics of the gauge with respect to the different mix types were examined. It was found that the precision and accuracy of gauge-determined densities varied with the types of mix tested. Better precision and accuracy were achieved with specimens that had more uniform density distribution within the mass and with specimens that were less porous. Recommendations concerning the use of gamma-ray probes for laboratory density measurements of bituminous paving mixtures are made. An illustration showing the ability of the twin-probe gauge to determine the density profile of a tall specimen is presented.

Measuring the density of laboratory-compacted specimens and field cores of bituminous materials is a requirement in routine laboratory testing of highway and airfield paving materials. The bulk specific gravity of bituminous paving mixtures with water-tight surfaces can be determined by weighing specimens in air and in water, as described in ASTM D2726. If the surface of a mixture is porous or if it permits the infiltration of water during the submerged weighing, specimens coated with paraffin must be used as specified by ASTM D1188. These two methods measure the overall average density of the specimen tested. For compacted specimens or field cores that contain layers of mixtures with different densities, other methods are needed if the densities of various layers are to be determined nondestructively.

This paper describes an alternative means of density measurement of bituminous mixtures in a nondestructive manner through the use of a nuclear device: a twin-probe gamma-ray gauge adapted from a direct transmission field gauge for laboratory density measurement. The precision characteristics of the twin-probe gauge with respect to different bituminous mixtures are examined. Three bituminous mixtures—a dense-graded asphaltic concrete, an open-graded mixture, and a sand asphalt mixture—are included in the study. Recommendations about the use of the gamma-ray probe for laboratory density measurement of bituminous paving mixtures are made.

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EXPERIMENTAL SETUP AND MEASUREMENT PROCEDURE

A schematic diagram of the twin-probe nuclear density gauge adopted in this study is shown in Figure 1. The gauge has a 5-milliCurie (mCi) source of cesium-137 that produces gamma photons of initial energy of 662 keV, a detector consisting of a sodium-iodide-thallium–activated crystal, NaI(Tl), and a scintillation counter capable of discriminating gamma photons according to their energy levels. The counter is designed to register only signals corresponding to photons of energy of 662 keV. The source and detector are rigidly fixed 280 mm apart. This is the recommended source-to-detector spacing for the gauge, arrived at in an earlier study by the authors (*1*); it is based on precision and accuracy considerations. The cross arm that holds the source and detector can be moved vertically on a rigid vertical guide by a drive motor. This enables density measurements to be made at different depths of a specimen. More details about the operating characteristics of the twin-probe setup are found elsewhere (*1,2*).

The attenuation of gamma radiation after passing through a matter can be described by the well-known gamma absorption law (*3,4*):

$$N = N_o F e^{-\mu t \rho} \quad (1)$$

or

$$\ln C_R = \ln(N/N_o) = \ln F - \mu t \rho \quad (2)$$

where

N_o = count rate registered by detector with no specimen between the source and detector,
N = count rate registered by detector with specimen in space,
F = a constant that is a function of the geometry of the gauge and specimen material properties,
μ = material mass absorption coefficient,
t = thickness of specimen,
ρ = density of specimen, and
C_R = count ratio, computed as the ratio of N to N_o.

Using the twin-probe gauge, Fwa and Tan (*2*) have shown that the following formula is applicable for density measurement of solid cylindrical specimens having diameters from 75 to 150 mm:

$$\ln C_R = \ln F - \mu c d \rho \quad (3)$$

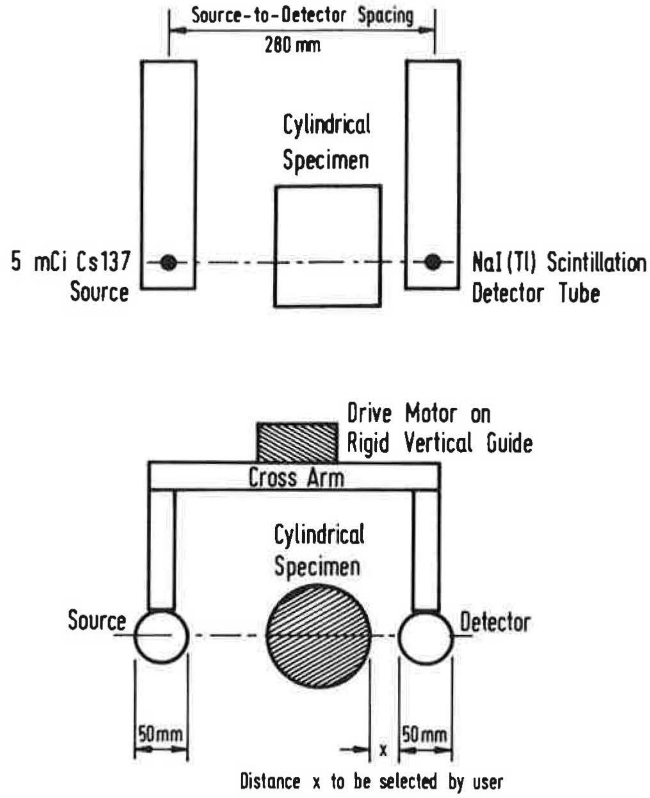

FIGURE 1 Experimental setup of twin-probe gamma-ray gauge: *top*, elevation view; *bottom*, plan view (not to scale).

where c is the diameter correction factor to account for circumference curvature of a cylindrical specimen and d is the diameter of the specimen.

For measuring the density of bituminous mixtures prepared with asphalt of a given grade and aggregates of a given source and adopting a fixed geometry of the experimental setup of the gauge as depicted in Figure 1, the factors F and μ can be taken as constants. Equation 3 may then be simplified as follows for testing with specimens of the same size:

$$\ln C_R = k_1 - k_2 \rho \qquad (4)$$

where k_1 and k_2 are constants that can be calibrated from measurements of bituminous specimens of known densities. Once calibrated, Equation 4 is used to calculate the density of a specimen from the count rate readings of the twin-probe gauge.

CONSIDERATIONS IN DENSITY MEASUREMENT OF BITUMINOUS MIXTURES

For meaningful interpretation of density measurements from the count rates of the twin-probe gauge, the operational features of the gauge and the characteristics of the composite structure (such as aggregate gradation and air void percentage) of bituminous mixtures must be considered.

Zone of Measurement

The so-called zone of measurement refers to the volume of specimen material covered in a density determination using the twin-probe gauge. The boundaries of the zone of measurement are dependent on the geometry of the gauge and the position of specimen between the source and detector. For the twin-probe setup in this study, the NaI(Tl) crystal in the scintillation detector is a cylinder 40 mm in diameter and 12 mm thick. The 5-mCi cesium-137 mass can be taken to be a point source. The measurement path of the twin-probe gauge may then be represented by a pyramid with a rectangular base of 12 × 40 mm and a height of 280 mm, as depicted in Figure 2 (*left*). Figure 2 (*right*) indicates that the mass of specimen material exposed to the gamma-radiation measurement is given by the intersection of the path of measurement and the specimen. This is defined by the volume *abcdefgh*. For a 100-mm-diameter cylindrical specimen placed at a distance x = 10 mm from the detector (see Figure 1 for definition of x), Figure 3 shows the plan view of the zone of measurement.

It is clear that the volume and mass of a specimen covered in each density measurement by the twin-probe gauge are considerably smaller than those involved in a conventional density measurement by means of the water-displacement principle. This localized density determination capability of the twin-probe gauge offers two obvious advantages: (a) locational variations of density in a plane perpendicular to the

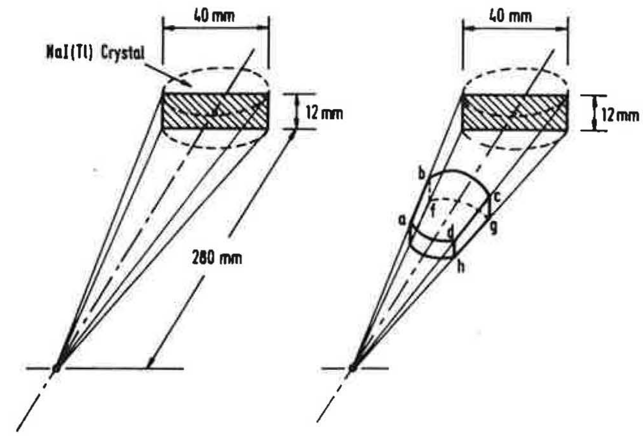

FIGURE 2 Zone of measurement in twin-probe nuclear gauge density determination: *left*, path of measurement; *right*, volume of specimen measured (not to scale).

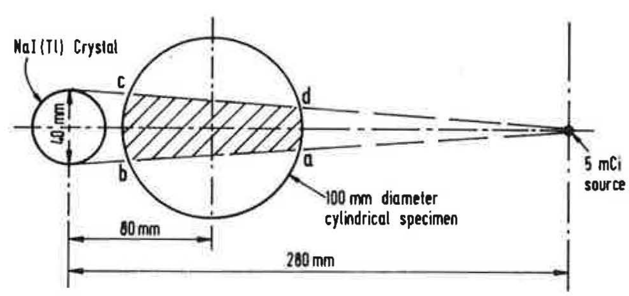

FIGURE 3 Plan view of zone of measurement (*abcd*) for cylindrical specimen.

measurement path can be identified; this allows one to determine the horizontal and vertical distribution patterns of density of a laboratory-compacted specimen or a field-extracted sample; and (b) directional variations in a plane parallel to the measurement path can also be determined. For a cylindrical specimen as shown in Figure 3, this is achieved simply by rotating the specimen horizontally so that different zones of measurement can be covered.

Relating Gauge Measurements to Bulk Density

In laboratory testing of bituminous mixtures for pavement engineering applications, reference is often made of the bulk density of cylindrical laboratory-prepared specimens or field cores. There is therefore the need to relate nuclear gauge density measurements to the bulk density measured by the conventional water-displacement method. In the event that the specimen measured is homogeneous in nature and has uniform density distribution, gauge-measured densities can be directly related to bulk densities. This is not likely with a bituminous mixture because its three basic constituents—aggregates, air, and asphalt—differ greatly in density. Depending on the type of mix and gradation of aggregates, the density distribution in a bituminous mix can be far from uniform.

One possible approach to obtain bulk density from gauge density readings is to make multiple measurements to cover the entire volume of the specimen, with no overlapping of zones of measurement. This approach, however, is not practical for cylindrical specimens because the change in geometry in each measurement requires a separate calibration of Equation 4. In addition, considerable errors due to increased curvature effects are expected because measurements are made away from the centerline of a cylindrical specimen (*1*).

The approach adopted in this study involves making nuclear density measurements from selected directions spaced at equal angles about the center of the specimen tested. Figure 4 shows the measurement directions for different cases. In each case, an estimate of bulk density is computed as the mean of the gauge-determined densities obtained from different directions. In general, it is likely that the more nonuniform the density distribution of a specimen, the higher is the number of measurement directions needed to arrive at a sufficiently accurate assessment of its bulk density.

Gauge Calibration

For density measurement of cylindrical specimens of the same diameter, the calibration coefficient k_2 in Equation 4 is a function of μ, the material mass absorption coefficient. For common civil engineering materials composed mainly of carbon, oxygen, aluminum, silicon, and calcium, with only a small amount of heavy elements such as iron, μ can be taken as a constant (*3–6*). This means that the density calibration of these materials, according to Equation 4, will lie on a straight line on a $\ln(C_R)$-versus-density plot. Using the twin-probe nuclear gauge described in this study, the authors (*1,2*) have verified this linear relationship experimentally using cylindrical specimens of aluminum (bulk density = 2.70 g/cm^3),

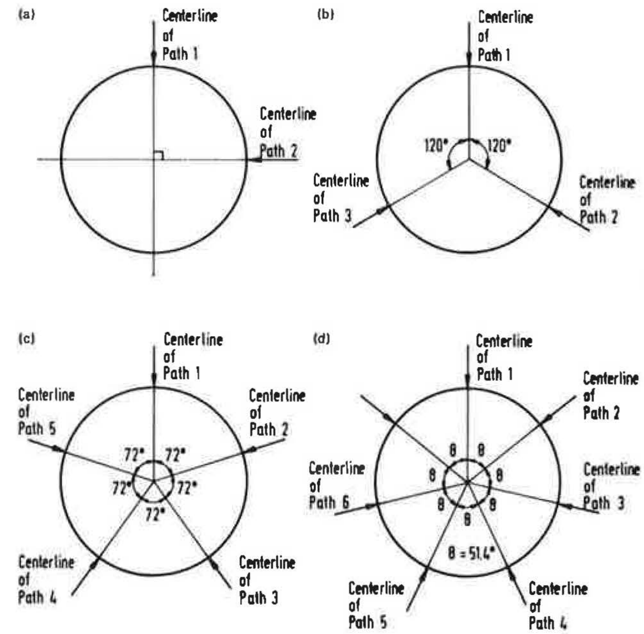

FIGURE 4 Gamma-ray density measurement in more than one direction (arrows indicate centerline and direction of measurement path): *a*, for two directional measurements; *b*, for three directional measurements; *c*, for five directional measurements; *d*, for seven directional measurements.

glass (2.51 g/cm^3), hardened portland cement (1.83 g/cm^3), perspex (1.18 g/cm^3), asphalt (1.00 g/cm^3), and paraffin wax (0.83 g/cm^3). A calibration plot for 100-mm-diameter cylindrical specimens is shown in Figure 5. Source-to-detector spacing is 280 mm and specimen-to-detector gap is 10 mm. The corresponding calibration equation is

$$\ln C_R = -0.01706 - 0.55166\,\rho \qquad (5)$$

This fitted equation has a statistical coefficient of multiple determination, r^2, equal to .999.

In a separate study on nuclear density measurements of granular materials, Tan and Fwa showed that the calibration

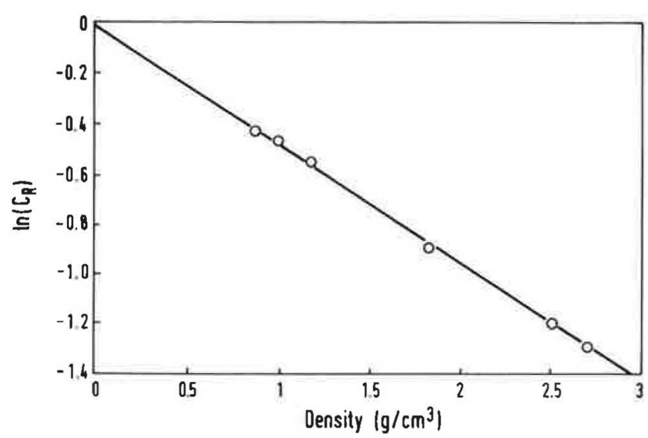

FIGURE 5 Calibration plot of twin-probe gamma-ray gauge.

based on Equation 5 was also valid for density measurements of granite aggregates and siliceous sand masses with different porosities (7). Because bituminous mixes are mixtures of asphalt and aggregates, both of which follow the calibration relationship of Equation 5, it is logical to expect the same relationship to be applicable to these mixes. Three types of bituminous mix are investigated in this study to verify this.

DENSITY MEASUREMENTS AND ANALYSIS

This section describes the tests performed to determine the precision and accuracy characteristics of the gamma-ray probe in density measurements of compacted bituminous mixes. A dense-graded mix and an open-graded mix, with aggregate gradations as described in Table 1, were prepared with asphalt contents of 5.5 and 7.0 percent, respectively. The third mix type was a sand asphalt prepared using an asphalt content of 8 percent and natural siliceous sand with a nominal maximum size of 2.36 mm. These mixes were chosen to cover the range of density commonly found for compacted bituminous mixtures.

In making the precision and accuracy assessments, the following aspects were examined for each of the three mixes: (a) repeatability of density measurements for a fixed path of measurement, (b) number of directional measurements required to achieve a desired level of accuracy, and (c) comparison with bulk densities determined by the conventional water-displacement method.

TABLE 1 Aggregate Gradations of Dense- and Open-Graded Mixes

Sieve Size (mm)	Percent Passing (Dense-Graded Mix)	Percent Passing (Open-Graded Mix)
25	100	100
19	100	95
13	95	75
9.5	85	55
4.75	70	27
2.36	50	10
1.2	37	5
0.3	19	0
0.075	6	0

Repeatability of Density Measurements

Three specimens of each of the three mix types were tested for repeatability of nuclear gauge density measurements. For each specimen, a measurement path was arbitrarily chosen and 40 readings of 1-min counts were obtained. Figure 6 shows typical frequency distribution plots of 1-min counts for the three mix types. Also shown in the same figure are the corresponding frequency distributions of densities, in which each density was computed from a 1-min count using the calibration relationship of Equation 5. It can be seen that both the count rate and density distributions are approximately Gaussian.

Table 2 summarizes the statistical characteristics of nuclear density measurements for single measurement paths. The results show that the sand asphalt specimens had the lowest density, followed by open-graded and dense-graded specimens in the order of increasing density. The corresponding standard deviations in density from the sand asphalt to dense-graded specimens varied from 0.009 to 0.012 g/cm³. This follows the general trend in nuclear density measurements, that precision improves as the count rate increases (or as the density decreases) (2).

On the basis of the Gaussian theory, a precision statement can be made for single-path density measurements of each of the three mix types. This is shown in Table 2, in which the ranges of error associated with different numbers of repeated 1-min counts were computed. For the three bituminous mixes, it may be concluded that a minimum of four 1-min counts are required for each measurement path to give a precision on the order of ±0.01 g/cm³ at a confidence level of 95 percent. The level of precision achieved is of the same order of magnitude as those obtained for the solid materials shown in Figure 5. This precision is adequate for most engineering applications. Therefore, four 1-min counts are recommended for each measurement path and used in all gamma-ray density measurements in this study.

Required Number of Directional Measurements

The presence of different sizes of aggregates and air voids in the mass of a bituminous specimen makes it necessary to

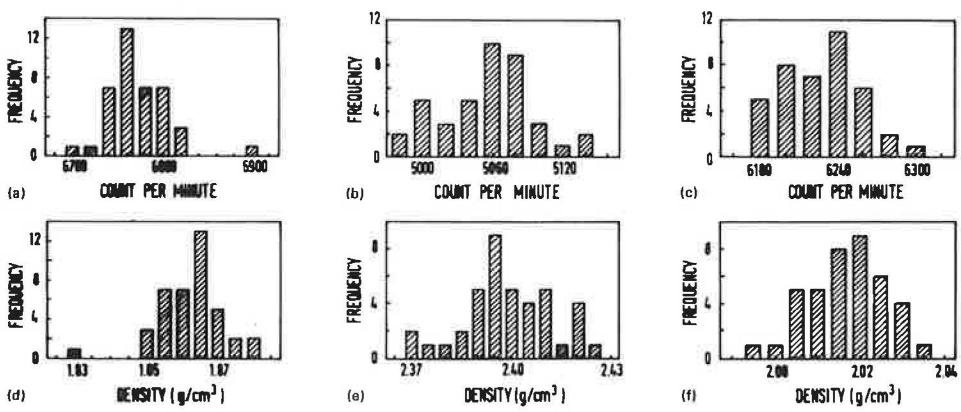

FIGURE 6 Count and density distribution for bituminous mixes: *a*, sand asphalt mix count distribution; *b*, dense-graded mix count distribution; *c*, open-graded mix count distribution; *d*, sand asphalt density distribution; *e*, dense-graded mix density distribution; *f*, open-graded mix density distribution.

TABLE 2 Characteristics of Single-Path Measurements of Density by Twin-Probe Gamma Ray Gauge

Type of Mix	Mean One-Minute Count	Path Density (g/cm³)		Precision Characteristics	
		Mean	Std Dev	n *	e **
Sand Asphalt	6,761	1.821	0.0088	2 3 4	±0.012 ±0.010 ±0.008
Open-Graded Mix	6,217	1.974	0.0090	2 3 4	±0.012 ±0.010 ±0.009
Dense-Graded Mix	5,047	2.352	0.0126	2 3 4	±0.018 ±0.014 ±0.012

*n is the number of repeated one-minute counts.
**e is the range of error in density at confidence level of 95%, expressed in units of g/cm^3.

perform more than one directional measurement to obtain a representative assessment of the bulk density of the specimen. In general, one would expect that the less uniform the density distribution of a specimen is, the more directional measurements will be needed.

Following the measurement patterns of Figure 4, all the three specimens of each of the three mix types were subjected to 2-, 3-, 5-, 7-, 11-, and 15-path directional measurements of densities. For each pattern of directional measurements, Path 1 was first randomly selected, followed by fixing of the directions of the remaining paths according to the arrangement in Figure 4 so that all the measurement paths were equally spaced on the perimeter of the specimen. This procedure was repeated 30 times per pattern for each specimen. The sample mean and standard error for each set of 30 density measurements were then computed.

The results of the analysis are summarized graphically in Figure 7. The coefficient of sample variation, CV, calculated by dividing the standard error by the mean, is plotted against the number of directional measurements. It is observed that whereas the mean did not vary much with the number of directional measurement paths for all the three mix types, the variability of measurements as represented by the range of CV decreased rapidly from path size of two. The variations in CV began to stabilize at a path size of about five for the sand asphalt and dense-graded mix and at a path size of about seven for the open-graded mix.

It is interesting to note that the mean CV of the three bituminous mixes provides a quantitative measure of the degree of nonuniformity of their density distributions. The sand asphalt specimens, with their mean CV in the order of 0.4 percent, had the most-uniform density distributions. The density distributions of the dense-graded specimens were less uniform, giving a mean CV of about 1.0 percent. The open-graded specimens, having mean CV of about 2.3 percent, were the least uniform in density distribution among the three mix types.

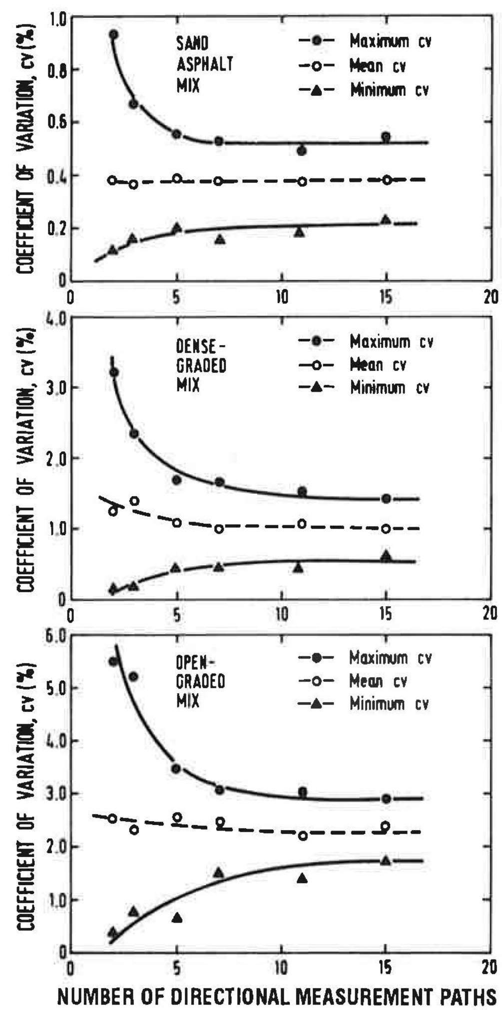

FIGURE 7 Variations of density measurements with number of measurement paths: *top*, sand asphalt mix; *middle*, dense-graded mix; *bottom*, open-graded mix.

Procedure for Estimating Bulk Densities

From the precision analyses presented in the preceding sections, the requirements for nuclear gauge density measurements of bituminous mixes outlined in Table 3 were adopted. Using the results of mean CV obtained earlier for each of the three mix types, estimates of the probable error were computed. Using five directional measurement paths each, the precisions obtained for the sand asphalt and dense-graded specimens were respectively within ±1 percent. For open-

TABLE 3 Requirements Adopted for Estimating Bulk Densities Using Twin-Probe Nuclear Gauge

Type of Mix	Number of Directional Measurement Paths	Number of One-Minute Counts Counts per Path	Range of Error in Density at Confidence Level of 95%
Sand Asphalt	5	4	±0.35%
Dense-Graded Mix	5	4	±0.87%
Open-Graded Mix	7	4	±1.70%

graded specimens, a precision of ±1.70 percent was achieved with seven directional measurement paths. Additional directional measurement paths may be used if higher precision is desired. For example, to achieve ±1 percent precision for density measurement of the open-graded mix, the number of directional measurement paths required is 20.

Comparison with Water-Displacement Bulk Densities

The accuracy of bulk densities of bituminous mixtures determined using the twin-probe nuclear gauge can be assessed by comparison with the corresponding densities obtained by the commonly accepted water-displacement method. For consistency in testing the different mixes, ASTM D1188, which uses paraffin-coated specimens, was adopted. In addition to the nine specimens described in the preceding sections, eight other dense-graded specimens were included. These eight specimens, having the same aggregate gradations as the dense-graded specimens described in Table 1, were intentionally given different degrees of compactive effort during preparation to produce compacted mixtures of different densities.

The final results are plotted in Figures 8 and 9. In Figure 8, the test results are plotted with the twin-probe calibration line. It is seen that the calibration relationship fits reasonably well with the density measurements of the different types of bituminous mixes tested. In Figure 9, the bulk densities determined by the water-displacement method are plotted against the gauge-determined densities. The bulk densities determined by the two methods were highly correlated with a coefficient of correlation, r, equal to .968. Assuming the bulk density determined by the water-displacement method to be the true density, the plot suggests that the accuracy achievable by the gamma-ray gauge varies with the type of mix tested. In general, the relative order of the three mix types in terms of the accuracy achievable was similar to those reported in the precision analysis. The best accuracy was obtained with sand asphalt specimens, followed by those dense-graded specimens that were adequately compacted to yield densities higher than about 2.30 g/cm^3. The nuclear gauge–determined densities of the open-graded specimens were comparatively least accurate. The order of accuracy obtained with undercompacted dense-graded specimens was comparable to that of the open-graded specimens.

There are two possible reasons that might have contributed to the differences in the accuracies of nuclear gauge–determined densities of different bituminous mixes. The relative uniformity of density distribution is believed to have a direct effect on the results. Another possible reason is the influence of air voids. Tan and Fwa have shown that the presence of voids in the zone of measurement of a coarse granular material tends

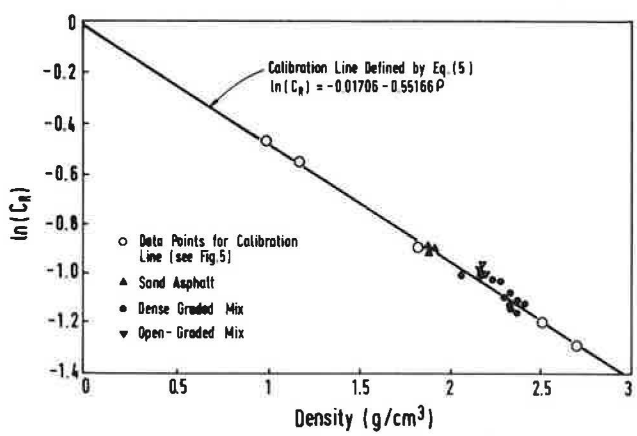

FIGURE 8 Plotting density data with twin-probe gauge calibration line.

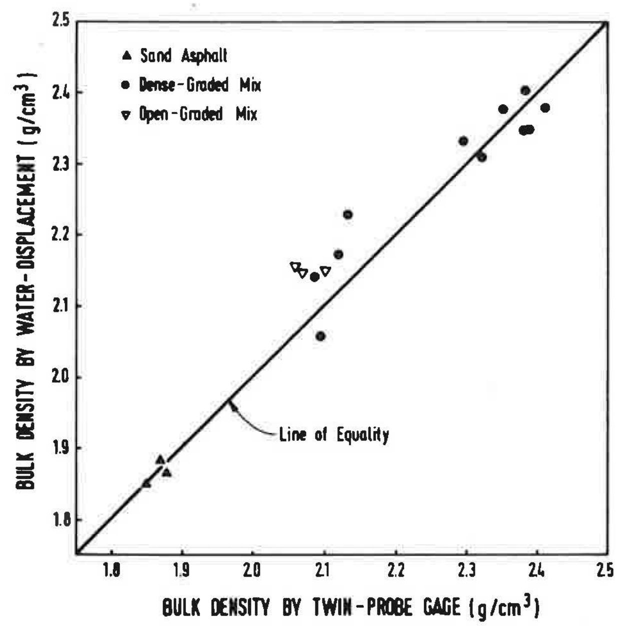

FIGURE 9 Comparison of gamma-ray density measurements with densities determined by water-displacement method.

to cause the gamma-ray gauge to underestimate bulk density (7). This effect of voids appears to explain well the trend of the test results of open-graded specimens and undercompacted dense-graded specimens.

APPLICATION: DENSITY PROFILE BY GAMMA-RAY GAUGE

Because of the number of directional measurements and repeated 1-min counts needed, the bulk density measurement of a bituminous specimen by means of the twin-probe gauge takes 20 to 30 min. The most attractive feature of the probe, however, is its ability to measure density in a predetermined localized volume. A useful application of the twin-probe gamma-ray is to obtain the density profile of a layered field core for identifying its construction history or of a laboratory-compacted specimen for ensuring that the specimen is uniformly compacted at different depths. Being nondestructive, the gauge can also be used effectively to monitor changes in density of test specimens undergoing various treatments.

An example of density profile with depth obtained using the twin-probe gamma-ray gauge is illustrated in Figure 10. It is the density profile of a cylindrical specimen 250 mm tall and compacted in four layers. The number of compaction blows applied to each layer was varied to produce layers of different compacted densities. Three directional measurements, spaced 120 degrees apart, were made. For each directional measurement, density was determined at vertical intervals of 5 cm. The effects of different compactive efforts and the changes of density from layer to layer can be seen easily from the plot.

Although this example deals with layers of bituminous mixtures of the same mix design, the same experimental technique applies to the testing of field cores composed of layers of different mix types. However, depending on the mix types encountered, the number of directional measurements required may vary from layer to layer.

SUMMARY AND CONCLUSION

An evaluation of the feasibility of applying a twin-probe gamma-ray gauge for density measurements of cylindrical bituminous

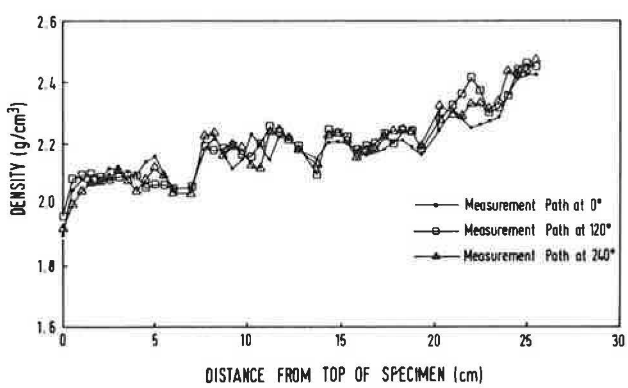

FIGURE 10 Example of density profile measurement using twin-probe gamma-ray gauge.

specimens has been presented. Sand asphalt and dense- and open-graded specimens were studied. Guidelines for gamma-ray density measurements of each mix type were recommended. From the experimental work and analyses performed in this study, the following recommendations and conclusions can be made:

1. The gamma-ray technique is a reliable method of nondestructively measuring density of common bituminous mixtures used for road construction. The calibration relationship derived from referenced materials such as aluminum, glass, perspex, and paraffin wax blocks is valid for such density measurements.
2. Considering a single path of density measurement, the precision characteristics were found to be dependent on gamma-ray count rate and hence the density of the material measured. For the range of density (from 1.8 to 2.5 g/cm^3) tested in this study, four 1-min counts per measurement path were required to give a precision on the order of ± 0.01 g/cm^3 at a confidence level of 95 percent.
3. Because of nonuniformity of point density distribution within a bituminous mixture and the limited volume of material covered in each measurement path of the twin-probe gauge, more than one directional measurement of density is required for determining the bulk density of a cylindrical bituminous specimen.
4. The number of directional measurements required is a function of the degree of nonuniformity of density distribution of the material tested. Of the three mix types tested, sand asphalt specimens had the most-uniform density distribution, followed by dense-graded and open-graded specimens in order of increasing nonuniformity. Their corresponding coefficients of variations in density were 0.4, 1.0, and 2.3 percent for 15 directional measurements. It was suggested that for determining the bulk density of cylindrical specimens, five directional measurement paths be used for sand asphalt and dense-graded specimens and seven for open-graded specimens. The errors in density associated with this measurement scheme were ± 0.35, ± 0.87, and ± 1.70 percent at a confidence level of 95 percent for the three mixes, respectively.
5. The accuracy of gauge-determined densities measured against densities obtained from the water-displacement method varied with the type of mix tested. Test results suggest that better accuracy is achieved with specimens that have more-uniform density distribution and with specimens that are less porous. Gauge-measured densities of sand asphalt specimens were more accurate than those of dense- and open-graded specimens. Undercompacted dense-graded specimens, which were more porous than the well-compacted specimens of the same mix, also produced poorer accuracy in gamma-ray density measurements than open-graded specimens.
6. The results of this study indicate that the precision and accuracy of gamma-ray density measurements of bituminous mixtures vary with their mix design and degree of compaction. In measuring the density of a bituminous mixture using a gamma-ray device such as the twin-probe gauge, there is a need to establish a measurement scheme so that the desired precision and accuracy levels can be achieved. The experimental procedure described in this paper provides useful information and guidelines in this aspect.

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