Effects of Type of Material on Nuclear Density Measurements

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Laboratory and field investigations were carried out to improve the practical application of the nuclear method for moisture content and density control in highway construction. Various factors have been studied, including the effective depth of measurement and effects of source energy and soil type on density measurements.

Two methods are described for the possible elimination of the effect of soil type in practical density measurements. In the first, direct transmission is used as an auxiliary test to normal backscatter measurements. Results are given to illustrate the advantage of this method for determining the correct calibration curve for backscatter measurements.

In the second method, introduction of an air gap between the surface probe and the soil surface is used to obtain a count ratio which, when plotted against density, gives a positive slope relationship independent of soil type for densities up to 400 pcf. This method only employs the backscatter technique and is, therefore, completely nondestructive. The air-gap method can also be used for effective density measurements on soil layers. Measurements at predetermined air gaps would also permit continuous records of density to be obtained by using a suitable rate meter.

•ONE OF THE major drawbacks in the practical application of the nuclear backscatter method for density measurements is the effect of material properties on these measurements. This effect has been independently verified by various investigators (1, 2, 3), as well as in the commercial use of this type of equipment.

A practical method of overcoming this difficulty consists of prior calibration with the sand replacement density test on the particular soil layer to be tested. This procedure is, however, time consuming and unreliable, unless a large number of correlation tests are carried out. A different correlation (3), established between the activity of the soil and the deviation of nuclear density data from a single calibration curve, has also proved unacceptable as a means of overcoming this difficulty. Extensive work carried out in the University of Chicago (4) has shown that limited improvements can be achieved by electronic pulse discrimination and mechanical gamma filters. Different approaches to a more acceptable solution have been investigated in the National Institute for Road Research, the results of which are presented here.

THE EFFECT OF SOURCE ENERGY ON DENSITY MEASUREMENTS

The possibility that the type of source may influence nuclear density measurements cannot be ruled out. Therefore, a series of tests were carried out in which the densities of widely different materials were measured using three different types of radioactive source.

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TABLE 1

NUCLEAR DENSITY MEASUREMENTS WITH DIFFERENT SOURCES

Material	Density (pcf)	Counts/Sec		
		Co-60	Ra-Be	Cs-137
Hardboard	69	1,410	635	940
Sandstone	133	900	380	390
Aluminum	165	712	290	258
Granite	185	594	238	185
Sintered slab:				
A	83.5	984	435	452
B	77	1,018	455	493
C	102.5	856	360	352
D	112	812	334	310
E	125	734	298	253
F	142	654	267	199

The test materials were selected to represent extreme variations in the effect of soil type. The so-called reference materials, covering a wide range of density, consist of hardboard, sandstone, aluminum and granite. They were found from previous tests not to exhibit a marked soil type effect. Sintered slabs specially made for calibration purposes, and covering the same range of density, were also used in these tests. These, on the other hand, showed large deviations from the single line calibration curve of the reference materials.

Density tests were carried out on these materials with the same gage but alternately using one of three different radioactive sources in the probe (Table 1, Fig. 1). The sources consisted of 15 mC cobalt-60, 5 mC radium-beryllium and 8 mC cesium-137. The gamma emission energies, as well as their distribution, varied considerably among these sources.

Calculation of the percentage difference between the calibration line for the reference materials and that for the sintered slabs shows that the source emitting the softer gamma radiation (Cs-137) gives the biggest deviation (41 percent) from a single line calibration curve through the results for the reference materials. The Ra-Be (24 percent) and Co-60 (22 percent) show a smaller influence of soil type.

These results also indicate that the higher energy gamma component of a source is relatively more important than the low-energy gammas in determining its influence on the soil-type effect. Results obtained with the different sources showed that, although about 70 percent of the gamma emission of the Ra-Be source is below 0.67 mev (the average emission energy of Cs-137) and only a relatively small portion is of the order of 1 to 2 mev, the performance of the Ra-Be source nevertheless corresponds more closely with that of Co-60 (average energy about 1.2 mev).

Comparing the slopes, K, of the straight lines in Figure 1 the sensitivity of the Cs-137 appears to be greater than that of the Ra-Be or Co-60 sources. However, when

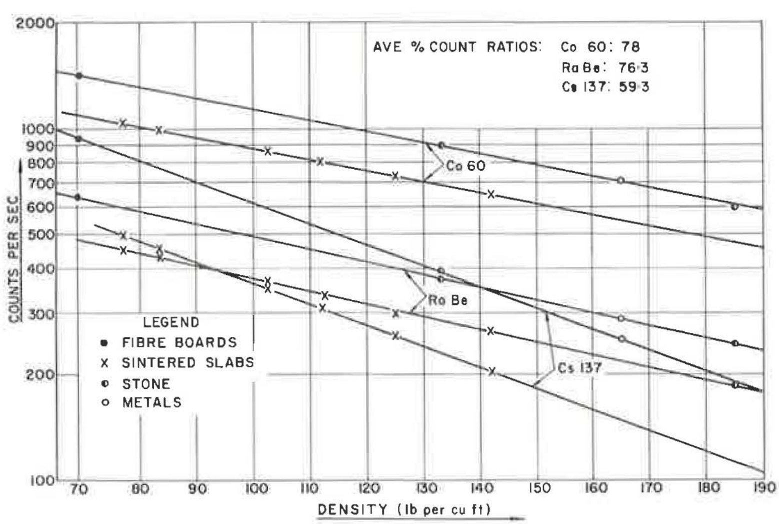

Figure 1. Effect of type of material on density measurement with various sources.

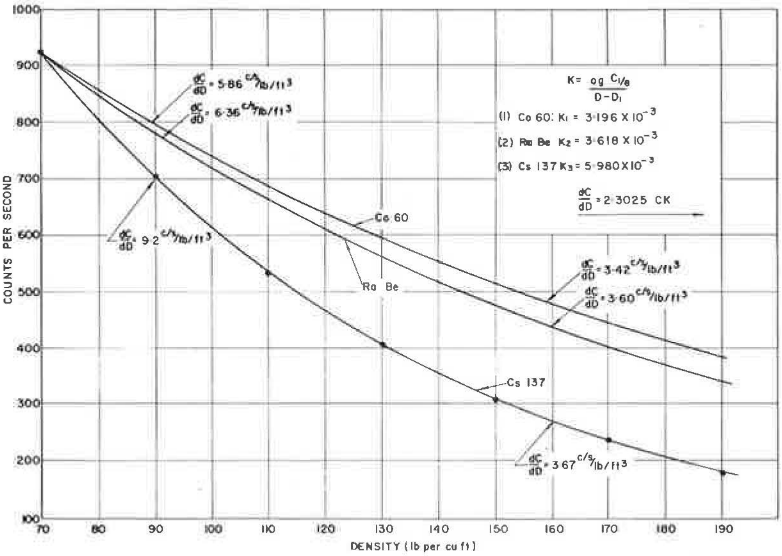

Figure 2. Normalized count rate vs density.

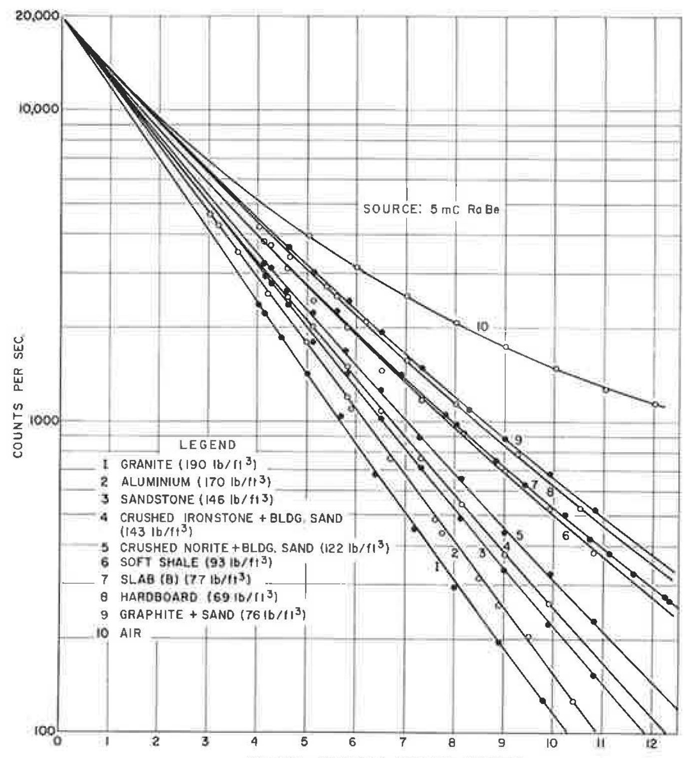

Figure 3. Density measurement by direct radiation.

normalizing these results to the same counts per second, C, at 70 pcf (Fig. 2), values of the actual sensitivity, dC/dD, can be calculated at various densities, D. These results indicate that, although the sensitivity obtained with the Cs-137 source is higher than those of the Co-60 and Ra-Be sources at low densities, all these sensitivities are approximately the same at high densities. From these results, therefore, the Ra-Be source appears to be the most suitable for use with the backscatter method, especially if its further use for moisture determiniations is considered.

DENSITY MEASUREMENT BY DIRECT TRANSMISSION

The possibility of using direct transmission of gamma rays as a means of calibrating the backscatter method for the effect of soil type on density measurements was shown in experiments carried out by Viatec (Pty) Ltd. In this work, a Geiger-Muller tube was lowered vertically into a hole in the material while use was made of the source located in a surface backscatter probe. Tests carried out on various types of soil using the direct transmission method have shown that the effect of soil type is much less than in corresponding backscatter density measurements.

To supplement this work, a series of similar tests were carried out in the National Institute for Road Research in which the Geiger-Muller tube was used in a horizontal, instead of a vertical, position. Initial correlation tests were carried out in which the source-detector distance was varied by: (a) changing the perpendicular distance between source and detector, and (b) moving the detector along the surface of the material relative to the source maintained in a fixed position in the material. No significant difference was found between the results obtained by these two methods and a wide variety of materials of different densities were subsequently tested using either method of source-detector variation.

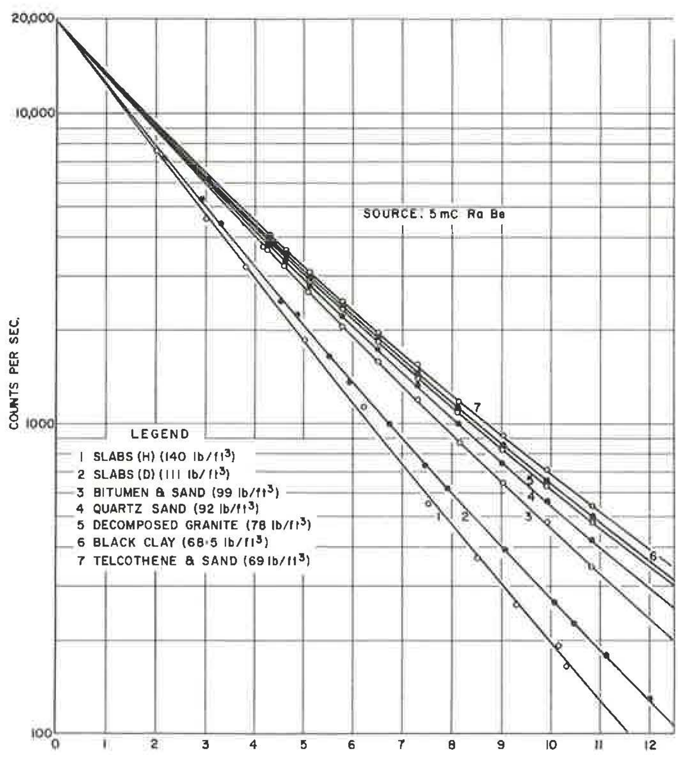

Figure 4. Density measurement by direct radiation.

The results obtained are shown graphically in Figures 3 and 4. Included in the materials tested are the sintered slabs which, from previous measurements with the back-scatter method, showed a marked effect of material type.

The data in Figures 3 and 4 have been used to prepare Figure 5, which shows the variation of count rate with density. Relatively small deviations occur from a single straight line for all materials except the sintered slabs. Further tests carried out on a variety of soils have confirmed these findings. It can, therefore, be assumed that

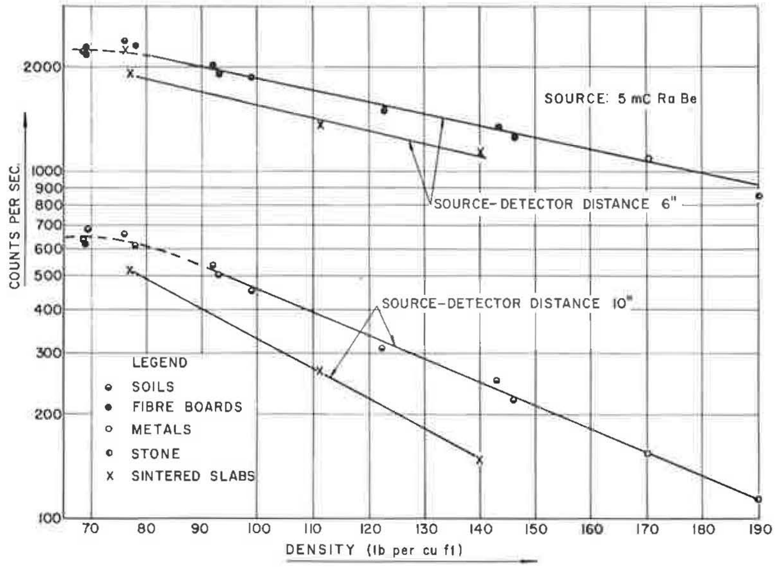

Figure 5. Results of direct transmission tests.

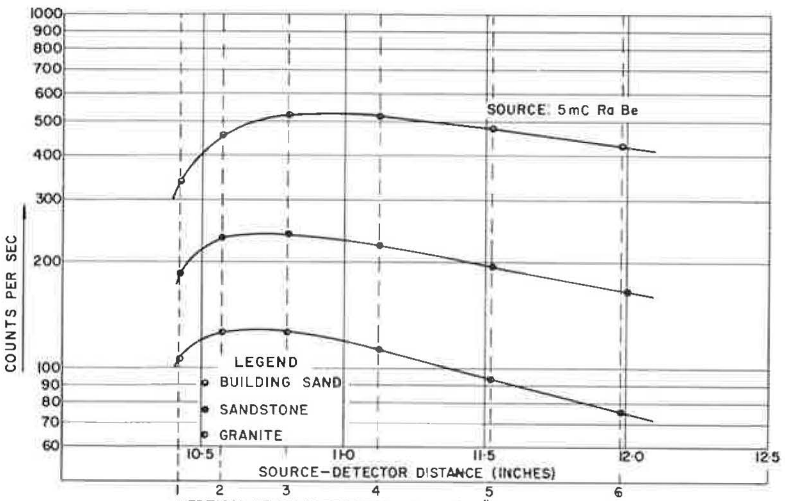

Figure 6. Effect of depth of detector below surface probe in practical density measurement by direct transmission.

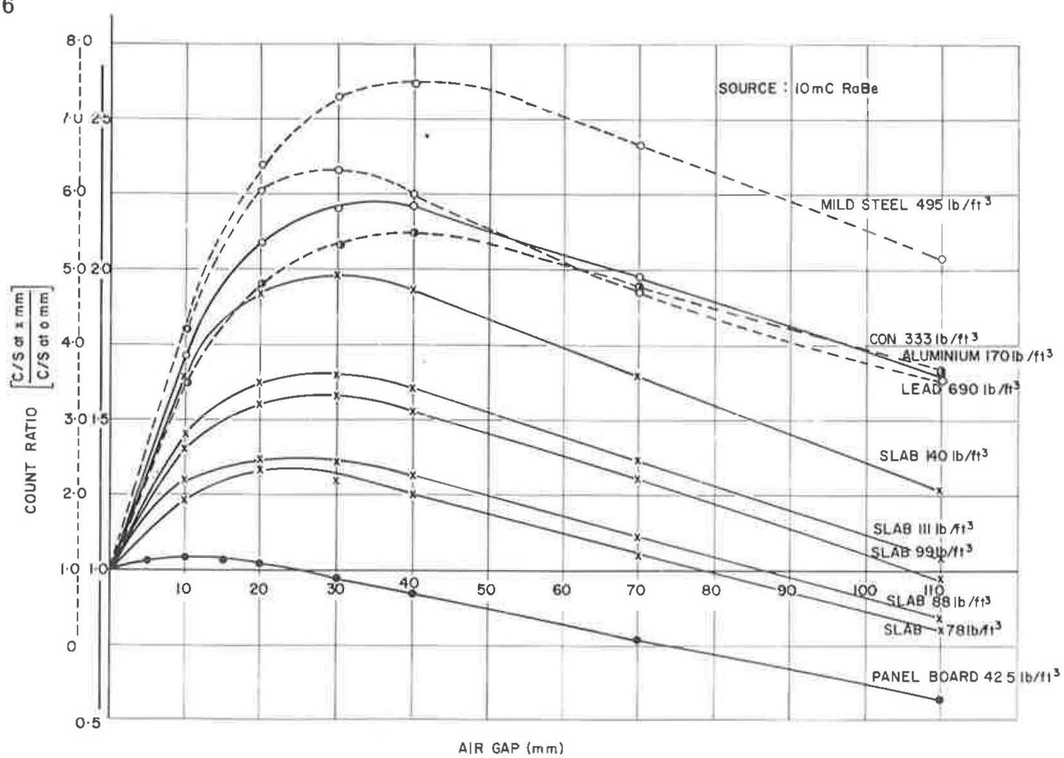

Figure 7. Measurement of various materials exhibiting soil-type effect.

the effect of soil type does not play a significant part in density measurement for the source-detector distances used in these tests.

Using a direct radiation attachment with a backscatter surface probe, the effect of the proximity of the Geiger tube to the surface probe in direct transmission measurements was further examined for different vertical distances between the underside of the probe and the horizontally placed Geiger tube. The results shown in Figure 6 indicate that deviations from the straight line relationship occur for depths less than 3 in.

From these results it appears that the direct transmission test can, under certain circumstances, be used with advantage to calibrate for the effect of soil type. It provides, furthermore, a means by which the density gradient of a soil layer can be established. The disadvantage, however, is that it will not always be possible to prepare a hole or a vertical face on the material as required in the use of the Geiger-Muller tube for the vertical and horizontal positions. A further limitation is the disturbing effect of the surface probe on measurements near the soil surface.

THE AIR GAP OR COUNT RATIO METHOD

The need for a convenient and nondestructive method for the calibration of the soil-type effect prompted further investigations to be carried out using the backscatter method only. Difficulties encountered in reducing these effects in single measurements indicated that only limited advantages can be expected. The possibility of making dual measurements, thereby eliminating the unwanted effects by using count ratios, presented an alternative possibility.

Backscatter measurements were made on different materials covering a wide density range. Measurements were taken with the probe in contact with the materials and also at increasing air gaps between the probe and material surface. Count ratios at different air gaps were obtained in this way by dividing the count rate at a particular air gap by the count rate at zero air gap. The results obtained are shown in Figures 7 and 8 and indicate that the count ratio passes through a maximum. Near the maximum the count ratio is relatively independent of the air gap. This feature indicated a practical advantage in that a rough texture of the material surface will not significantly affect the count rate at the air gap setting giving maximum count ratio. Plots of the count rates against density for the zero air gap condition and the condition where the

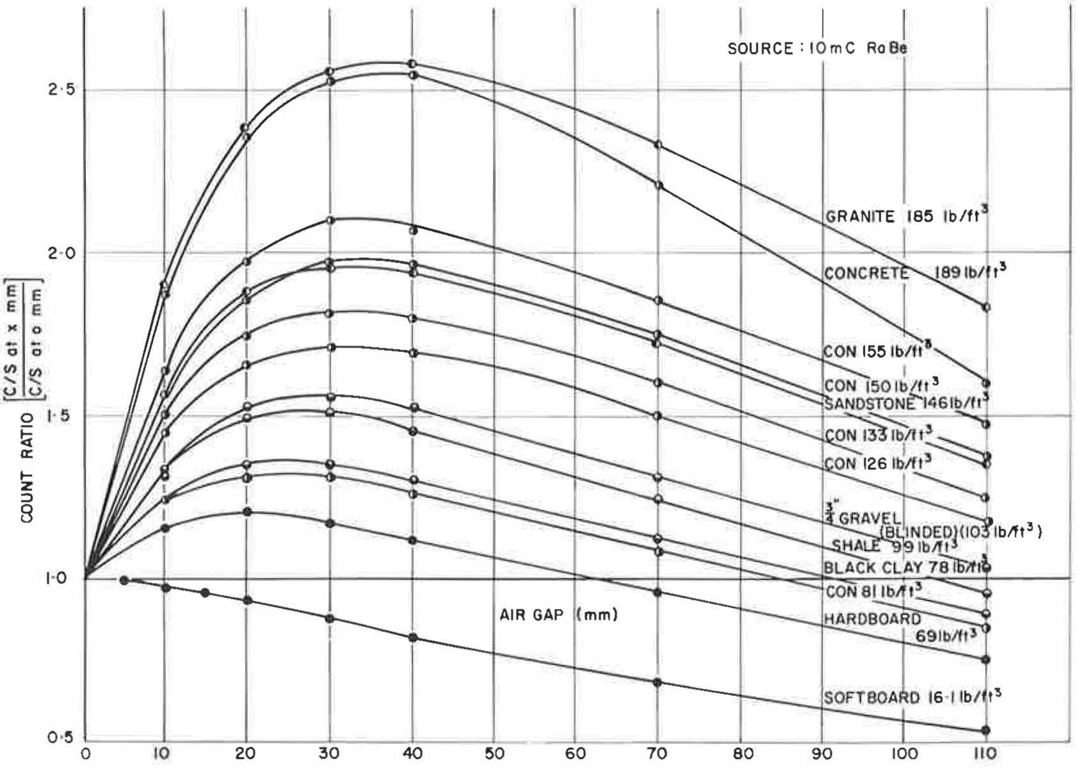

Figure 8 Measurement of various materials exhibiting soil-type effect.

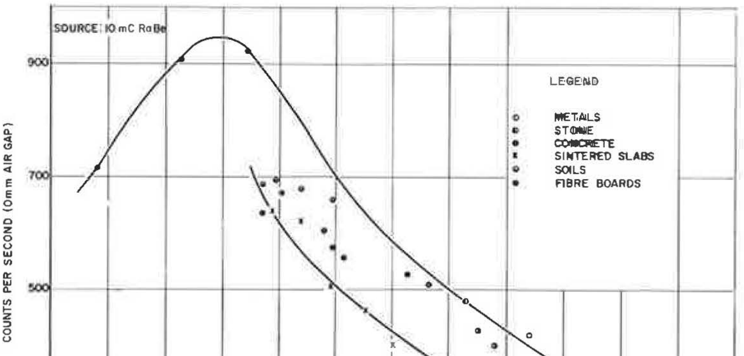

Figure 9. Measurement of materials exhibiting soil-type effect.

air gap results in a maximum count ratio for each material are shown in Figures 9 and 10, respectively. A significant soil-type effect exists under both these conditions.

Using the maximum count ratio values obtained from Figures 7 and 8, as well as similar results obtained with Co-60 and Co-137 sources, and plotting these against the corresponding densities of the materials, the relationships shown in Figure 11 are obtained. The effect of soil type has apparently been eliminated in this presentation

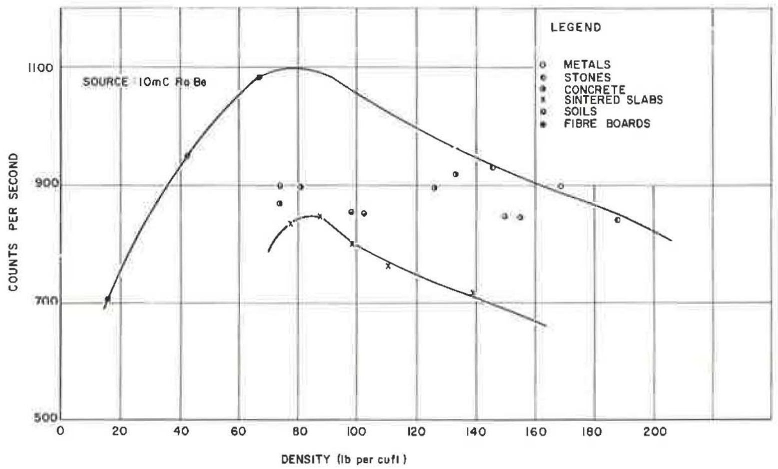

Figure 10. Measurement at air gap giving maximum count ratio for materials exhibiting soil-type effect.

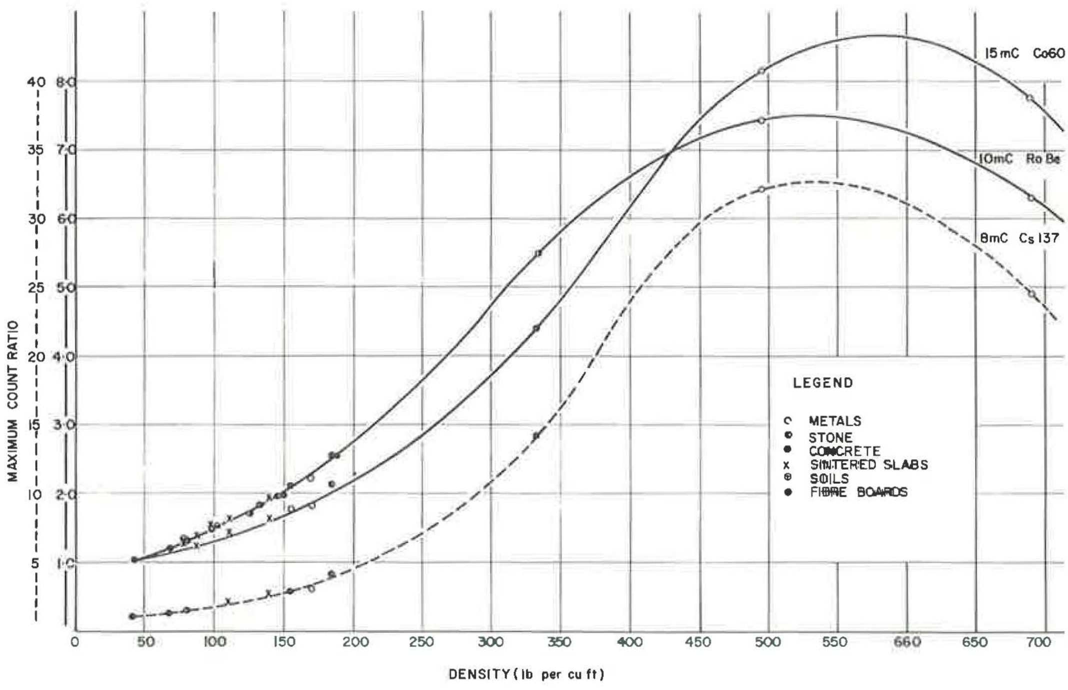

Figure 11. Maximum count ratio vs density for various sources.

and even such materials as the sintered slabs fall on a single calibration curve. These results fell on a straight line in a semi-log plot within the density range of 70 to 200 pcf. The reproducibility of the count ratio results is within ± 2 percent, resulting in errors of ± 2 and ± 1.5 pcf for the Ra-Be and Cs-137 sources, respectively. These results indicate that the cesium source is best suited to this type of measurement because the results are linear over a wide density range of 60 to 300 pcf and the ratio plot has a high sensitivity.

An alternative way of presenting the results of Figures 7 and 8 against density is shown in Figure 12 where the air gap at which the count ratio falls to unity after passing the maximum is plotted against the density of the material. This method of presentation permits the use of a comparative counting device such as a rate meter, thereby avoiding the need for time measurements.

It is evident from Figures 7 and 8 that the air gap at which the maximum count ratio occurs is a function of the density of the material. The relationships for the three sources used are given in Figure 13. For the particular gage geometry used in this investigation and the Ra-Be source, the air gap for maximum count ratio varies between 25 and 35 mm for a practical density range of 80 to 160 pcf. Using a constant air gap setting of 30 mm for practical tests, the maximum error introduced by this simplification in count ratio determination amounts to about 2 percent or a maximum variation in density of 2 pcf. A more accurate density determination can, however, be obtained by measuring the density first at the average air gap and subsequently at the exact gap read off from the relationship given in Figure 13. In a practical field setup, provision for a limited variation of the air gap setting can be provided by means of adjustable studs attached to the surface probe.

EFFECTIVE DEPTH OF MEASUREMENT

An important consideration in the possible practical application of the count ratio method is the question of the effective depth of measurement. Determination of the effective depth of measurement with the backscatter method at zero air gap has been carried out by various investigators (2, 5). The method used in most of these measurements consisted of determining the depth at which the count rate becomes constant

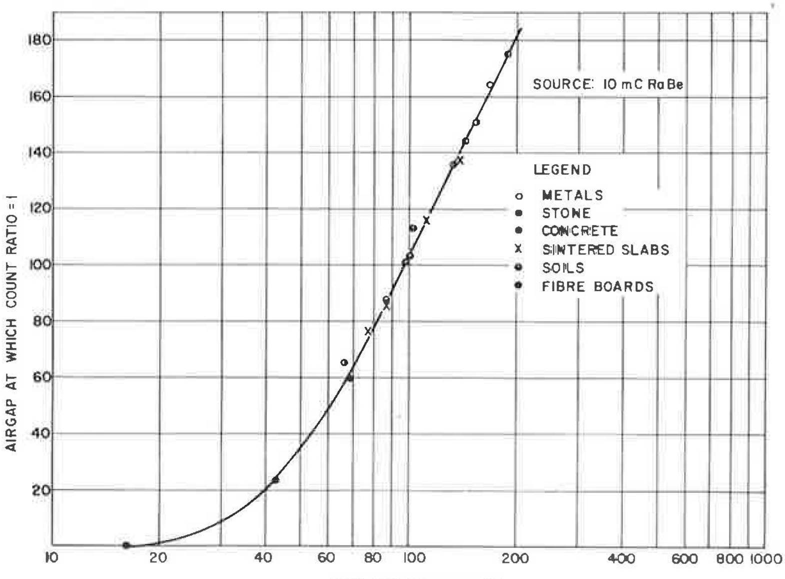

Figure 12. Density vs air gap at which count ratio returns to unity after passing through maximum.

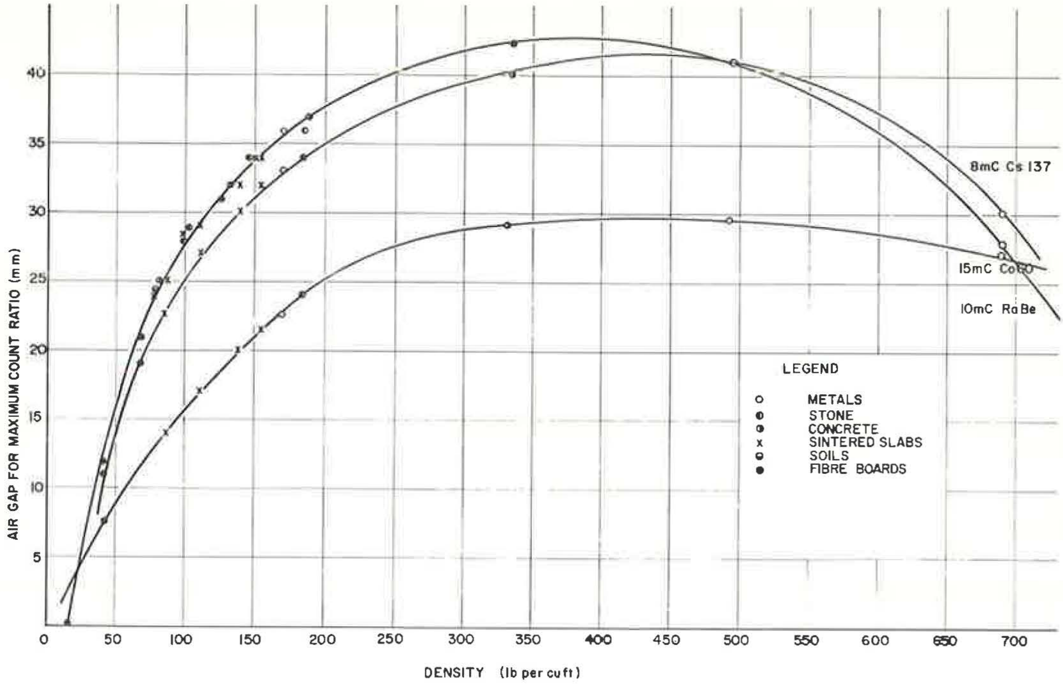

Figure 13. Density vs air gap for maximum count ratio.

with an increase in thickness of material using air as the second medium. This condition is, however, never satisfied in practice where an infinite depth of material is always encountered, although the penetration depth is limited. In a first series of tests, the effective depth of measurement for various materials was investigated by adding known thicknesses of the test material over an "infinite" thickness of a different material having a density within the normal range. Measurements taken in this way result in the type of curve shown in Figure 14 for aluminum on steel at zero air gap. Comparison of the effective depth in this case with the depth measured with air as the second medium (below the aluminum) shows that the true effective depth, 4 in., is considerably less than the apparent effective depth, 6 in., determined in the second case.

The results of further tests carried out on the same materials at both zero and 30 mm air gaps are also given in Figure 14 and show that the true effective depth at both zero and 30 mm air gap is substantially the same.

PRACTICAL EVALUATION OF COUNT RATIO METHOD

Density measurements carried out on various soils in field tests using the count ratio method are summarized in Table 2 and Figure 15, together with sand replacement densities and conventional backsetter measurements at zero air gap. It is evident from Figure 15 that the use of a single line calibration curve for the zero air gap condition would result in substantial errors of measurement. Comparison of the individual sand replacement and count ratio densities in Table 2, however, shows that a maximum error of only about 4 pcf exists, whereas no soil-type effect in the count ratio plot can be detected in Figure 15.

It has been found convenient, in this type of field test, not to use the count ratio method continuously but only as an occasional check on the calibration curve being used. The air gap procedure serves equally well for the measurements at zero air gap or at a fixed value of, e.g., 30 mm. Measurements in the off position, i. e., at

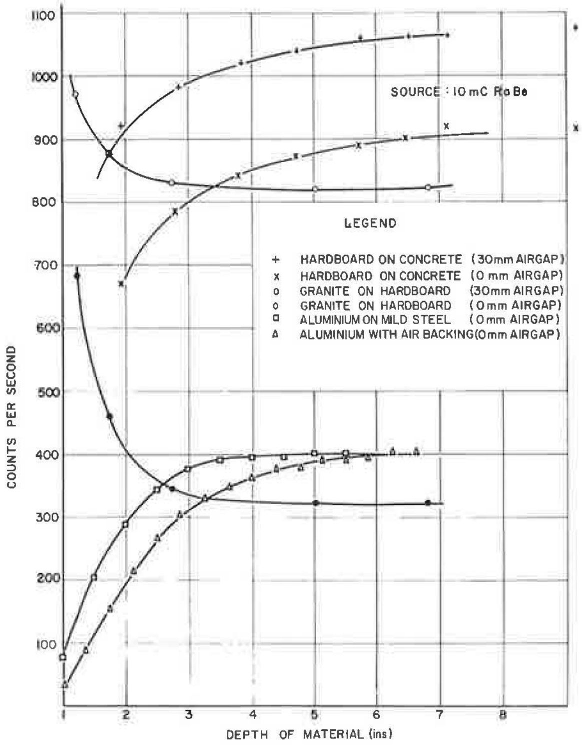

Figure 14. Effective depth of measurement in backscatter density determinations.

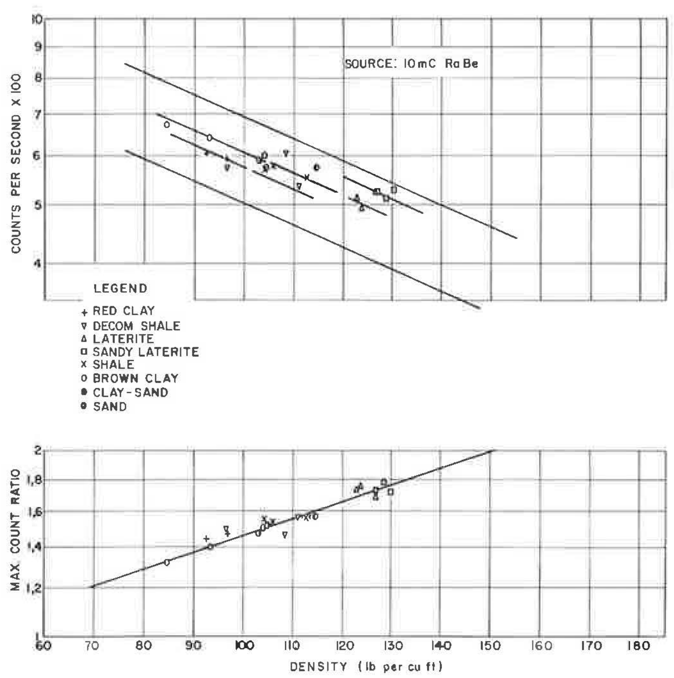

Figure 15. Field density results obtained by sand replacement and various backscatter methods.

TABLE 2

FIELD DENSITY RESULTS ON VARIOUS SOILS[a]

Material	CPS[b]	MCR	MCR Density	SRD	MCR-SRD
Red clay	604	1.46	97.5	92.5	-5.0
	594	1.47	101	96.7	-4.3
Decom. shale	539	1.56	111	111	0
	577	1.49	103.5	96.7	-6.8
	603	1.46	100.5	108.5	+8.0
Laterite	494	1.75	128.5	123.6	-4.9
	513	1.73	127.5	122.7	-4.8
	526	1.69	123.5	126.9	+3.4
Sandy laterite	530	1.72	126	130.3	+4.3
	516	1.78	131	128.6	-2.4
	530	1.73	127	127	0
Shale	555	1.56	111	112.7	+1.7
	570	1.55	109.5	104.3	-5.2
	578	1.53	107.5	106	-1.5
Brown clay	607	1.50	104.5	104.3	-0.2
	674	1.33	84.9	84.9	0
	643	1.4	93.4	93.4	0
	572	1.52	106	104.6	-1.4
Clay-sand	576	1.56	111.5	114.7	+3.2
Sand	594	1.47	101.5	103.3	+1.8

[a]Symbols used are as follows: CPS = counts/sec, MCR = maximum count ratio, and SRD = sand replacement density.

[b]At zero air gap.

30 mm, have the advantage that no bedding problems exist and also provide for the possibility of continuous recording of density by using a mobile surface probe maintained at the required distance above the soil and in conjunction with a suitable recording or indicating rate meter.

ACKNOWLEDGMENT

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Discussion

A. W. PARSONS and D. G. HARLAND, Road Research Laboratory, Department of Scientific and Industrial Research, United Kingdom.—For the past 5 yr, research has been carried out at the Road Research Laboratory into gamma-ray methods for determining bulk density of soils and base materials using both surface backscatter and direct transmission. It has been shown that the direct transmission method is by far the more promising for use in the control of compaction, although it can be applied only when the material under test allows the insertion of the probe without undue disturbance.

The principal criticism of the backscatter technique is that the measured radiation is not distributed uniformly through the compacted layer, most being scattered back from a thin surface layer. Investigations have shown that 50 percent of the radiation is scattered back within the top ½ to 1 in. and 80 percent of the radiation is scattered back within the top 2 to 2½ in. Under normal compaction conditions, the bulk density of the soil usually decreases from the top to the bottom of the compacted layer; the non-uniform distribution of the radiation in the backscatter method would be expected to cause the apparatus to register the high bulk density in the upper part only of the compacted layer. For the depth within which 95 percent of the detected radiation was scattered, even with satisfactory states of compaction, errors of as much as 2 pcf in bulk density can occur, and as compaction becomes less satisfactory this error increases. Direct transmission measurements are not affected by density gradients. However, both techniques have been found to exhibit variations in the calibration with changes in the soil type, although these were less with the direct transmission method.

Besides a soil-type effect, factors affecting the direct transmission method are the disturbance of the soil by the insertion of the probe and variations in the path length of the radiation between the radioactive source and the detector. The electronic stability of most pieces of equipment tested has been found to be low.

The researches into methods of eliminating the soil-type effect, as carried out by Mr. Kühn, are noted with particular interest.

EFFECT OF SOURCE ENERGY ON DENSITY MEASUREMENTS

Sensitivity, $\frac{dC}{dD}$, is taken by Mr. Kühn as the type of source. There appears to be little difference between the various sources at high densities. However, it could have been shown, by normalizing at a high density of, e.g., 170 pcf, that Cs-137 is the most sensitive of the three sources.

It seems more satisfactory to consider the theoretical minimum standard deviation in the density measurement caused by the inherent randomness of gamma emission and detection, and to compare radioactive sources of such strengths that they cause the same hazard at the surface of a portable shield. The minimum density deviation is inversely proportional to $K\sqrt{C}$, in which K is slope and C is the measured intensity of radiation. Measurements made with a type of equipment similar to that used by Mr. Kühn showed that the emission from the radium source was attenuated by a factor of 20 by the shield. The ratios of source strengths to give the same hazard at the surface of this shield for Cs-137:Ra:Co-60 are 81:2.4:1.06.

Taking the counts per milliCurie from Table 1, the ratios of $\sqrt{C}$ for Cs-137:Ra:Co-60 are 97:17.5:10 and 43:10.7:6.5 at 69 and 185 pcf, respectively. By multiplying these ratios by the K factors determined in Figure 2, the ratios of $K\sqrt{C}$ become 9:1:0.5 and 6.7:1:0.55 at 69 and 185 pcf, respectively.

The ratios of the inherent density deviations will be the reciprocals of these values. For the apparatus described and in the density range considered, a Cs-137 source would be from 6½ to 9 times more consistent than a radium source giving the same radiation hazard at the surface of the gamma shield. Alternatively, if the size of the cesium source were reduced until its standard deviation compared with that obtained using the optimum radium source, a much lighter shield could be used with the cesium source to give increased portability of the apparatus.

For moisture measurements, americium-beryllium is now available as a source of fast neutrons with virtually no gamma emission, and there seems little argument to support the continued use of radium-beryllium with its attendant radiation hazards for this application.

DENSITY MEASUREMENT BY DIRECTION TRANSMISSION

The results found by Mr. Kühn agree with those of the work at the Road Research Laboratory which shows that the effect of soil type is less in transmission measurements than in backscatter measurements. Because of the few and widely scattered points given in Figure 5, the elimination of material-type effect for materials other than the sintered slabs is in doubt. In addition, there is no evidence to show whether backscatter measurements on these particular materials would have exhibited a soil-type effect. In fact, the author states that reference materials (hardboard, sandstone, aluminum and granite) did not exhibit a marked soil-type effect with a backscatter apparatus. These materials are included in Figure 5, together with a number of others which mostly contained sand.

AIR GAP OR COUNT RATIO METHOD

This attempt to eliminate the effect of soil type in the backscatter technique is interesting; it would probably be of assistance to other research workers if the hypothesis behind the method could be explained. It must be remembered, however, that even if this method eliminates the effect of variations in soil type, it does not remove the effects of density gradients on the measurement.

The small scale used to portray the laboratory results for the count ratio method (Fig. 11) makes it difficult to see whether the effect of soil type has been eliminated. On replotting results obtained from Figures 7 and 8 for 10 mC Ra-Be on a larger scale in the density range 60 to 170 pcf (i.e., the maximum range likely to occur in practice), it is noted that the best straight line through the results for the sintered slabs diverges from that for the concrete blocks by 4 to 9 pcf. As there are so few results, the statistical significance of these lines is low. It is unlikely that the soil-type effect has been completely eliminated, although it certainly has been greatly reduced. This divergence between the lines for sintered slabs and concrete blocks does not agree with the author's statement that "The reproducibility of the count ratio results is within ± 2 percent, resulting in errors of ± 2 pcf...for the Ra-Be...."

EFFECTIVE DEPTH OF MEASUREMENT

The term "effective depth of measurement" is misleading because it implies that the apparatus measures the average density over that depth. The distribution of gamma intensity with depth through the compacted layer in the backscatter method has already been discussed. Where there is a density gradient, it is clear that the backscatter apparatus measures the average density to a depth much less than the depth at which the detected radiation becomes constant, as specified by Mr. Kühn. Investigations at the Road Research Laboratory indicate that the true effective depth is likely to be about 2 in., although some measured radiation penetrates to a maximum depth of 4 to 5 in.

PRACTICAL EVALUATION OF COUNT RATIO TECHNIQUE

Comparison of the field density results (Fig. 15) for the normal backscatter method and for the count ratio technique confirms that the scatter of the results has been reduced by the latter method. However, errors up to a maximum of 8 pcf are noted in Table 2 for the count ratio technique. It is considered that the wide scatter of results within each soil type, probably caused by the presence of density gradients, completely masks any variations caused by the soil-type effect. The elimination of the soil-type effect in the field results is, therefore, left in considerable doubt.