DETERMINATION OF AIR CONTENT IN HARDENED CONCRETE BY GAMMA-RAY TRANSMISSION

MICHIGAN HIGHWAY RESEARCH LABORATORY DIVISION

MICHIGAN DEPARTMENT OF STATE HIGHWAYS

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ABSTRACT: An investigation of a method of determining air content of hardened concrete by gamma-ray transmission was conducted, based on the premise that since gamma ray transmission was related to density, it could also be related to concrete air content, depending on the correlation between air content and density. A direct statistical comparison was attempted between air content as measured by the linear traverse method and by gamma-ray transmission. A sealed source of radium 226, a scintillation detector, and appropriate scaler were used to measure cylindrical samples of hardened concrete of varying lengths made with three kinds of coarse aggregate. The theoretical assumptions proved to be incompatible with the experimental techniques and the analysis of error components, performed subsequent to this study, investigated and defined the effects on concrete density of variables other than air content. This study concludes that there are certain inherent limitations in the nuclear method for measuring air content of hardened concrete which cannot be eliminated by further research or additional instrumental development.

KEY WORDS: air content, concrete testing, concrete properties, gamma rays, testing equipment, radioactive materials.

PREFACE

A research project that fails to attain its objectives often proves to be of considerable value despite the initial disappointment accompanying its apparent lack of success. Such projects, although not directly productive or profitable, often prove to have significant, indirect value to future workers in the discipline concerned. The value of such studies lies in the guidance they provide to future experiment designers by delineating pitfalls to be avoided and the approaches that are non-productive of useful results.

The report that follows describes in detail the assumptions, equipment, procedures, and results of one such study. It describes an attempt to evolve a direct-transmission, nuclear-type, non-destructive measurement system for determining the air content of hardened concrete. As the study progressed it became apparent that the resolving power of the equipment developed was not sufficient to measure concrete density variations due to air content with the degree of accuracy required in highway work.

An analytical study of the density variation effects of the ingredients of concrete, other than air, has been made a part of the report (pp. 15-22). This analysis was performed subsequent to the main study and points up the inherent difficulties in measuring air content by density determinations. These results show that the magnitude of density variation due to air content alone is secondary to variation caused by the other constituents of highway concrete.

INTRODUCTION

Conventional methods of determining the air content of hardened concrete include derivation from density (unit weight) (1), the high-pressure method (2, 3), the linear traverse (Rosiwal) method (4), and the modified point-count method (4). Currently, the Michigan Department of State Highways uses the linear traverse method.

In April 1963, the Michigan Department of State Highways prepared a research project proposal to the U. S. Bureau of Public Roads for Federal financial participation under the Highway Planning and Research Program. The project was approved, and work was started in July 1963.

The purpose of the study was stated as the determination of the feasibility of a test for air content of hardened concrete based on the relationship between the air content and gamma-ray transmission, and development of such a test if shown feasible. From previous studies in the nuclear literature it is known that the density of a material is related to the linear attentuation factor (μ), which is used to measure the decrease in gamma rays as they pass through the specimen for which density is determined. In this study, it was assumed that if density could be measured, the air content of the concrete might also be obtained, since there should be some relationship between density and the concrete air content.

Theoretical Basis

If a beam of gamma radiation of intensity (I) is incident to a layer of matter of thickness (x), the intensity of the emerging beam will be a function of the energy, intensity, and collimation of the incident beam, and of the kind, density, and thickness of the matter. Under appropriate conditions use is made of these relationships in nuclear physics in determining the absorption coefficients (μ) of pure materials, where

$$\Delta I \doteq -\mu I \Delta x, \tag{1}$$

and after integrating

$$\frac{I_x}{I_0} = e^{-\mu x} \tag{2}$$

Kaplan (2) and others have shown that proper use of Equations 1 and 2 is restricted to situations in which the gamma radiation is monoenergetic and well collimated to a small solid angle, and the absorber is thin compared to its area. Under these conditions μ is found to be independent of x.

It was not known at the outset how μ would vary with x in the case of relatively thick layers of such a heterogeneous material as concrete; therefore, it was decided to hold x as constant as possible and to investigate the relationship subsequently. Moreover, a decision to use available radium 226 as a source of gamma radiation precluded any assumption of Kaplan's prerequisite of a monoenergetic incident beam. Nevertheless, it was felt that even under these conditions μ should be a function of specimen density and that its relation to air content should be explored. Solving Equation 2 for μ yields:

$$\mu = \frac{\ln I_0 - \ln I_x}{x} \qquad (3)$$

Specimens for Study

Since air content determinations on hardened concrete are normally conducted on cored field specimens, it was felt desirable to base the study on cylindrical specimens cast in the laboratory. Three series of specimens were therefore prepared, one series containing a natural gravel as coarse aggregate, one a limestone, and one a slag. The gravel series was prepared twice, the first time consisting of eight batches of different air contents, each of which was cast into three 6-in. diam by 12-in. long cylinders. The second gravel series and the limestone and slag series each consisted of five batches having different air contents, each batch also being cast into three 6- by 12-in. cylinders. All batches of the three five-batch series contained approximately 1.2 cu ft of concrete, permitting slump measurements and Acme low pressure air content determinations (ASTM Designation C 231) on material not used in casting the cylinders. For the slag series, Roll-A-Meter air checks (ASTM Designation C 173) were made in lieu of low pressure readings. Cylinders were removed from the molds 24 hr after casting for early determination of their nuclear μ values, and then cured for 28 days in the moist room. Table 1 gives mix proportions for all series.

TABLE 1

TEST SPECIMEN MIX PROPORTIONS

Series	Batch No.	Cement, lb(a)	Dry Aggregate, lb Fine (2 NS)	Coarse(b) (6A)	Net Water, lb	Air-Entraining Agent, ml(c)	Slump, in.	Fresh Mix Air Content, percent	Wet Unit Weight, pcf
Eight-Batch Series	1	19.2	56.4	67.2	9.15	0.0	2 7/8	2.1	151.8
	2	19.2	53.1	67.2	8.42	3.0	2 5/8	3.95	149.9
	3	19.2	49.8	67.2	7.98	6.0	2 7/8	4.4	149.6
	4	19.2	49.8	67.2	9.00	9.0	1 3/4	4.9	147.3
	5	19.2	49.8	67.2	8.91	9.0	2 1/8	5.8	146.0
	6	19.2	46.5	67.2	8.48	12.0	2 1/8	6.1	145.9
	7	19.2	46.5	67.2	8.06	25.0	4 1/8	8.7	142.5
	8	19.2	43.2	67.2	7.72	30.0	3 7/8	9.5	141.7
Five-Batch Series: Gravel Series I	1	21.0	62.0	74.0	9.27	0.0	1 3/4	2.0	156.8
	2	21.0	62.0	74.0	8.14	2.0	1 1/8	3.8	154.5
	3	21.0	62.0	74.0	9.15	10.0	2 3/8	6.6	148.5
	4	21.0	62.0	74.0	8.40	5.0	1 5/16	4.4	153.5
	5	21.0	62.0	74.0	8.77	25.0	1 5/8	8.0	146.5
Five-Batch Series: Limestone Series II	1	21.0	62.0	74.0	10.48	0.0	2 1/4	1.4	153.8
	2	21.0	62.0	74.0	9.66	2.0	1 1/2	3.0	152.2
	3	21.0	62.0	74.0	8.22	5.0	1 7/8	4.8	150.0
	4	21.0	62.0	74.0	9.04	8.0	2 3/4	7.4	145.0
	5	21.0	62.0	74.0	9.66	12.0	3 1/8	8.8	142.5
Five-Batch Series: Slag Series III	1	21.8	64.5	65.0	9.85	0.0	1 3/4	2.5	145.7
	2	21.0	62.0	63.5	7.11	2.0	2 1/4	4.1	143.2
	3	21.0	62.0	63.5	9.48	5.0	3 3/4	6.8	140.7
	4	21.0	62.0	63.5	9.92	8.0	4 1/2	9.6	134.7
	5	21.0	62.0	63.5	9.10	12.0	4 3/4	9.6	133.8

(a) Peerless Type 1
(b) Gravel - Boichot, Lansing (1-in. max)
Limestone - Inland Lime & Stone
Slag - Levy, Detroit
(c) Darex

Design of Equipment

The equipment used in the study (Figs. 1 through 4) was patterned after normal laboratory setups used in studying the effects of absorbers on gamma radiation, with allowance for the large volumes of the test specimens. A housing was designed to accommodate a lead source holder, the specimen, collimating device, and sensor along a common axis, with provision for varying distances as required. Enough shielding was built into the housing so that when the source holder contained a 5-millicurie source of radium 226-beryllium, not more than 5 milliroentgens per hour of gamma radiation was present at any point of the surface of the housing.

Geometry. The lower portion of Figure 4 shows the geometrical arrangement of the setup schematically. The impinging gamma-ray beam subtended all but the outer 1/2 in. of the incident face of the specimen, in order to avoid marginal irregularities such as chipped edges. Similarly,

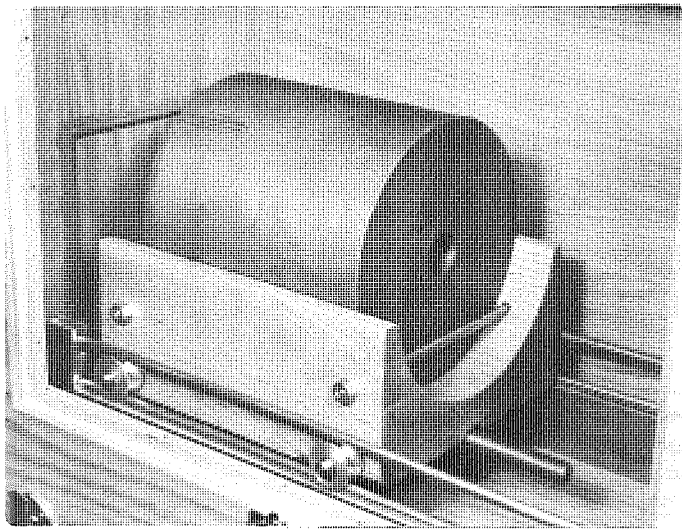


Figure 1. View of source compartment showing source container and tracking mechanism.

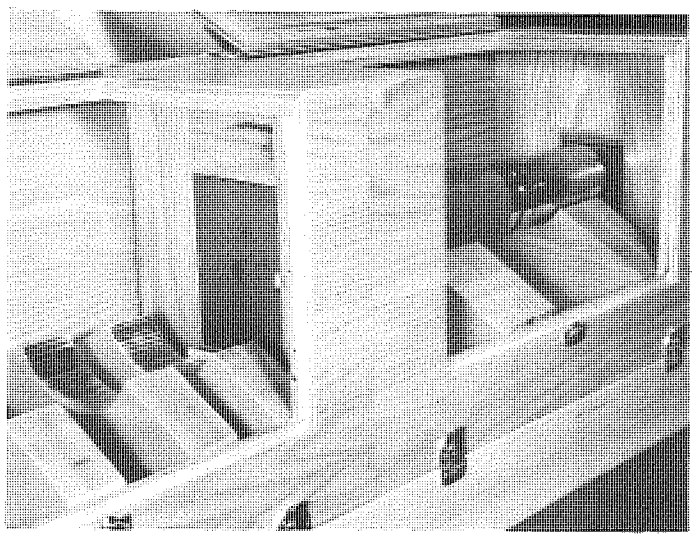
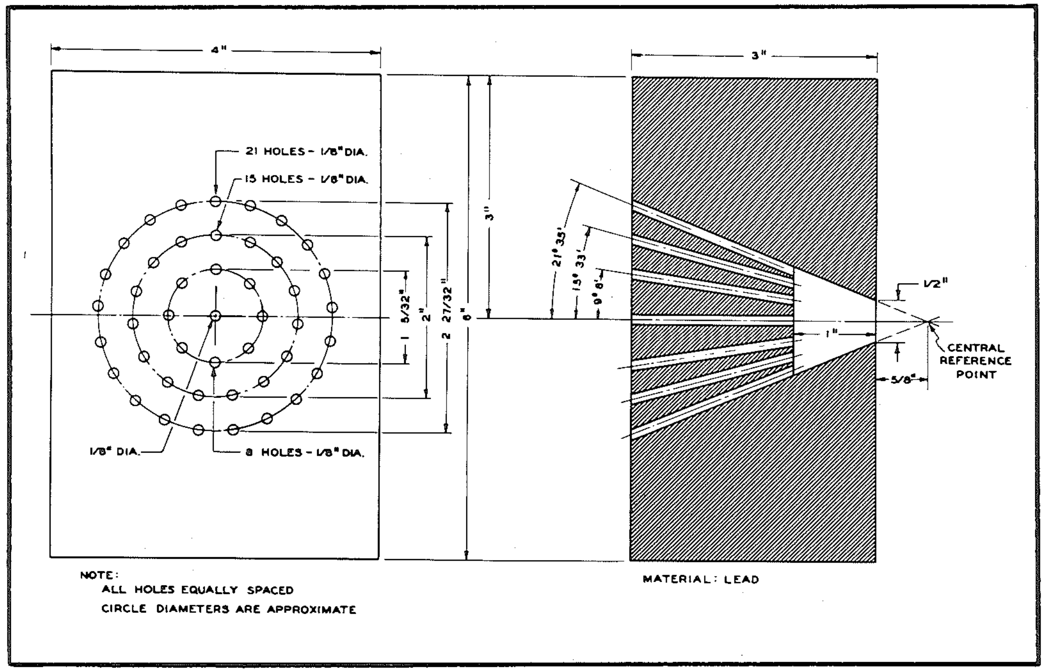


Figure 2. View of specimen and sensor compartments showing specimen supports, collimator, and scintillation detector.



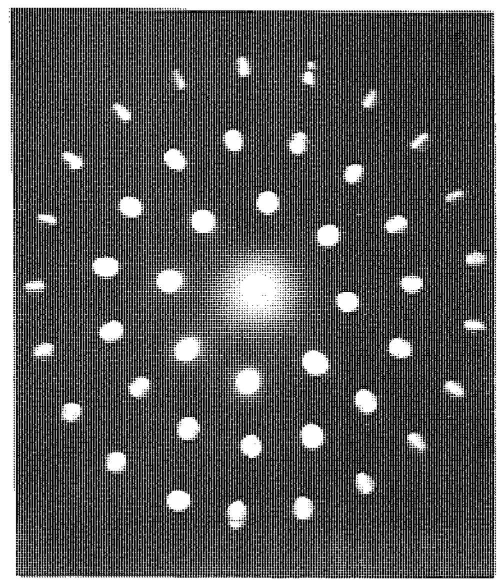


Figure 3. View from front of conical multitubular collimator with light source at focus, and schematic drawing.

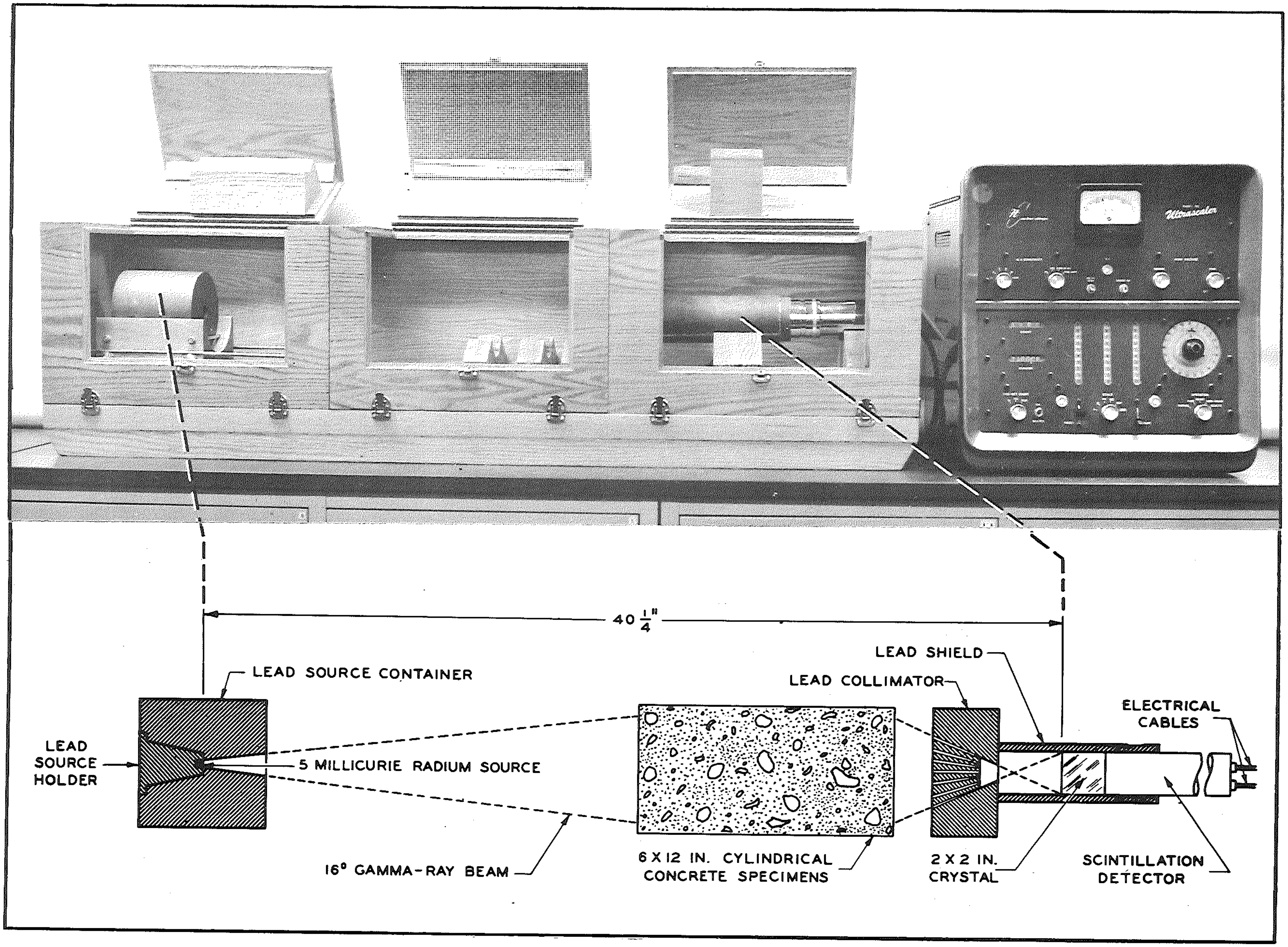


Figure 4. View of entire instrument and scaler, and schematic representation.

radiation passing through the specimen was selected for measurement only from portions of the emergent face no closer than 1/2 in. to the edge. A conical taper of the source collimator of 16° fixed a source-to-specimen distance of 20-1/2 in. between the source capsule and the incident face of the specimen, and a taper of 43° 10' in the detector collimator fixed a separation of 7-3/4 in. between the emergent specimen face and the leading face of the scintillation crystal. These distances were based on the use of 6-in. diam specimens, whose length ("x" in Eqs. 1, 2, 3) might have any value up to 12 in. The housing was therefore constructed to provide a maximum source-to-crystal separation of 40-1/4 in. as shown in the diagram, with provision for altering the parameters as required in order to accommodate 4-in. diam specimens. The axis of the source container was coincident with the longitudinal axes of the specimen and sensor. A source holder that could be detached from the rear portion of the source container permitted source removal without movement of the 70-lb container. A boresighting insert could be placed in the opening provided for the source holder to facilitate visual alignment. The housing consisted of three compartments supported by a common base.

Source Compartment. The source container rested upon an oak cradle having two wheeled axles (Fig. 1). The wheels rode on an aluminum supporting frame, and traversing was aided by a 20-turn-to-the-inch screw. The assembly could be traversed so that the source-to-specimen distance remained constant regardless of specimen length, or this distance could be altered if desired. A cover clamp locked the entire compartment.

Specimen Compartment. This compartment, located in the center of the housing, contained three oak supporting members spaced to accept the complete range of specimen sizes (Fig. 2). The emergent face of the specimen was placed in contact with a stop, which projected from the support nearest the sensor compartment. Thus, a constant specimen-to-sensor distance was maintained regardless of specimen length (this distance could be altered if desired by changing the location of the stop). Provision was made to accept samples of 4-in. diam by means of supporting member adaptors.

Sensor Compartment. The sensor compartment (Fig. 2) was designed around a conical multibular collimator and a scintillation detector. The collimator (Fig. 3) "saw" all but the outer 1/2 in. of the specimen's emergent face. It was adapted from the theory underlying the development of the Potter-Bucky grid, useful in x-ray technology for permitting passage only of radiation parallel to the openings. The scintillation detector was at such a distance from the collimator that the gamma photons emerging from the collimator crossed over to form a divergent beam covering the entire 2-in. crystal. Lead shielding covered the detector shell to reduce spurious radiation at the crystal. A clamp in the compartment cover held the detector in the operating position.

LABORATORY PROCEDURE

Effect of the Random Nature of Radioactivity

With any system based on nuclear disintegration of matter, the random nature of the disintegrations introduces an uncertainty into determination of the disintegration rate. The magnitude of this uncertainty is a function of the square root of the total number of disintegrations observed. The present study required the determination of two count rates for each test (with and without the specimen), and it was operationally convenient to have the random errors of these count rates equal. This was accomplished by determining the count rate (intensity) from the time required to record a given total count, rather than by recording the total count reached in a fixed time period. Coincidence losses are not taken into account in these relationships.

Three total count values were considered: 10^4, 10^5, and 10^6 counts. The 0.95 errors of count rates based on these total counts are about 1.96, 0.62, and 0.196 percent, respectively. This means in effect that there are 95 chances out of 100 that the uncertainty due to the random nature of radioactive decay will not exceed the percentages cited. Counting times for 6-in. diam, 12-in. long concrete cylinders were found to average 0.7, 7.0, and 70 minutes, respectively, for total counts of 10^4, 10^5, and 10^6 per specimen. A total count of 10^5 was therefore selected as a standard, requiring approximately 7 minutes to achieve with the specimen in place, which was considered a reasonable length of time. With the specimen removed, the same total count was reached in about 1-1/4 min.

Effect of Length Measurement

It can be seen from Eq. 3 that consideration must be given to the error in determination of the specimen length (x). Test specimens deviate in varying degrees from true right cylinders, and average cylinder height (x) was estimated. To preserve accuracy in measuring cored samples, which were used later in the study, it was found necessary to saw off the lower jagged portion of the sample before measuring and testing.

In determining x, the specimen was placed upright on a metal plate and its height measured with a height gage (Fig. 5). Twenty-five readings taken to the nearest 1/64 in. at random locations on the top surface were averaged to arrive at a value of x that was considered reliable. Individual readings taken on a specimen in this manner had a standard deviation from the mean of 0.035 in.

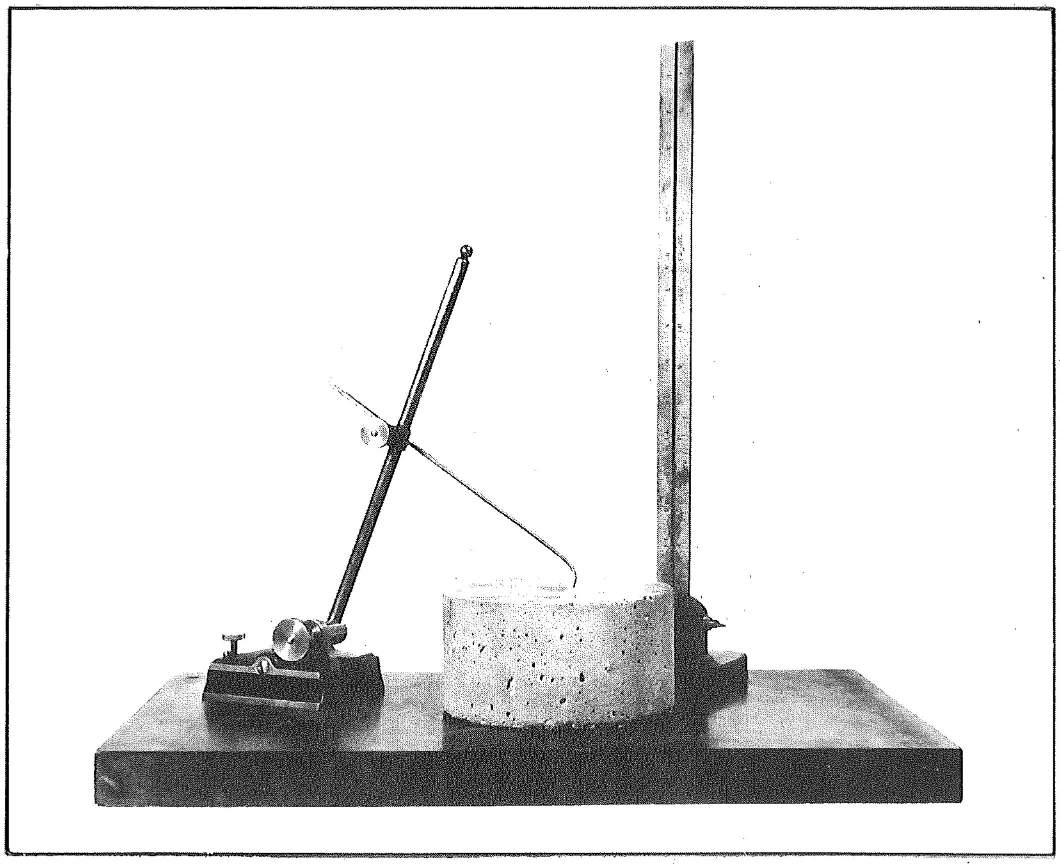


Figure 5. Determination of specimen length.

Effect of Moisture

It is known that hardened concrete of a given air content may vary in moisture content. It is therefore necessary to ascertain how variations in moisture content will affect the correlation between μ in Eq. 3 and the air content as determined by conventional methods. It was decided to investigate this effect at the extremes of moisture content.

After completion of the curing period, all 24 specimens of the first gravel series were checked for air content by the high-pressure method.

This had the effect of saturating them with water under high pressure. While still saturated, their μ values were determined according to Eq. 3. The average μ value of the three specimens in each batch was plotted against average air content of the batch as determined by the high-pressure method. The specimens were then oven dried for 72 hr at 225 F, cooled to room temperature, and their μ values redetermined. Figure 6 shows both sets of μ values plotted against the high-pressure air content results.

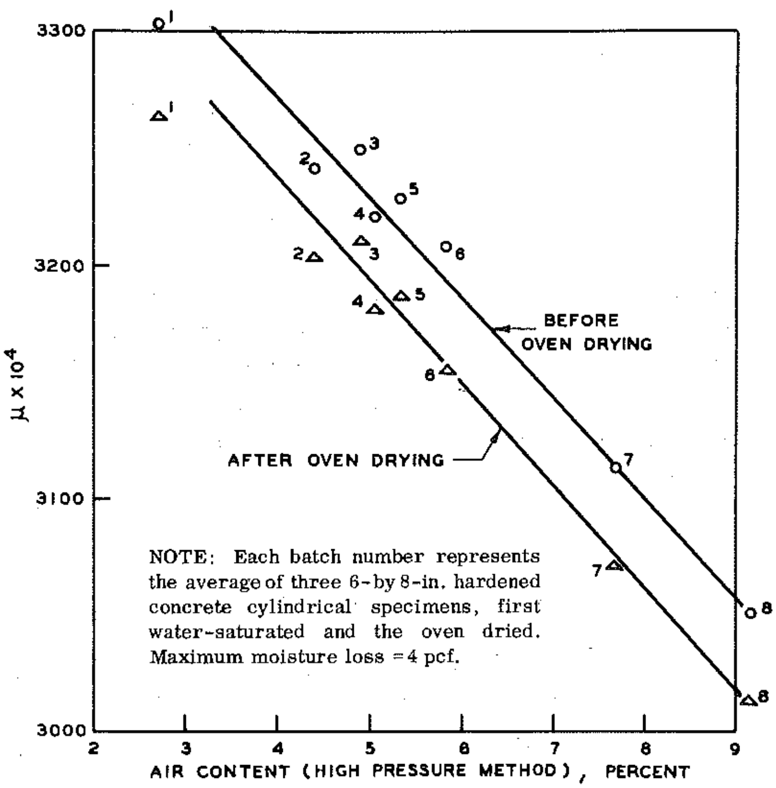


Figure 6. Effect on μ of moisture extremes in gravel specimens.

Weight losses after drying indicated that the specimens had contained as much as 4 pcf of free water. Comparison of the two curves in the figure shows that the difference in μ values at the extremes of water content corresponds to a difference of about 0.8 percent of air. The range of moisture found in typical field hardened concrete cores would not be this great and therefore the error from this source would be proportionally reduced. (However, for high porosity aggregates such as slag, the moisture range could be greater than for the specimens in Fig. 6.)

Development of Calibration Curves

Effect of Source Type. The effect of source type was determined experimentally. Three sealed gamma-emitting sources were available--cobalt 60, cesium 137, and radium 226-beryllium. Using each in turn, a preliminary trial setup was arranged with the aid of temporary supports, and μ values were obtained for all of the cylinders of the eight-batch series containing gravel aggregate. The sensor employed in these experiments was a Geiger tube mounted in a counting chamber with the door open. Temporary shielding and partial collimation were used.

The results, shown in Figure 7, indicate no evident advantage of cobalt or cesium over radium. In fact, the correlation between linear traverse air content results and the μ values obtained with radium is somewhat better than with the other two sources. Moreover, the extremely long half-life of radium 226 (1620 years) eliminates the need for periodic recalibration which would be required with cobalt and desirable with cesium. The range of uncertainty in predicting air content from nuclear measurements when using a cobalt 60 or cesium 137 source is approximately 2.7 percent air while for a radium 226 source it is approximately 2 percent. The specimens used in the experiments were normally 4-in. sections cut from the original 12-in. cylinders. The detector employed was a Tracerlab TGC-2 counter operated at 1350 v. N was 128,000 counts for each determination.

Calibration Curves for Fresh Concrete. Using the preliminary trial setup, but with the Geiger tube replaced by a DS-5 scintillation detector, μ values were determined for each of the 15 cylinders prepared as test specimens in each of the three five-batch series, 24 hr after molding. N was 10^5 counts in all cases, with an applied voltage of 1200. Figure 8 shows the individual μ values plotted against batch air contents determined on the fresh mixes by the Acme low pressure meter (ASTM Designation C 231) for concrete of varying air contents and a single source of gravel and a single source of limestone, and by the Roll-A-Meter (ASTM Designation C 173) for concrete with a single source of slag. The data indicate that separate calibration curves are required for concretes made with different coarse aggregates. Data for the points in the graphs are given in Table 2.

Calibration Curves for Hardened Concrete. Using the final, completely housed, shielded, and collimated unit shown in Figure 4, μ values were redetermined for the 12-in. cylinders. The new values are shown plotted against linear traverse air content results in Figure 9. Two effects in particular are to be noted: 1) μ values have been reduced in magnitude,

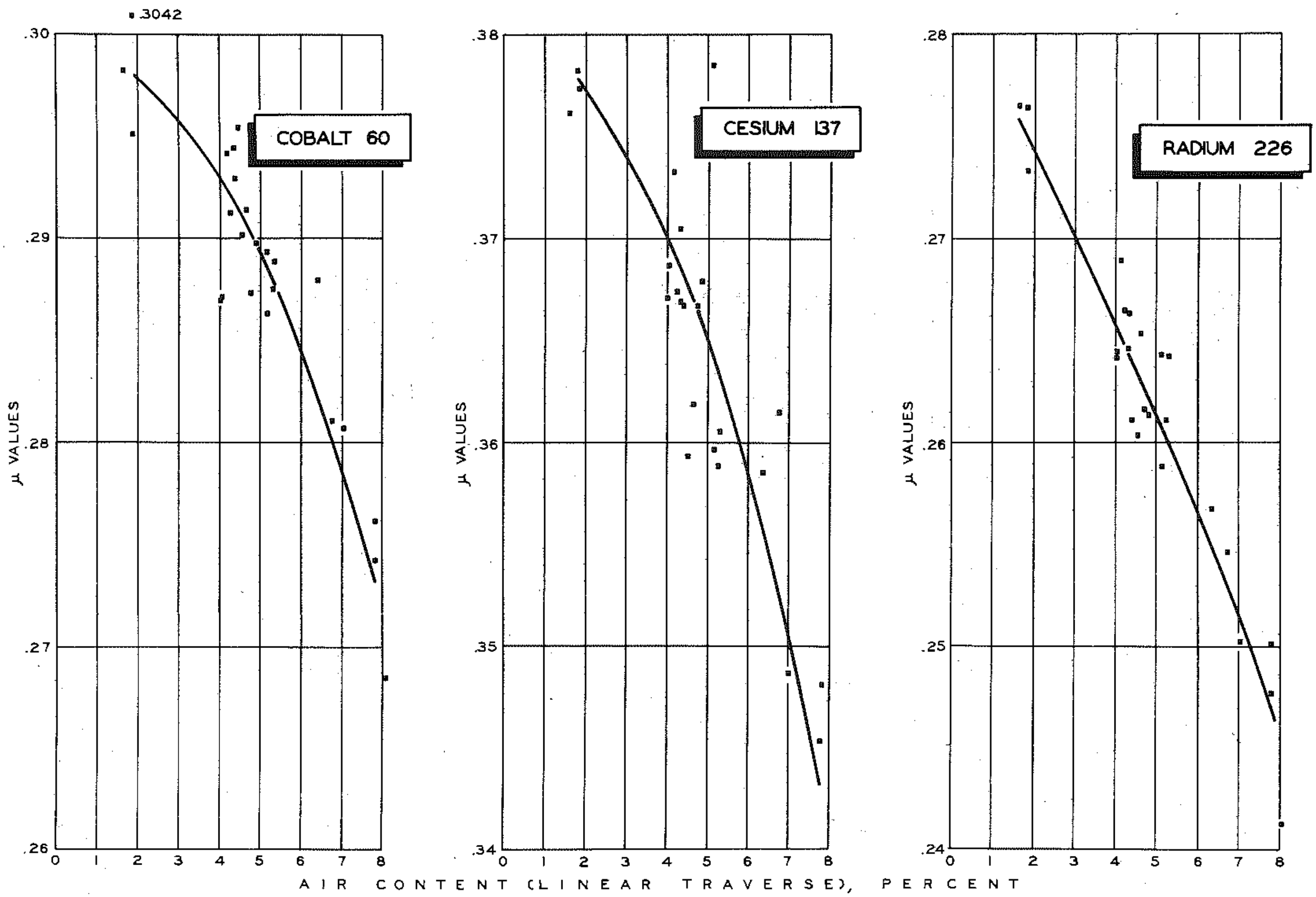


Figure 7. Effect of source type on μ value. Points represent individual cylinders.

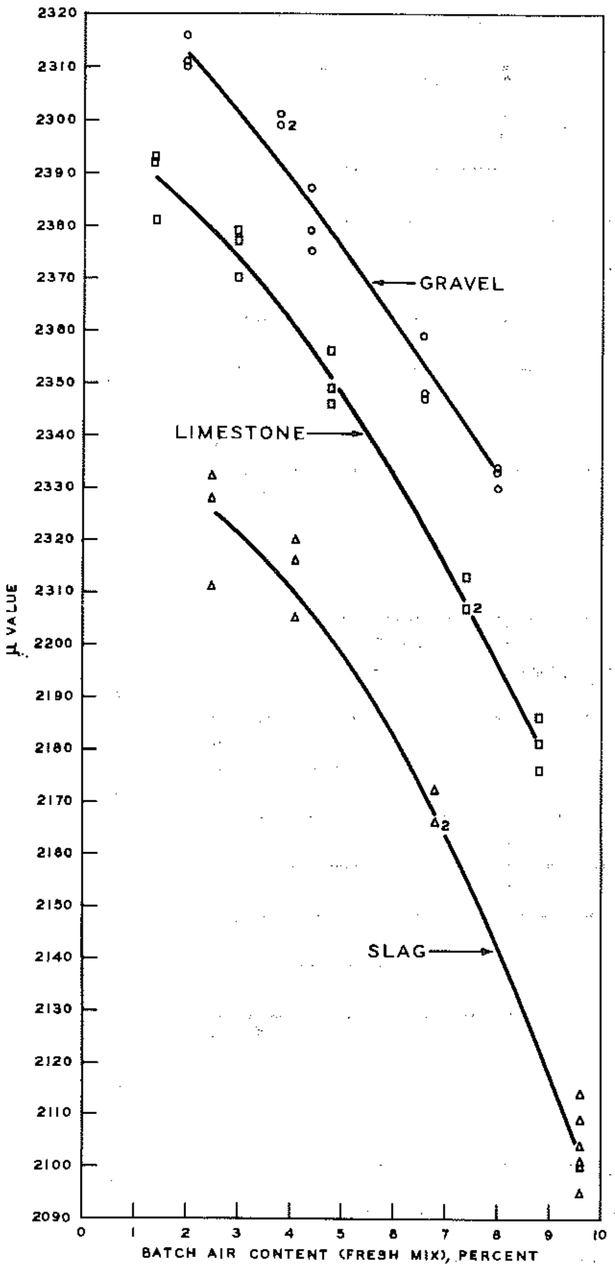


Figure 8. Relationship of aggregate type and μ value.

Figure 9. Calibration curves with confidence intervals for individual specimens in terms of percent air content. Each point represents an individual 6- by 12-in. hardened concrete specimen containing the coarse aggregate indicated. Michigan specification for air-entrained highway concrete is 5.5 ± 1.5 percent air.

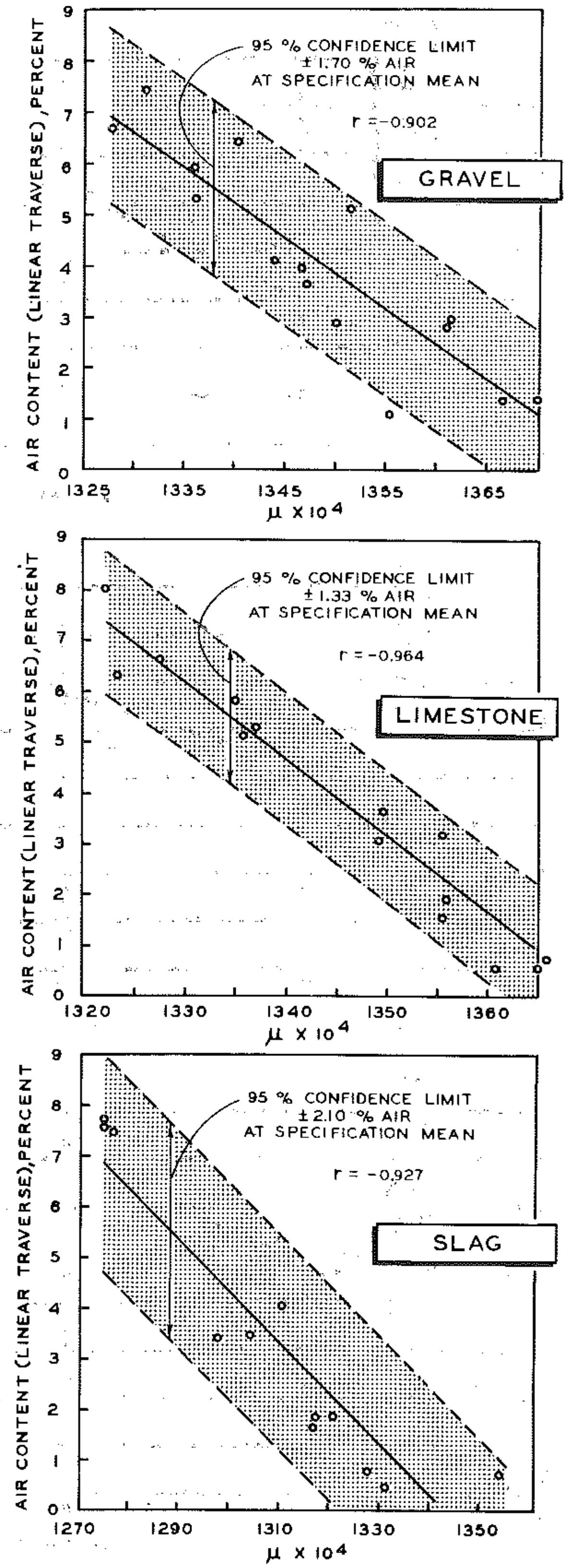


TABLE 2
SUMMARY OF FRESH CONCRETE TEST DATA

	Cylinder	μ Value 24 hr After Molding	Fresh Mix Air Content, percent	Density of Cylinder 24 hr After Molding, pcf
Gravel	G 1211	0.2311	2.0	150.74
	G 1212	0.2310	2.0	149.84
	G 1213	0.2316	2.0	150.25
	G 1221	0.2299	3.8	148.18
	G 1222	0.2301	3.8	148.78
	G 1223	0.2299	3.8	148.16
	G 1231	0.2248	6.6	142.56
	G 1232	0.2247	6.6	142.22
	G 1233	0.2259	6.6	142.33
	G 1241	0.2287	4.4	146.09
	G 1242	0.2275	4.4	146.09
	G 1243	0.2279	4.4	146.67
	G 1251	0.2234	8.0	141.40
	G 1252	0.2233	8.0	141.29
	G 1253	0.2230	8.0	141.40
Limestone	L 1211	0.2281	1.4	149.00
	L 1212	0.2293	1.4	148.94
	L 1213	0.2292	1.4	149.10
	L 1221	0.2277	3.0	147.19
	L 1222	0.2279	3.0	147.42
	L 1223	0.2270	3.0	147.56
	L 1231	0.2249	4.8	145.09
	L 1232	0.2246	4.8	144.31
	L 1233	0.2256	4.8	145.06
	L 1241	0.2207	7.4	140.32
	L 1242	0.2207	7.4	140.67
	L 1243	0.2213	7.4	140.92
	L 1251	0.2181	8.8	138.12
	L 1252	0.2186	8.8	138.12
	L 1253	0.2176	8.8	137.50
Slag	S 1211	0.2211	2.5	146.01
	S 1212	0.2232	2.5	145.70
	S 1213	0.2228	2.5	145.70
	S 1221	0.2205	4.1	145.35
	S 1222	0.2216	4.1	144.42
	S 1223	0.2220	4.1	144.04
	S 1231	0.2172	6.8	139.46
	S 1232	0.2166	6.8	138.75
	S 1233	0.2166	6.8	139.53
	S 1241	0.2109	9.6	133.72
	S 1242	0.2114	9.6	133.93
	S 1243	0.2100	9.6	133.42
	S 1251	0.2101	9.6	135.57
	S 1252	0.2095	9.6	135.41
	S 1253	0.2105	9.6	133.42

and 2) the relationships have become more nearly linear than with the preliminary trial setup. N was 10^5 counts, with linear traverse determinations made on planes cut about 4 in. from the tops of the cylinders.

It should also be pointed out that these calibration curves were established under highly controlled conditions--that is, using only one source of gravel, one of limestone, and one of slag. Also, the mix proportions were the same for all mixes. Thus, the calibration results would be expected to reflect a much smaller variation than would be obtained under a test condition where the relationship between concrete density and air content would vary for any of the following reasons:

1. Deviation of coarse aggregate specific gravity from that of the calibration specimen.

2. Deviation of fine aggregate specific gravity from that of the calibration specimen.

3. Deviation of coarse aggregate-to-mortar ratio from that of the calibration specimen.

4. Deviation of maximum size and gradation of coarse aggregate from those of calibration specimen.

5. Deviation in chemical composition of coarse aggregate from that of the calibration specimen.

6. Deviation in the angularity characteristics of the coarse aggregate from those of the calibration specimen.

Effect of Specimen Length. The effect of length of the specimen was investigated simultaneously with a study of the effect of the distance between the source capsule and detector, or sensor. Since it was necessary to conduct both studies on the same cylinders, to keep as many variables constant as possible, and since the cylinders had to be cut, the studies were conducted concurrently.

One 6-in. diam by 12-in. long cylinder was selected from each of the gravel, limestone, and slag series, such that their air contents did not vary by more than 0.5 percent from their mean value of 3.6 percent previously determined on the wet mixes. These cylinders had been molded from material used to determine slump.

As noted previously (see "Geometry"), a 40-1/4 in. source-to-sensor separation was provided in the housing to accommodate 12-in. cylinder lengths in a manner designed to avoid edge effects by restricting the collimation at both ends to areas no closer than 1/2 in. to the perimeter. This separation, which could be varied at will by means of the tracking mechanism, had to be 36-1/4 in. for similar collimation at both ends of 8-in. long cylinders, and 32-1/4 in. in the case of 4-in. long cylinders. The housing could be adjusted to other separations, to provide the same collimation for cylinders of any length up to 12 in.

The following steps were involved in this particular study. The housing track mechanism was adjusted to provide 40-1/4 in. source-to-sensor separation. Values of μ were then determined on the three 12-in. long cylinders. Next, the upper 1 in. (approximately) was sawed off the top of each cylinder, leaving the cylinders about 11 in. long. Values of μ were determined on the 11-in. lengths at each of the following four source-to-sensor separations: 1) separation adjusted to give collimation (avoiding edge effects) for the precise cylinder length measured, 2) 40-1/4 in., 3) 36-1/4 in., and 4) 32-1/4 in. Another slice of approximately 1 in. was sawed off the tops, and the same determinations repeated. This procedure was carried out until the cylinders were approximately 1-in. long (actually, slabs about 1-in. thick and 6-in. diam).

The experimental results are plotted in Figure 10, which shows μ values vs specimen lengths. It can be seen that the μ value-vs-length curves level off and become nearly parallel to the abscissa (length coordinate) when the source-to-sensor distance is maintained constant. When it is adjusted to provide constant end collimation at each specimen length, however, the curve becomes steeper, the effect of length is more pronounced, and the curve is straighter. In fact, it was found that in the latter case the square of the μ value bears an almost linear relationship inversely with the square root of the specimen length. This same procedure was followed with a 6-in. diam aluminum cylinder, with the results plotted alongside the curve for the gravel-aggregate concrete specimen in Figure 10. Aluminum has a density close to that of concrete, and of course is a pure, homogeneous material.

Analysis of Error Components

Batch Variance is variation in batch density due to variation in specific gravity and proportions of mix components. Sample Variance is variation in density from core to core, or cylinder to cylinder, for a given batch due to random location of aggregates. Assume total density variance to be a linear function of batch variance $\sigma^2_{\rho_B}$ individual core sample variance

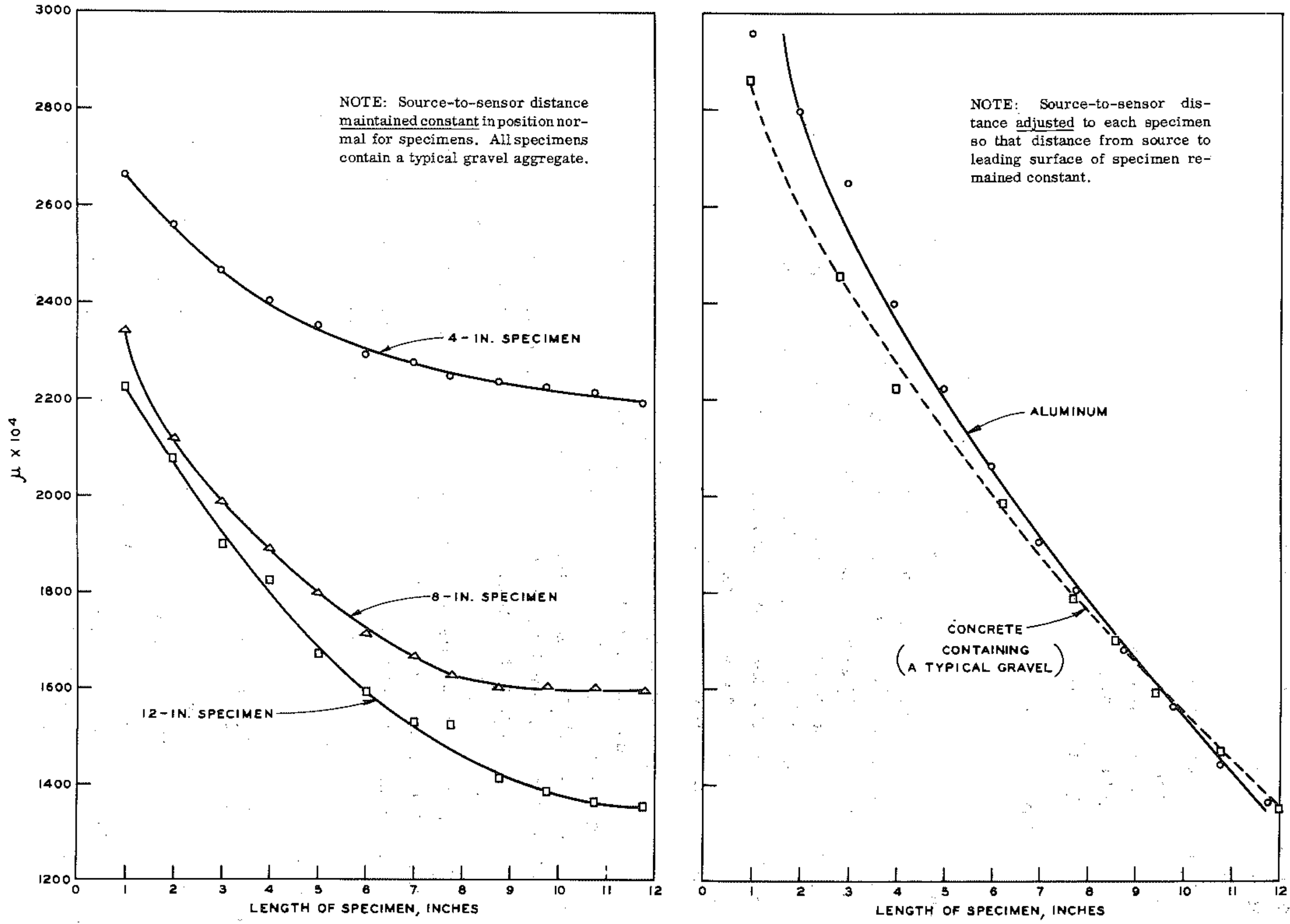


Figure 10. μ vs. length of specimen showing effect of source-to-sensor separation.

$\sigma^2_{\rho_S}$ and the variance resulting from the random nature of gamma ray emission σ^2_N. The effect of moisture is eliminated by oven drying. Mathematically expressed, these assumptions are as follows:

$$\sigma^2_{\rho_T} = \sigma^2_{\rho_B} + \sigma^2_{\rho_S} + \sigma^2_N \qquad (4)$$

Now, batch density variance can be caused by variations in the total weight of coarse aggregate W_{CA} or fine aggregate W_{FA} as well as the other components ΣW_O. Using these terms batch density ρ_B can be expressed as:

$$\rho_B = \frac{W_{CA} + W_{FA} + \Sigma W_O}{V} = \frac{\rho_{CA} V_{CA} + \rho_{FA} V_{FA} + \Sigma(\rho V)_O}{V} \qquad (5)$$

where V is the batch volume.

By expressing between-batch density variance in terms of the presumed independent mix component variances, using a Taylor expansion (5, 6), we have:

$$\sigma^2_{\rho_B} = \frac{1}{V^2}\left[\bar{\rho}^2_{CA}\sigma^2_{V_{CA}} + \bar{V}^2_{CA}\sigma^2_{CA} + \bar{\rho}^2_{FA}\sigma^2_{V_{FA}} + \bar{V}^2_{FA}\sigma^2_{\rho_{FA}} + \sigma^2_{\Sigma(\rho_V)_O}\right] \qquad (6)$$

No data are available on variation in other components, which is probably small, however, and will be assumed to equal zero. The specific gravities of Michigan concrete mix materials for 1963 and 1964 were as follows:

Aggregate		Density[(a)], g/cm^3		Volume[(b)]	
		Average $\bar{\rho}$	Standard Deviation σ	Batch Percentage $\bar{V}$	Standard Deviation, percent σ
Gravel	(CA)	2.68	0.042	Not known	Not known
Limestone	(CA)	2.68	0.020	Not known	Not known
Slag	(CA)	2.27	0.010	44.8	2.0
Sand	(CA)	2.63	0.028	32.3	2.8

(a) Data from 1963 to 1964 "Aggregate, Cement and Soils Summaries," published by the Testing Laboratory Division, Michigan Department of State Highways.

(b) Data from F. E. Legg's "Study of the Mixing Efficiency of a 34-E Dual-Drum Paving Mixer," Testing Laboratory Division, Michigan Department of State Highways, February 1959.

Next, we study the expression for between-sample density variance $\sigma^2_{\rho_S}$. This will be developed on the basis of 1-in. maximum size aggregate (gravel, limestone, or slag for 12-in. cylinders), with all other mix variables held constant. By using data from Figure 11 obtained in a correlation analysis between air content by the linear traverse method and oven-dry density, the following estimates of between-sample variance $\sigma^2_{\rho_S}$ are obtained.

Aggregate	Standard Error of Estimate, pcf	$\left(\text{Standard Error of Estimate, pcf}\right)^2$
Gravel	1.87	3.50
Limestone	1.25	1.56
Slag	0.63	0.40

We have developed expressions for $\sigma^2_{\rho_B}$ and $\sigma^2_{\rho_S}$ in terms of density units (g/$\overline{\text{cm}}^3$). However, to understand their influence on air content determinations, we must convert them to equivalent percent air (by volume) units. This can be accomplished by noting the regression line slopes fitted to the data in Figure 11. The slopes for gravel, limestone, and slag are -0.0257, -0.0255, and -0.0259, respectively. Taking -0.0257 as the common conversion factor, we find that a unit change in specific gravity is equivalent to 40 units change in air content. After converting these values to percent air, we can add them to $\sigma^2_{\rho_S}$ and σ^2_N to provide the estimate of $\sigma^2_{\rho_T}$ the square root of which is plotted in Figure 12.

An estimate of variance due to radio-counting error σ^2_N can be computed from the Michigan data using an error analysis procedure similar to that already presented. For a proper experimental setup using only transmitted emission, this source of error can be made extremely small for practical counting times. Because of excessive scattered gamma radiation in the present setup, additional counting error was experienced. The following values for radio-counting error for various total counting times (also shown in Fig. 12) were obtained taking these factors into consideration:

Time, min.	σ_N, percent air
1	2.82
5	1.26
10	0.89
15	0.74
30	0.53
60	0.39

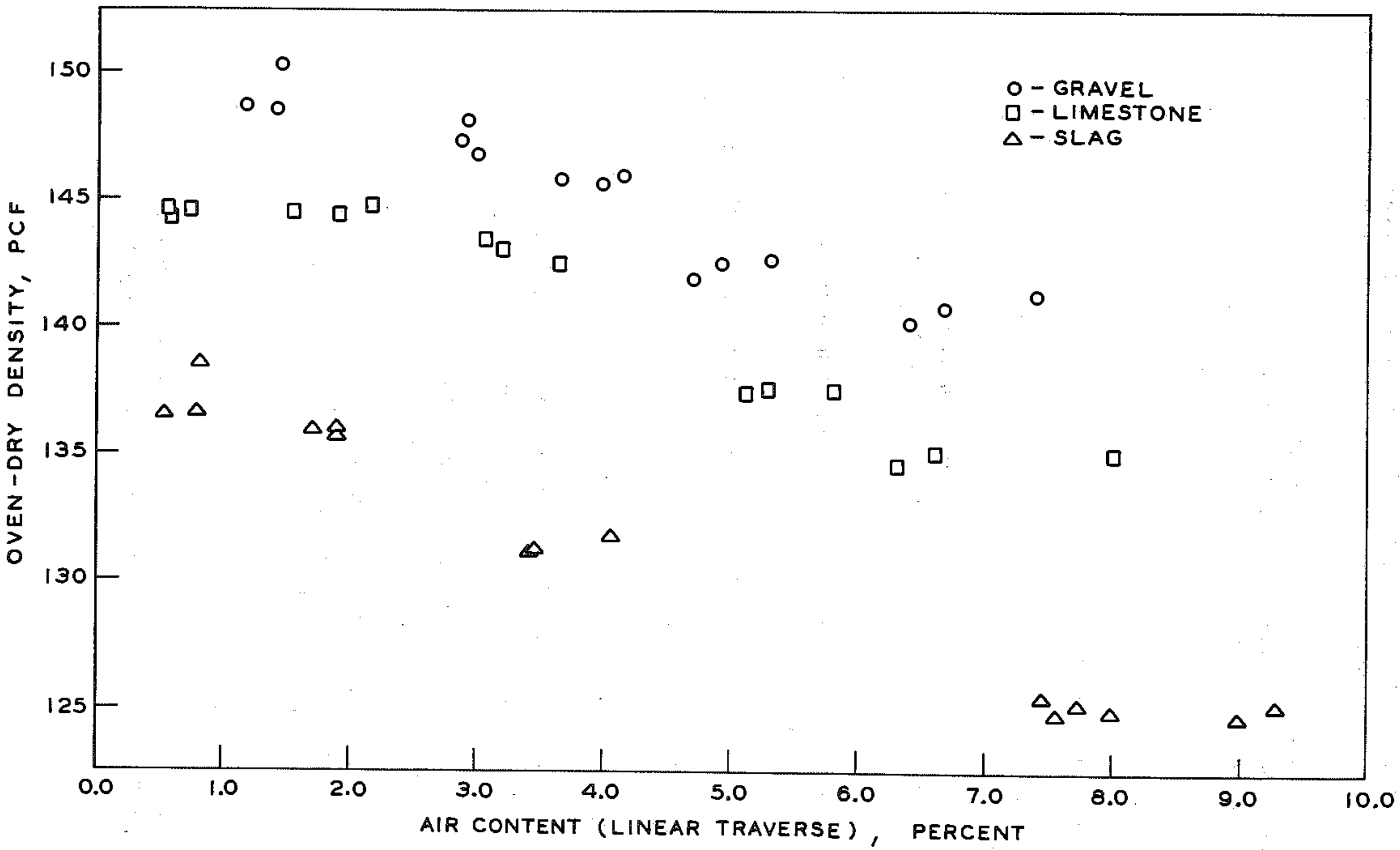


Figure 11. Relationship between density and air content for bridge concrete containing 1-in. maximum size aggregate.

However, because of space limitations, development of these error values is omitted from this report.

Figure 12 shows that 66 percent of the air content test results (one standard deviation) can be expected to fall within plus-or-minus the value shown on the top line for various counting times. For reduction of error to the lower limits in the regions designated, the assumptions are as follows:

<u>All Regions</u>

Samples are oven dried.

<u>Region A</u>

1. Error in this region can be reduced with proper experimental technique. This involves proper "geometry," counting time, and nuclear source.

2. Coarse aggregate distribution in the test specimens does not effect linear attenuation factor μ.

3. Chemical effects on gamma rays are uniform for all cylinders.

4. Counting time variability is zero.

<u>Region B</u>

Error in this region might be reduced somewhat (but not entirely) if the following exact calibration curves are available:

1. For specific gravity of coarse aggregate.
2. For specific gravity of fine aggregate.
3. For coarse aggregate gradation.
4. For proportion of coarse aggregate.
5. For proportion of fine aggregate.
6. For water-cement ratio.

<u>Region C</u>

Error in this region is irreducible because of between-sample (cylinder) variability in densities due primarily to fluctuations in coarse aggregate quantities.

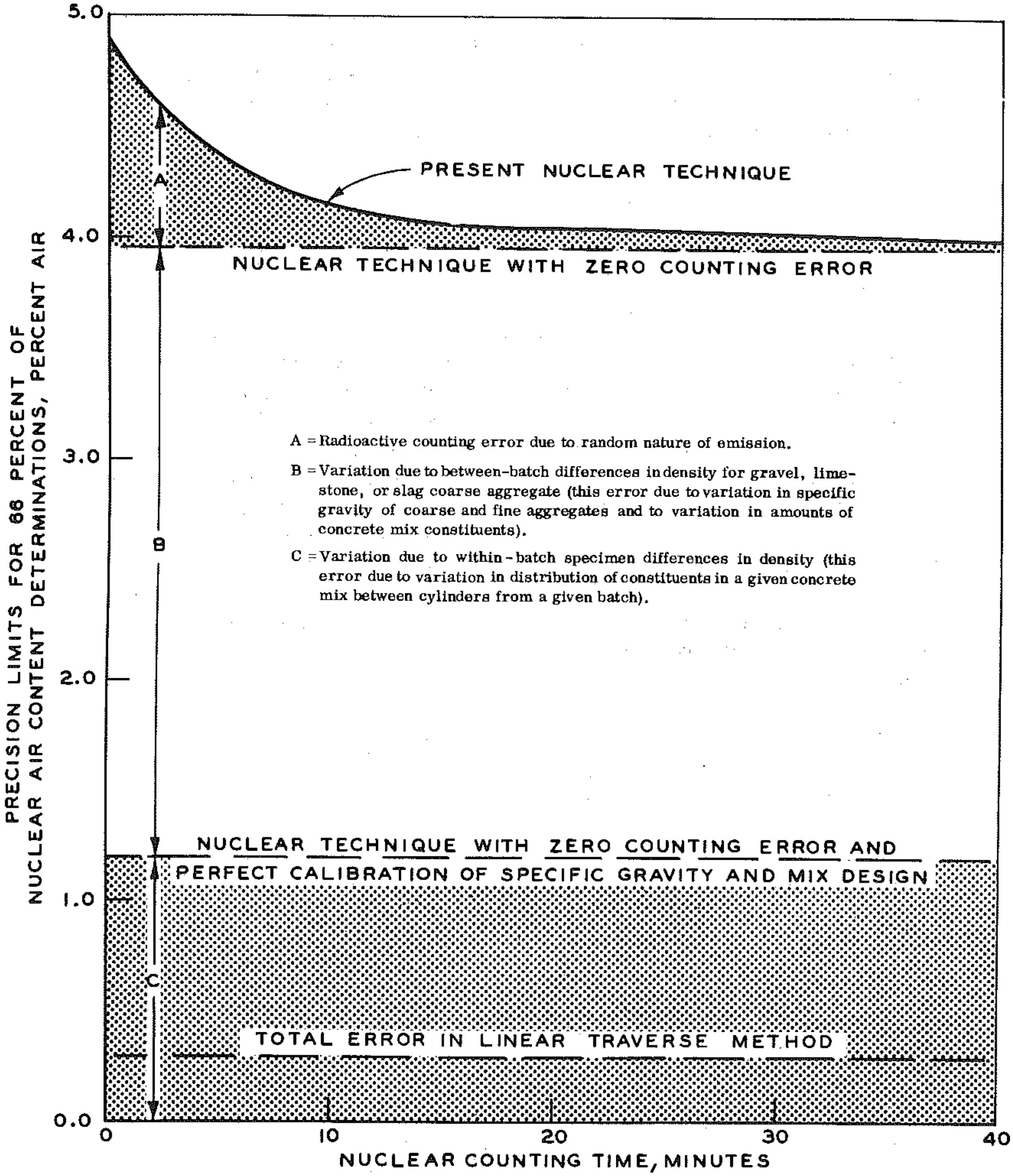


Figure 12. Approximate error curves for 1-in. maximum size gravel, limestone, or slag.

The analysis for this report is for 1-in. maximum coarse aggregate which is commonly used in bridge construction. Error analysis for pavement concrete using 2-in. maximum aggregate was impossible, because no significant relationship between air content and density could be found for the air content range available.

Tests Using Field Specimens

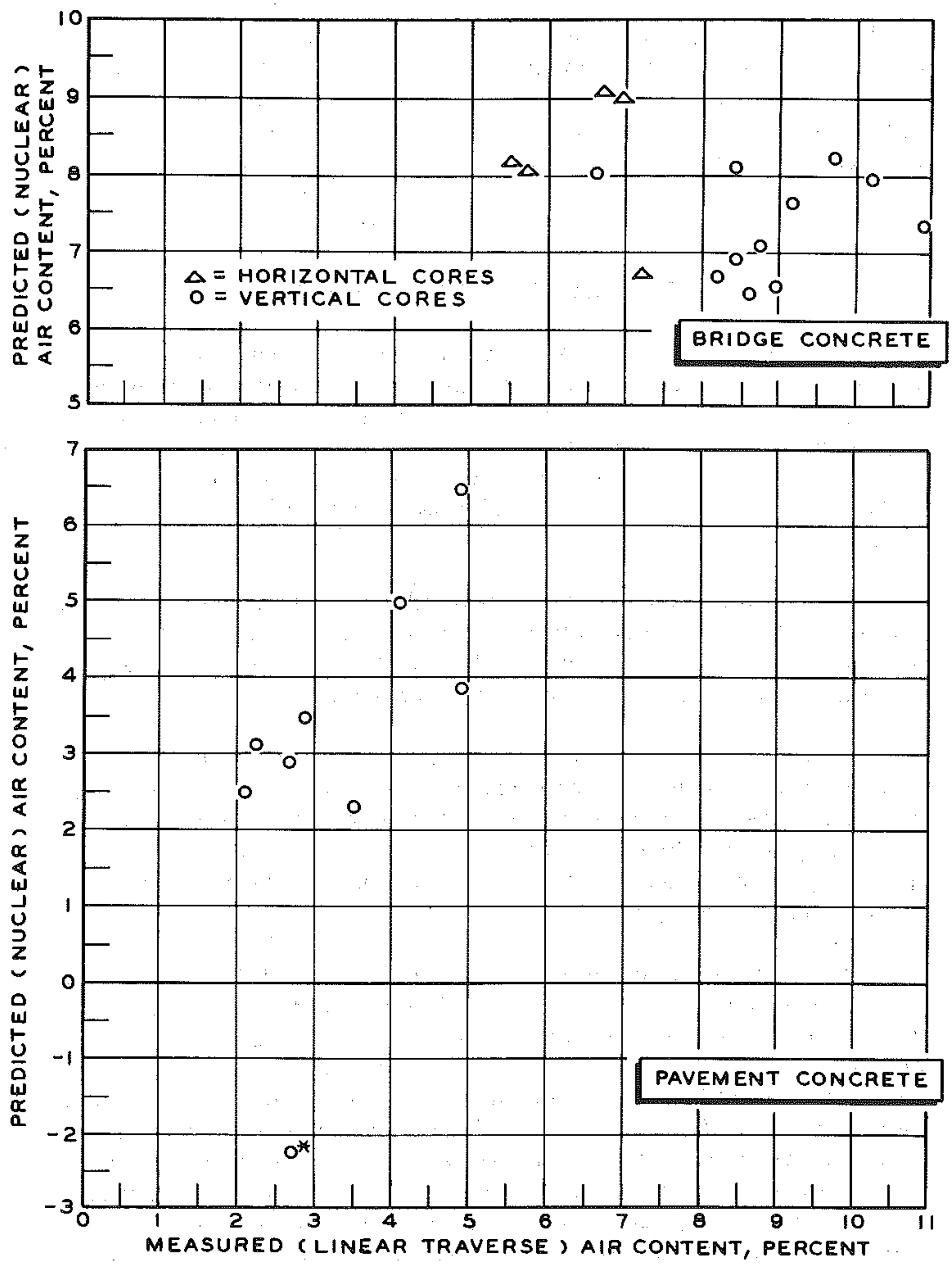
To determine the gamma-ray method's predicting power for field specimens, two air content tests series were conducted with field cores, using both the linear traverse and nuclear methods. In the first series, pavement concrete cores containing 2-in. maximum size gravel were tested using calibration curves based on 1-in. maximum size gravel, with results shown in Figure 13. In the second, bridge concrete cores of 4-in. diam containing 1-in. maximum size coarse aggregate were tested. The linear traverse and nuclear test methods failed to correlate in either test series, even though the air content ranges by the linear traverse method were 2 to 5 percent and 5.5 to 11 percent, respectively. As shown in the preceding analysis of error components, errors in measuring air content of field specimens can be traced to the following causes:

1. Variation in density among different mixes, caused by differing specific gravities of coarse and/or fine aggregates, or by varying proportions of mix components.

2. Variation in density among cores from the same mix.

3. Variation inherent in radio counting.

Effect of these three error components are shown for the nuclear method in Figure 12. These error sources, if expressed as variances, are additive, thus permitting estimation of overall, total, or composite error in field use of the method. For example, for a core found to contain 5-percent air by the linear traverse method, two-thirds of the nuclear determinations using current calibration curves will range from 1 to 9 percent air, and one-third beyond that range. It should be noted that increasing nuclear counting time by any duration beyond 10 minutes would result in very little reduction in this range. Even if coarse and fine aggregate specific gravities, as well as exact batch proportions for all constituents, were accurately known--a practical impossibility--then this range could be reduced only to 3.81 to 6.19 percent air by the nuclear method for a 5-percent linear traverse reading. From a practical standpoint, calibration of the nuclear method could not reduce this range to



* Predicted value, based on extrapolation of calibration curve.

Figure 13. Comparison of air content predicted by the nuclear method, with air content measured by the linear traverse method.

much less than ± 3.95 percent air. By comparison, two-thirds of linear traverse determinations by the same operator fall within a range of only ± 0.43 percent air. Similarly, gravel, limestone, and slag determinations fall within ± 0.09, ± 0.08, and ± 0.29 percent air, respectively, using the high pressure (Lindsay) method.

SUMMARY AND PROJECT CRITIQUE

A method of determining air content of hardened concrete by gamma-ray transmission was investigated. This investigation was based on the premise that since gamma ray transmission was related to density, it could also be related to concrete air content, depending on the correlation between air content and density. A direct statistical comparison was attempted between air content as measured by the linear traverse method and by gamma-ray transmission.

Specialized equipment was designed and constructed, including devices for source-holding and shielding, beam-collimating, sample supporting and aligning, and separation and tracking; and an integral housing for safe containment of source, specimen, and sensing pickup.

The method entails use of a 5-millicurie sealed source of radium 226, a scintillation detector, and an appropriate scaler. Neither pulse-height nor energy-discrimination circuitry was employed in the study. Samples consisted of right cylinders of hardened concrete of 6 in. diam and varying lengths up to and including 12 in., made with natural gravel, limestone, and slag as coarse aggregates.

No advantage was found to the use of either cobalt 60 or cesium 137 rather than radium 226, as a source of gamma radiation. Calibrations were made for concrete specimens containing coarse aggregate of three different types--a gravel, a limestone, and a slag. It is not known from the present investigation whether each coarse aggregate source would require separate calibration, but it would appear from the experimental results and results of other investigations that the factors discussed previously (including: variations in specific gravity of coarse aggregate, variations between mixes in coarse aggregate or angularity of particles or chemical composition), would have an adverse effect on accuracy determinations of air content. Therefore, separate calibrations for variations in these items may be necessary to improve between-batch results and bring them closer to within-batch results as shown in Figure 12.

The report section titled "Effect of Specimen Length" points up the fact that the laboratory apparatus developed was not successful in achieving the "good geometry" required if Eq. 3 $\left(\mu = \frac{\ln I_0 - \ln I_x}{x}\right)$ is to be applied.

Possible solutions to this problem would include:

1. Redesigning the laboratory apparatus to eliminate as much gamma-ray scattering as possible.

2. Incorporating discrimination circuitry into the apparatus. Scattered gamma-rays, being of reduced energy, could thereby be eliminated from the overall counts.

3. Completely eliminating Eq. 3 from the procedure. Maintaining sample length and apparatus variables at constant levels would permit using count rate itself as an index of density. This would also eliminate the necessity for an I_0 reading, thereby further simplifying the procedure.

As stated in the Preface to this report, the theoretical assumptions are incompatible with the experimental techniques used in this inquiry. The analysis of error components performed subsequent to the primary study (and included in this report), investigates and defines the effects on concrete density of variables other than air content. Had this work been performed prior to undertaking the study, the poor relationships found to exist between gamma ray transmission and air content might have been predicted.

CONCLUSIONS

From experimental results obtained, it is apparent that separate calibrations are required for predicting air content of concretes with the three types of coarse aggregate--gravel, limestone, and slag. Further, from limited testing of field cores, the inconsistency in results when using the calibration curves for concrete with a given coarse aggregate in predicting air content, in comparison with the linear traverse method, indicates that further calibration controls are necessary to obtain correlations that would be satisfactory. (It is suggested that the limiting accuracy for an air content measurement would have to be within $\pm$ 1 percent at a 95-percent confidence limit.) Study of error components in nuclear determination of air content indicates that even though the calibrations were perfect for the specific gravity of the coarse aggregate and for the mix proportions, the variation would be larger than $\pm$ 1 percent for one standard deviation and approximately $\pm$ 2.4 percent for a 95-percent confidence limit. Thus, even an inordinate amount of calibration to eliminate between-batch variations in density as a source of air content measurement variations would not give sufficient precision for practical application. The nuclear method, while giving some indication of air content, is not sufficiently precise to be a practical method for such a measurement. This conclusion holds even if "good geometry" could be obtained thereby removing the effects of specimen length on μ determinations.

It is also apparent from this study that the nuclear method has certain inherent limitations in measurement precision of air content of hardened concrete which could not be eliminated by further research or additional instrumental development.

ACKNOWLEDGEMENTS

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NOTE

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