ABSTRACT

CONCRETE MIXING STUDIES
BY GAMMA-RAY ABSORPTION

by Carlos A. Zapata

The quality and economy of fresh concrete depend on its ingredients, their proportions, and the homogeneity of the finished product. Selection of the proper ingredients and their proportions are important factors in achieving the desired mix consistency. However, a basic problem is the need for simple and rapid means of measuring uniformity of concrete and of finding the optimum mixing time for the blending operation.

A nondestructive, simple, rapid technique was developed for checking the times involved in various stages of the mixing process, together with an indication of the homogeneity of the concrete mixture throughout the batch. In addition, when fresh concrete was designed with strength as the basis for acceptance, the method developed was capable of determining the optimum mixing time needed to produce maximum strength.

The method involved use of a gamma-ray absorption apparatus (densitometer) in which an external radiation source was placed on one side of a drum-type concrete mixer with the transmission recorded on the opposite side.

The experimental data were recorded as a function of change in bulk density of the mix. From these data and with the aid of the attenuation law for gamma rays, linear absorption coefficients for concrete materials were obtained. These results were of considerable assistance in evaluating and predicting overall performance of the gamma-ray densitometer.

This technique's ability to detect important variations involved in the concrete mixing operation was confirmed by a concrete-mixing study using sodium chloride. Dry sodium chloride was mixed with the concrete materials. Several samples were taken at successive time intervals during the entire cycle and titrated with silver nitrate. The general distribution of the results obtained followed a regularity very similar to that found in the gamma-ray data, especially during the clumping period. Furthermore, the end of this clumping period also appeared to be the end of the variability of sodium chloride values before falling within the range of experimental error. In both methods this period ranged between 60 and 85 seconds.

CONCRETE MIXING STUDIES

BY GAMMA RAY ABSORPTION

By

Carlos A. Zapata

A THESIS

Submitted to
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MASTER OF SCIENCE

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1961

To

My Wife, Sarita

and

My Mother, Tulia

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INTRODUCTION

Although a great deal of work has been done in sampling, mixing time, and testing of freshly-mixed concrete, most efforts have been concentrated in evaluating concrete uniformity in terms of such properties as compressive strength, workability, and durability by applying well-known standard procedures.

A strong, durable concrete is obtained by correctly proportioning and uniformly blending the required quantities of water, cement, and aggregates (sand and gravel) throughout the batch. The relation of water to cement, usually referred to as the water-cement ratio, affects the compressive strength and durability of the concrete mixture. The higher strengths frequently are obtained with the higher water-cement ratios, but too much mixing water reduces concrete strength and durability. Measurement of the effects of water content on concrete is possible by the standard slump test (45). Since this test gives a good indication of the water content of the batch, it provides a basis for control of consistency or stiffness of the fresh concrete mixture. Usually, the limits for this test should be maintained within 1 to 3 in. of slump.

When air-entrained cement is used, care should be taken to keep the air content of the freshly mixed concrete within a given limit (usually 3 to 6 percent by volume). Should the air content be higher than 6 percent, concrete strength will be reduced without any gain in durability. If the air content of the concrete is less than 3 percent, the mixture may offer poor resistance to alternate freezing and thawing after the concrete has hardened. Measurement of the air

content of freshly mixed concrete is usually included in any program for testing uniformity of concrete (5, 14).

Workability or plasticity of the concrete is considerably influenced by the quality of the mortar paste (cement, sand, and water), which fills all the voids and keeps the coarse aggregate sufficiently separated so that it may move freely during the mixing period. Consequently, water and cement content of mortar and the percentage of coarse aggregate in the concrete are usually determined in any mixer performance test (5, 14).

Finally, concrete quality is also influenced by the amount of mixing required to produce adequate homogeneity. With given concrete materials and similar conditions of mixing, a longer mixing time will reduce the air content and the strength of the finished product. Some specifications require that minimum mixing time for a standard drum-type mixer should be no less than 1 minute for mixers having a capacity of 1 cu yd, with an increase of 15 seconds in mixing time for each additional 1 cu yd of concrete mixed when larger mixers are used (5). But when freshly-mixed concrete is used with strength as the basis for uniformity, careful attention must be given to mixing time between batches.

Despite the fact that all these conventional tests are time-consuming and destructive in nature, very little effort has been concentrated toward developing rapid and nondestructive methods to evaluate uniformity of concrete and optimum mixing time. For instance, it is well known that elements present in ordinary concrete show different radiation absorption properties when they are exposed to gamma rays (32, 33), yet little attention has been given to the use of radioactivity in testing the uniformity of fresh concrete.

A recent investigation using radioisotopes for study of mixing efficiencies in ready-mixed concrete was conducted by Overman and Rohrman (31). This study examined mixing times for heavier and less homogeneous materials, using a small cement mixer and colloidal gold 198 as the tracer. This work has not yet been fully reported. Another investigation is being conducted by the Georgia Institute of Technology for the Atomic Energy Commission (41). The Georgia study is concerned specifically with determination of cement content by neutron activation. Samples of cement mortar of known cement content are activated by the "Van de Graaff" machine and the calcium 49 produced is counted in the Penco 100 channel analyzer. Count rates with energies above 2.0 million electron volts (mev) have been recorded for each known cement content. Some inconsistencies have been observed in these results.

R. M. Main (13) has recently pointed out the limitations of radioactive tracer techniques for rapid determination of uniformity of mixing. Random sampling variation, sample size, and tracer technique applied to quality control are discussed in his paper. The tracer technique involves adding a small amount of radioactive compound to the material being mixed, and after the blending operation has proceeded, taking several samples to determine their content of tracer.

Other investigations have been concerned primarily with the radiation-shielding properties of hardened concrete (32, 33).

Gamma-ray absorption techniques have been used successfully for measuring density of opaque materials and solids concentration in fluids (7); for measuring density of liquids flowing inside a pipe (21); and for controlling thicknesses of solid materials and liquid levels inside tanks (17, 35).

The measurement of density is based on the known interaction of gamma rays and the orbital electrons of atoms comprising the absorbing material. Another application of the gamma-ray technique, based on back-scattering radiation, is the determination of density of soils and similar granular systems (11, 10, 36).

The present investigation was intended to evaluate the ability of an external gamma-ray system to detect significant variations during concrete mixing, and to determine, if possible, the optimum mixing time. The program was divided into three major parts.

1. The first was acquisition of a basic understanding of the nature of the problem and any relevant theory associated with it.

2. The second phase was verification in the laboratory of those results found in the literature which bear on the problem, such as attenuation characteristics and absorption coefficients of concrete materials. For this, a given composition of concrete materials was mixed in a standard drum-type mixer of 1.5 cu ft capacity. As an external radiation source 5 mc of Cs^{137} was used, together with a standard scintillation counter and a recorder. In addition, to verify the results found in terms of optimum mixing time by using the gamma-ray absorption method, other techniques were used, such as photography, tracing sodium chloride in the mixture, measuring compressive strength, determining air content, and conducting a slump test.

3. Finally, the design problems were considered for a permanent installation of the gamma-ray system to test uniformity of large batches of concrete (3 to 8 cu yd), and some experimental results were obtained in the field.

RADIATION HISTORY

The process of giving off particles or rays from the nucleus of unstable atoms is known as radioactivity, sometimes termed nuclear radiation, disintegration, or radioactive decay.

In 1896, Henri Becquerel found that compounds of uranium were capable of spontaneously emitting radiations that were able to affect a photographic plate in the same manner as if the plate had been exposed to light. He also found that such radiations could ionize air. In 1898, Pierre and Marie Curie carried on Becquerel's work and discovered the element radium, which was very much more active than uranium itself. Shortly afterward a new compound, polonium, was produced which was also active, and since that time many radioactive elements have been found. Four series of radioactive elements have been identified deriving from uranium, thorium, actinium, and neptunium. The first three decompose through a number of successive radioactive changes, emitting radioactive particles until a non radioactive end product is finally obtained. Natural lead is a mixture of the three end products plus a fourth isotope, Pb^{204}. The discovery of the neptunium was a result of many experiments with the atomic pile. This series has an isotope of bismuth as its end product.

The radiations emitted from radioactive substances are of three types, designated as alpha particles (α), beta particles (β), and gamma rays (γ). More information related to radioactive hazards from these radiations are presented in the appendix.

INTERACTION OF GAMMA-RAYS WITH MATTER

Because continuous detection and measurement of gamma rays is a major subject in the present experimental work, some understanding of the mechanism on which these measurements are based is desirable.

Practically all instruments available for detecting and measuring natural or artificial radiation depend on the ionization produced directly or indirectly through the interaction of radiation with matter. The ionizing effect of charged particles, such as alpha and beta rays, is produced directly in the interaction of such particles with the atoms of the traversed matter. But gamma rays do not produce ionization in matter directly. They interact with matter by producing secondary ionization which takes place in three ways, designated as photoelectric, pair production, and Compton effects.

In the photoelectric effect, an atom irradiated with a gamma photon absorbs the radiation by ejecting an electron (Fig. 1). The gamma photon is completely absorbed, resulting in the excitation or ionization of atoms of the matter. This mechanism of absorption of gamma rays is important only for photons with less than 0.1-mev energy.

When the energy of gamma radiation is greater than 1.02 mev, the mechanism of pair production is possible. The gamma photon disappears and an electron pair is created (Fig. 2).

For gamma radiation with energy ranging between 0.1 and 10-mev, the mechanism of Compton effect becomes important. This effect can be treated as an elastic collision between a gamma-photon and an electron. The photon

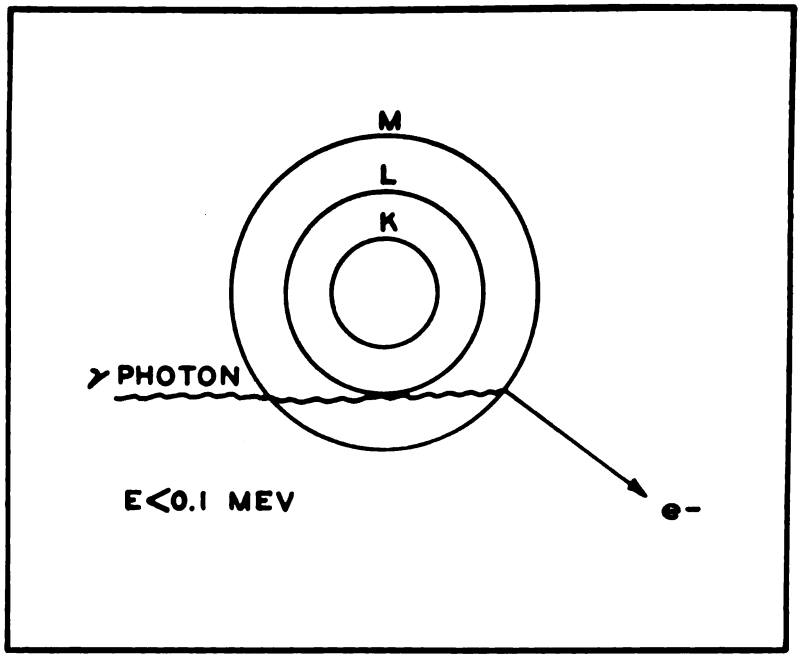


Figure 1. Photoelectric effect on atom.

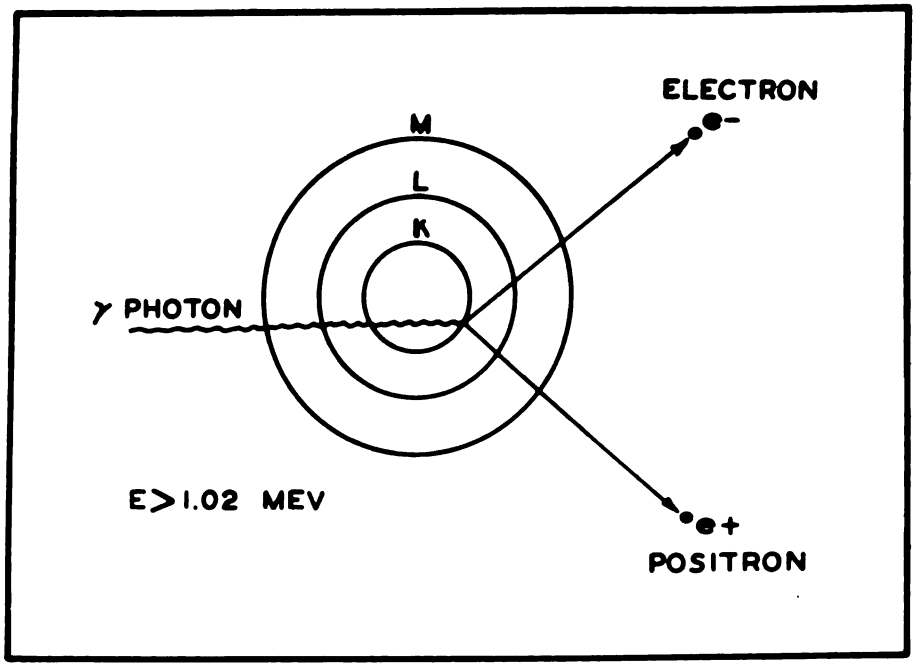


Figure 2. Pair production effect on atom.

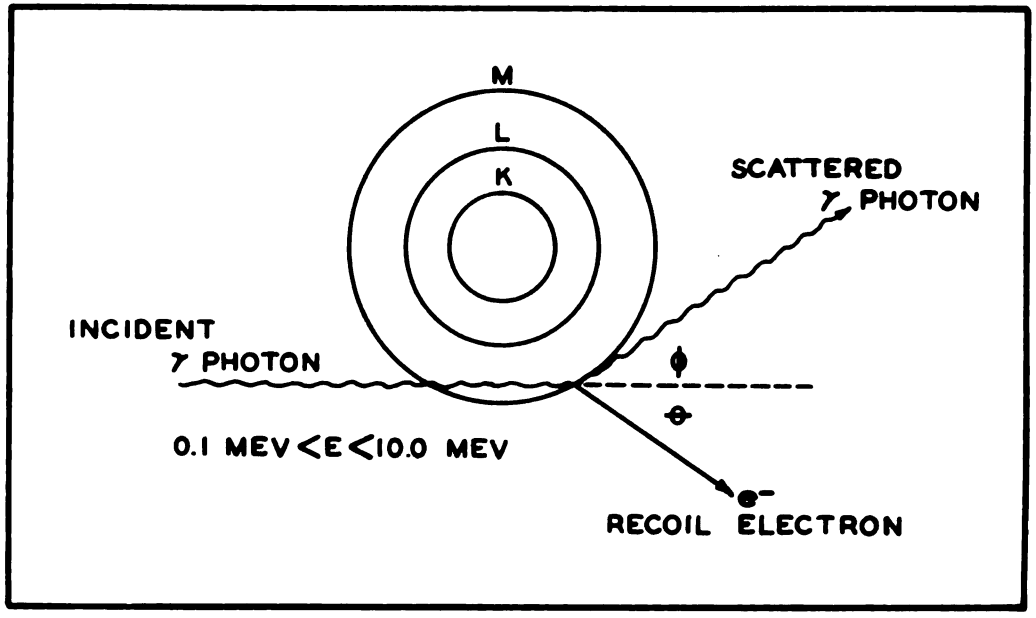


Figure 3. Compton effect on atom.

rebounds in some direction, making an angle ϕ with respect to the original path. The electron recoils at an angle θ (Fig. 3).

The Compton effect will be the only important process in the present experimental work.

FUNDAMENTAL LAW OF RADIOACTIVE DISINTEGRATION

In performing gamma-ray experiments such as those associated with the present project, it is important to compute the amount of radioactive source and activity involved. This can be done by applying the fundamental equation of radioactive disintegration:

$$N = N_0 e^{-\frac{0.69t}{t_{1/2}}} \qquad (1)$$

where N = decayed intensity in millicuries (mc)
N_0 = original intensity in mc
t = elapsed time since irradiation
$t_{1/2}$ = half-life of the particular radioactive substance.

One of the characteristics of a radioactive decay process is half-life, defined as the time required for radiation to decrease to half the original value. The half-life of each isotope is constant and cannot be changed by currently known electrical, physical, or chemical forces.

In the case of gamma-ray emitters (which were used in the current experimental work), strength is often given in terms of curies. The curie is a unit of radioactivity defined as the quantity of any radioactive material giving 3.7×10^{10} disintegrations per second. The millicurie (mc) which is one-thousandth of a curie, and the microcurie (μc) which is one-millionth of a curie, are equivalent to amounts of radioactive material giving 3.7×10^{7} and 3.7×10^{4} disintegrations per second, respectively. Practical calculations of the amount of radiation source and its activity are illustrated in the appendix.

OPERATIONAL THEORY FOR GAMMA RAYS

The gamma-ray-absorption method utilizes the effect resulting from exposing material to incident radiation. This method is based on the principle that gamma rays are absorbed in proportion to the thickness or density of the interposed material. When a collimated or narrow beam of gamma rays hits a sample of concrete material, the beam is attenuated according to the fundamental equation:

$$I = I_0 e^{-\alpha \rho L} \tag{2}$$

where I = intensity of radiation after passing through the absorbing material
I_0 = intensity before passing through the absorber
α = the mass absorption or attenuation coefficient
ρ = density of the material
L = actual radiation path length.

The second fundamental law is that the radiation intensity, I_0 , is inversely proportional to the square of the actual radiation path, L .

In the literature alpha is often expressed as:

$$\alpha = \frac{\mu}{\rho} \ (cm^2/g) \tag{3}$$

where μ = "linear attenuation or absorption coefficient," in units of (cm^{-1}).
ρ = density of the material in (g/cm^3).

Equation 2 is also written as:

$$\frac{I}{I_0} = e^{-\alpha x} \tag{4}$$

where $\frac{I}{I_0}$ = "attenuation factor or transmittance"
x = total mass of absorbing material per unit area in $(\frac{g}{cm^2})$.

The coefficient alpha depends only on the composition of the absorbing material and not on the bulk density. The linear coefficient, μ, depends on the chemical and physical states of the absorbing material. It is proportional to the sum of the Compton, photoelectric and pair production effects.

For the elements present in ordinary concrete, radiation absorption is mainly due to the Compton effect for gamma rays with energy ranging from 0.2 to 3.0 mev. This may be observed in Fig. 4 from data given by Overman and Clark (18). Values of μ are shown for the three mechanisms of gamma-ray absorption by aluminum (or by concrete) as a function of gamma-ray energy.

Typical curves of the absorption coefficient, μ, as a function of gamma-ray energy (in mev) appear in Fig. 5 as reported in the literature (1).

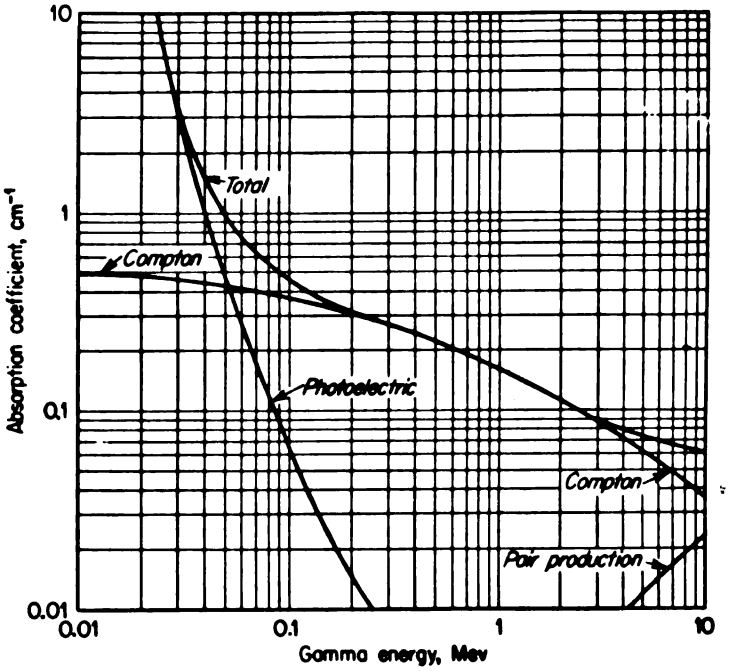


Figure 4. Values of μ for three mechanisms of gamma-ray absorption as a function of gamma-ray energy, from Overman and Clark (18).

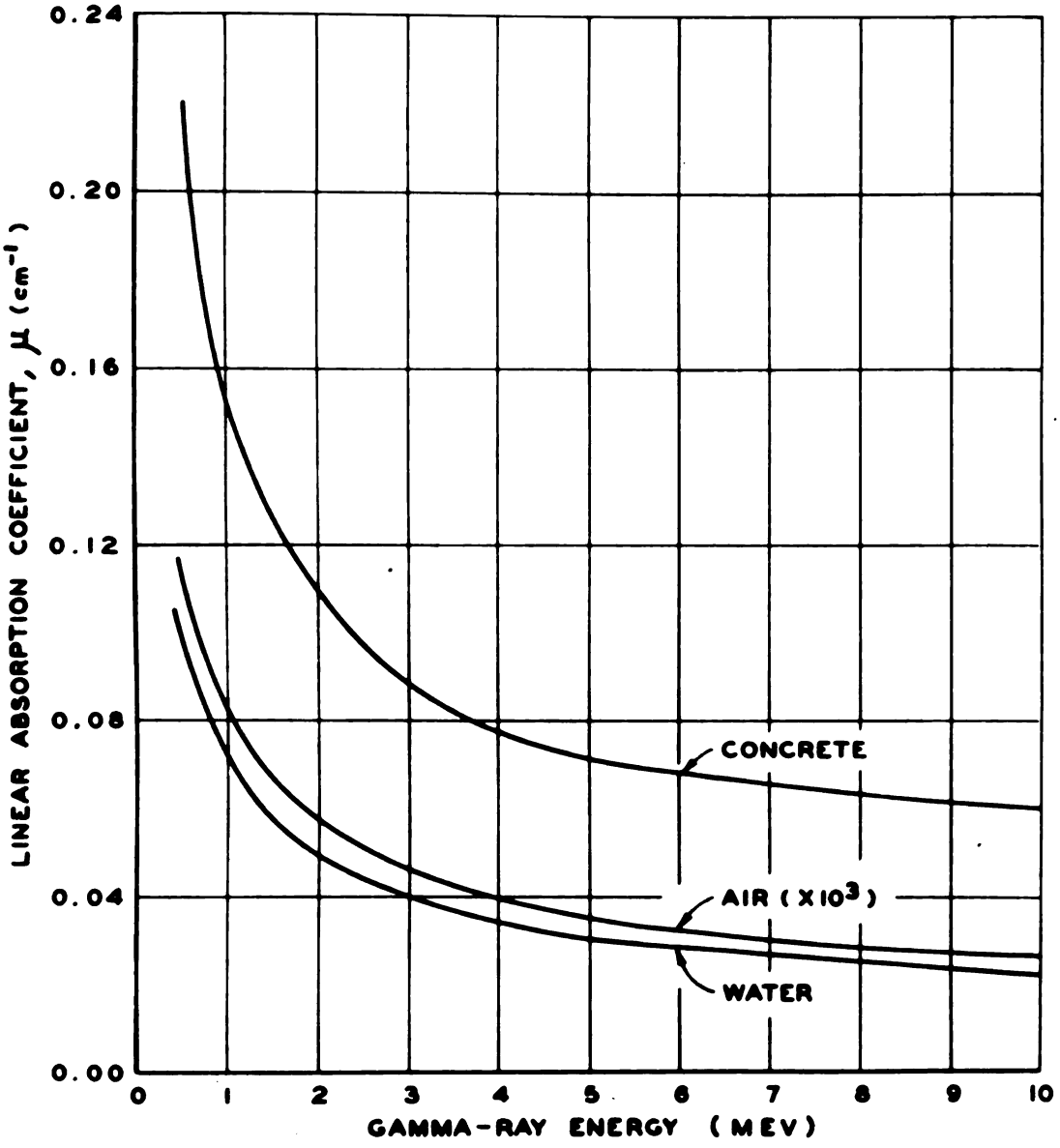


Figure 5. Typical curves of absorption coefficient, μ, as a function of gamma-ray energy (1).

THE GAMMA-ABSORPTION MEASURING SYSTEM

The different functional parts of the gamma absorption apparatus (Fig. 6), arranged for the purpose of detecting important variations during a concrete mixing operation, include: 1) the gamma ray source, 2) the scintillation counter, 3) the ratemeter, 4) the amplifier, and 5) the recorder.

While the mixing operation is in progress, changes in the physical characteristics of the concrete materials are continuously exposed to a narrow beam of gamma rays. These gamma rays are absorbed in proportion to the thickness or density of the interposed material according to Equation 2. The attenuated rays are detected and converted into electrical signals by a scintillation counter. These random signals or pulses are either converted into an average count rate in a ratemeter, or amplified to produce a continuous record of those variations involved in the mixing process.

For the purpose of evaluating and predicting the overall performance of this gamma ray densitometer, the following equations of Alcock and Ghosh (17) are of great assistance:

$$\Delta x = \frac{e^{\alpha x/2}}{\alpha (3.0 \times 10^6 \, q \, \Omega \, S \tau E)} \tag{5}$$

and

$$\frac{\Delta x}{x} = \frac{e^{\alpha x/2}}{x \alpha (3.0 \times 10^6 \, q \, \Omega \, S \tau E)} \tag{6}$$

where Δx = resulting error in measurement of absorbing material's mass in mg per cm^2

$\frac{\Delta x}{x}$ = relative mass error

α = mass absorption coefficient in cm^2 per mg

S = source strength in millicuries (mc)

q = number of gamma photons produced per disintegration

Ω = solid angle of radiation subtended by the detector

τ = time elapsed in detecting a given amount of radiation

E = detector efficiency.

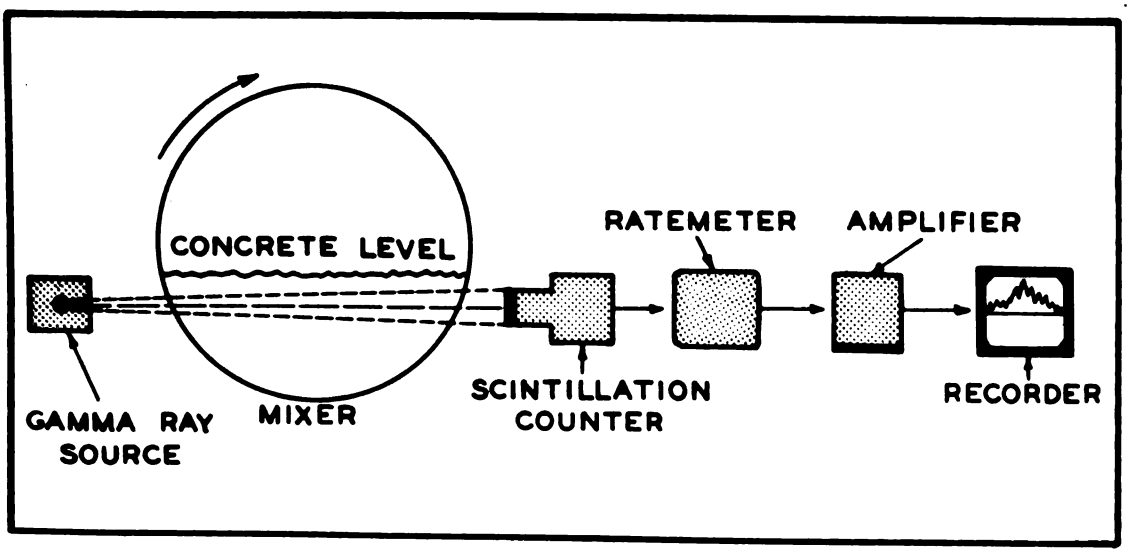


Figure 6. Gamma-ray absorption measuring system.

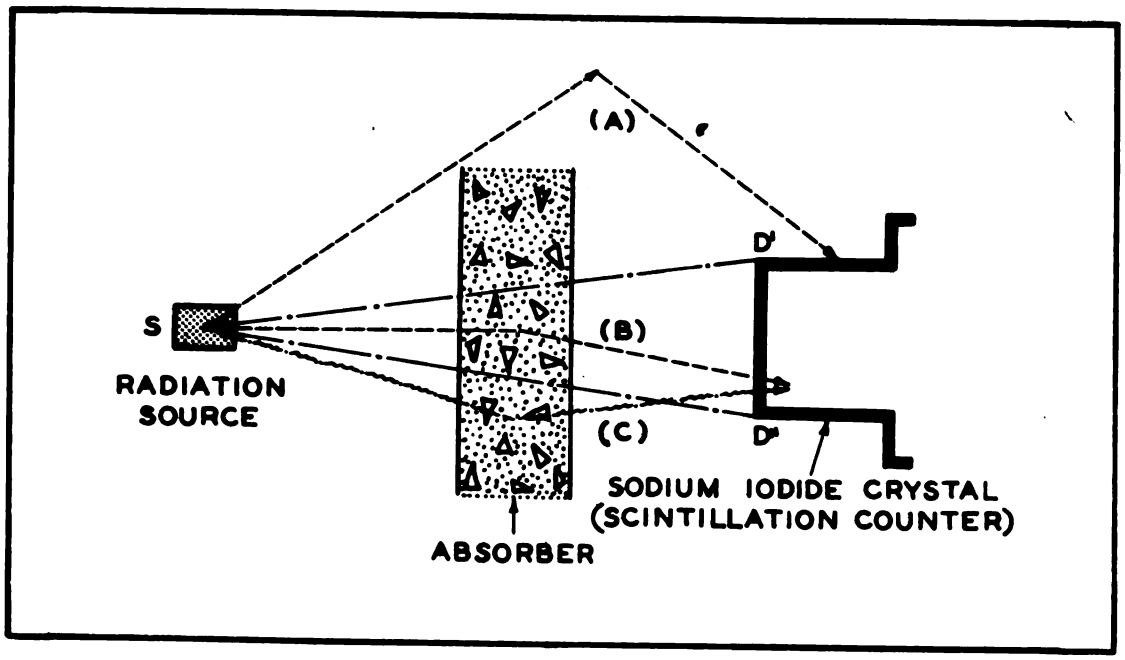


Figure 7. Detecting scattered radiation.

Equations 5 and 6 indicate that the absolute and relative mass errors will have a minimum value when $\mathfrak{I}$, Ω , S , τ , and E are maximum. Consequently, the overall performance of the present measuring system can be optimized by finding the proper relationship among the fundamental factors involved in the experiments.

These factors may be separated into two main types:

1. Those included in the analytical Equation 6, and
2. Those associated with environmental conditions.

The major variables involved in Equation 6 are: a) strength of the radiation source, b) actual radiation path of the gamma rays, c) solid angle of radiation subtended by the scintillation counter, d) counter efficiency, and e) counting time elapsed while radiation is falling on the detector. On the other hand, among those factors associated with environmental conditions, particular attention should be paid to background radiation which comes from cosmic rays or from other sources of radioactivity in the vicinity, and scattered gamma rays which come from surrounding environment or from parts of the apparatus not directly in the absorption path.

As a practical example, the design problems of the present gamma ray densitometer may be considered.

The Radiation Source

According to Equation 6, by increasing the strength of the source, relative mass error is reduced, and consequently improved measurements are obtained. By doing so, more signals, pulses, or counts per a given time are collected in the ratemeter or recorder. In other words, the larger the radiation source, the more counts are detected, and consequently the more accurate is the reading.

Since the random nature of radioactive disintegration obeys the law of statistics, all instrument readings are in error according to the following formula:

$$\epsilon = \frac{1.65}{\sqrt{N}} \tag{7}$$

where ϵ = relative reliable error commonly used in radiocounting and sometimes called "nine-tenths error" because there are nine chances out of ten that the error will be smaller

N = total number of observed counts.

For instance, an instrument reading of 10,000 counts per minute gives a reliable error of 1.65 percent. This statistical error must be added to the other errors introduced by the ratemeter, amplifier, and recorder.

The major problems of enlarging the radiation source in order to increase accuracy are greater costs for both the source and the shielding to reduce the amount of external irradiation to permissible levels.

As was pointed out already, statistical fluctuations are inherent in radiocounting. So, when the radiation intensity is lowered sufficiently (i.e., N in Equation 7 becomes small) by the concrete materials under test, the relative reliable error or noise signal from such fluctuations becomes important. If the total number of observed counts becomes too small, the typical electrical signal being sought may be hidden by the statistical noise signal and not observed in the counter or recorder. Therefore, it is desirable to know the optimum radiation path giving the maximum signal-to-noise ratio. This optimum path, L', is found by differentiating Equations 5 and 6 with respect to α and χ and equating the results to zero. In each case the relationship $\alpha\chi = 2$, yields the maximum signal-to-noise ratio which corresponds to a transmittance of

$\frac{I}{I_0} = \frac{1}{e^2} = 13.6$ percent. Similarly, the optimum radiation path, L', in terms of maximum absolute signal for density change occurs when the transmission is $\frac{I}{I_0} = \frac{1}{e} = 37$ percent.

For the concrete materials used in the present research program, approximate values of L' were computed as listed in Table I.

The Solid Angle Subtended by the Counter

Referring back to the Equation 6, by enlarging the solid angle Ω enclosed by the counter, improved readings are obtained since more counts are collected. But this condition is particularly applicable to those systems where the mass of the absorber is sufficiently large that surface effects associated with scattered radiation are completely negligible. In the present study the situation is different. In fact, the geometry of the absorber (mixer plus concrete materials) is so closely connected with multiple scattering that the solid angle Ω must be adjusted to the desired precision in order to keep the large amount of scattered radiation from entering the detector.

Background Radiation

In practice, if high accuracy is desired, the counting rate should be corrected for background radiation due to the presence of naturally radioactive materials and cosmic rays. This is done by subtracting the background rate from the recorded counting rate. The background rate is determined by taking the count or reading shown in the meter when no radiation source is nearby.

Effects of Scattered Radiation

As stated before, scattered radiation associated with the geometry of the present system may increase the actual error in radiocounting if the solid angle Ω is not properly adjusted (Equation 6).

TABLE I

OPTIMUM PENETRATION OR RADIATION PATH, L', FOR MINIMUM ABSOLUTE MASS ERROR, Δx, AND RELATIVE MASS ERROR, $\frac{\Delta x^*}{x}$

Material	Approximate Penetration, L' (in.)	
	For $\frac{I}{I_o} = \frac{1}{e^2} = 13.6\%$	For $\frac{I}{I_o} = \frac{1}{e} = 37.0\%$
Water	10	5
Cement	8	4
Sand	7	3
Gravel	7	3
Dry mix	6	3
Fresh concrete	4	2

* Results obtained by using linear absorption coefficients of concrete mix materials as listed in Table IV. Radiation source: 5 mc Cs^{137}.

Since bulk density of concrete materials changes over a wide range of values while the mixing operation is in progress, the attenuation coefficient μ should vary quite markedly (Equation 3). This result is to be expected because the mass absorption coefficient remains nearly constant under the present experimental conditions.

If quantitative measurements of density variations in the mixture are required, care must be exercised to avoid the measurement of scattered radiation which would tend to decrease the apparent value of the coefficient μ.

Three types of scattered radiation are associated with the geometry of the measuring system (8):

a) Scattered radiation from the surroundings,

b) Gamma rays that hit parts of the system not directly in the sbsorption path, and

c) Gamma rays that are scattered through a small solid angle (less than 0.5 steradian) but still measured by the detector.

The three types of scattered radiation are illustrated in Fig. 7.

The scattered radiation from the surroundings or path (A) and the radiation outside the cone of gamma rays SD'D" or path (C) can be reduced to a negligible amount by collimating of both the source and the scintillation counter.

Since all gamma rays scattered through an angle inside the cone SD'D" as shown in Fig. 7 (i.e., path B) cannot be prevented from reaching the counter, their effect on the attenuation factor of Equation 4 may be illustrated by a simple model as shown in Fig. 8.

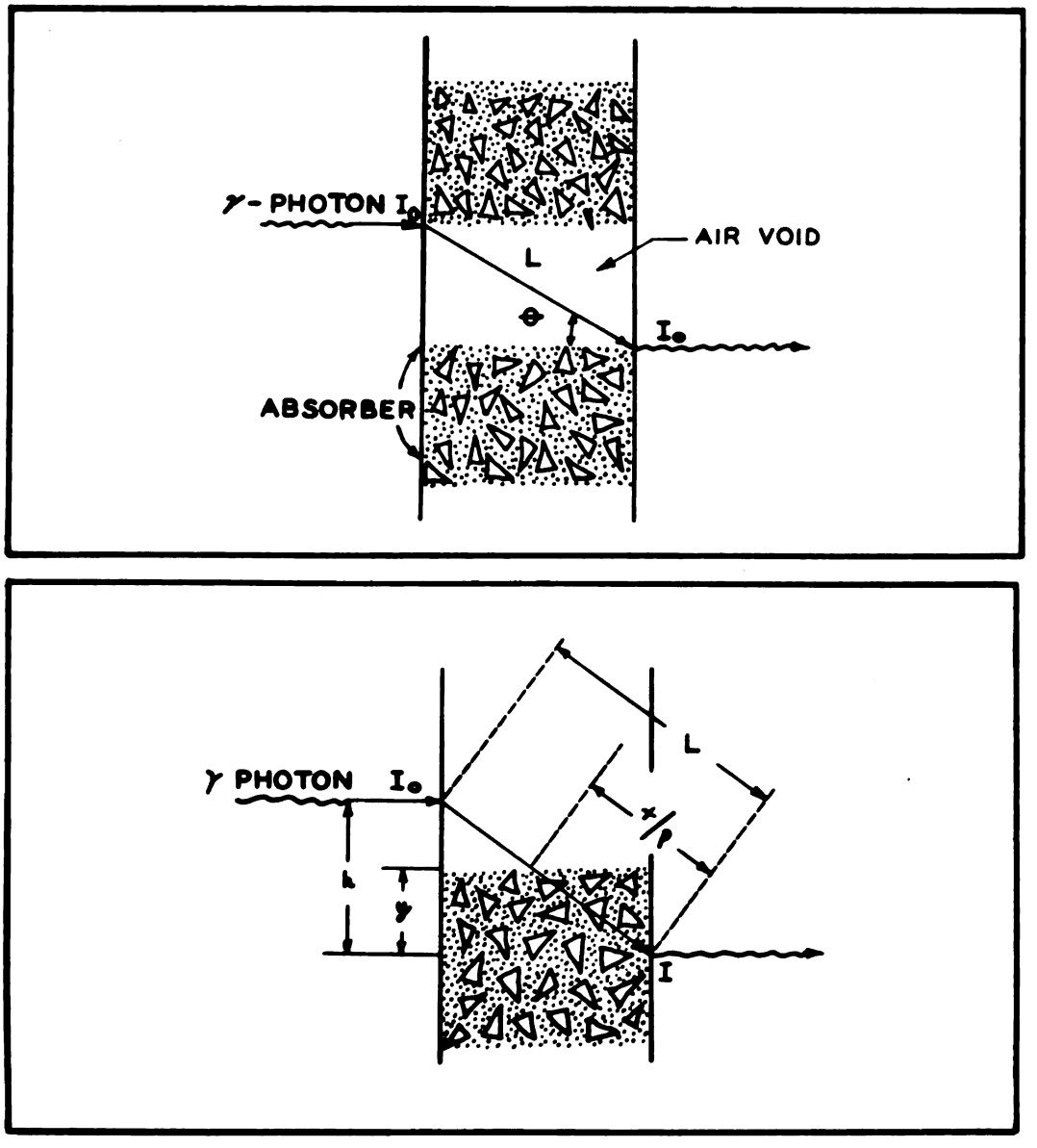


Figure 8. Gamma-ray scatter before (top) and after (bottom) mixing operations.

Consider an air void or a small space between aggregate particles characteristic at the beginning of the concrete mixing (Fig. 8). Like many others, this air void must be almost completely filled by cement paste, fine sand, gravel, water, or any combination of these, while the material is being mixed. This physical condition, if attained, is one of the important qualities desired in a properly designed concrete mix.

When no absorber is interposed in the radiation path L (Fig. 8), then from Equation 2, $\alpha \rho L = 0$, since the absorption coefficient for air is negligible; therefore $\frac{I}{I_o} = 1$. When the absorber is passing through the actual radiation beam, the attenuation factor varies continuously. Thus, from Fig. 8:

$$\sin \theta = \frac{y}{x/\rho} = \frac{h}{L} \tag{8}$$

or

$$x = \frac{y L \rho}{h} \tag{9}$$

By substituting the preceding equation into Equation 4:

$$\frac{I}{I_o} = e^{-\frac{\alpha y L \rho}{h}} \tag{10}$$

The data collected in Table II and plotted in Fig. 9 are based on μ values as listed in Table IV. A special case for L = 20 cm and h = 5 cm was selected to illustrate the effect of the concrete materials upon the attenuation factor when gamma rays scattered inside the cone SD'D'' (Fig. 7) are detected by the scintillation counter.

TABLE II

EFFECT OF ABSORBER HEIGHT, y, ON ATTENTUATION FACTOR, $\frac{I}{I_o}$ FOR GAMMA RAYS SCATTERED THROUGH CONCRETE MATERIALS*

Material	y = 1 cm	y = 2 cm	y = 3 cm	y = 4 cm	y = 5 cm
Water	0.75	0.56	0.42	0.31	0.22
Gravel or sand	0.63	0.39	0.25	0.15	0.10
Cement	0.68	0.46	0.32	0.22	0.15
Cement paste	0.71	0.51	0.36	0.26	0.18
Dry mix	0.60	0.36	0.22	0.13	0.07
Fresh concrete	0.50	0.24	0.12	0.06	0.03

* Based on μ values listed in Table IV.

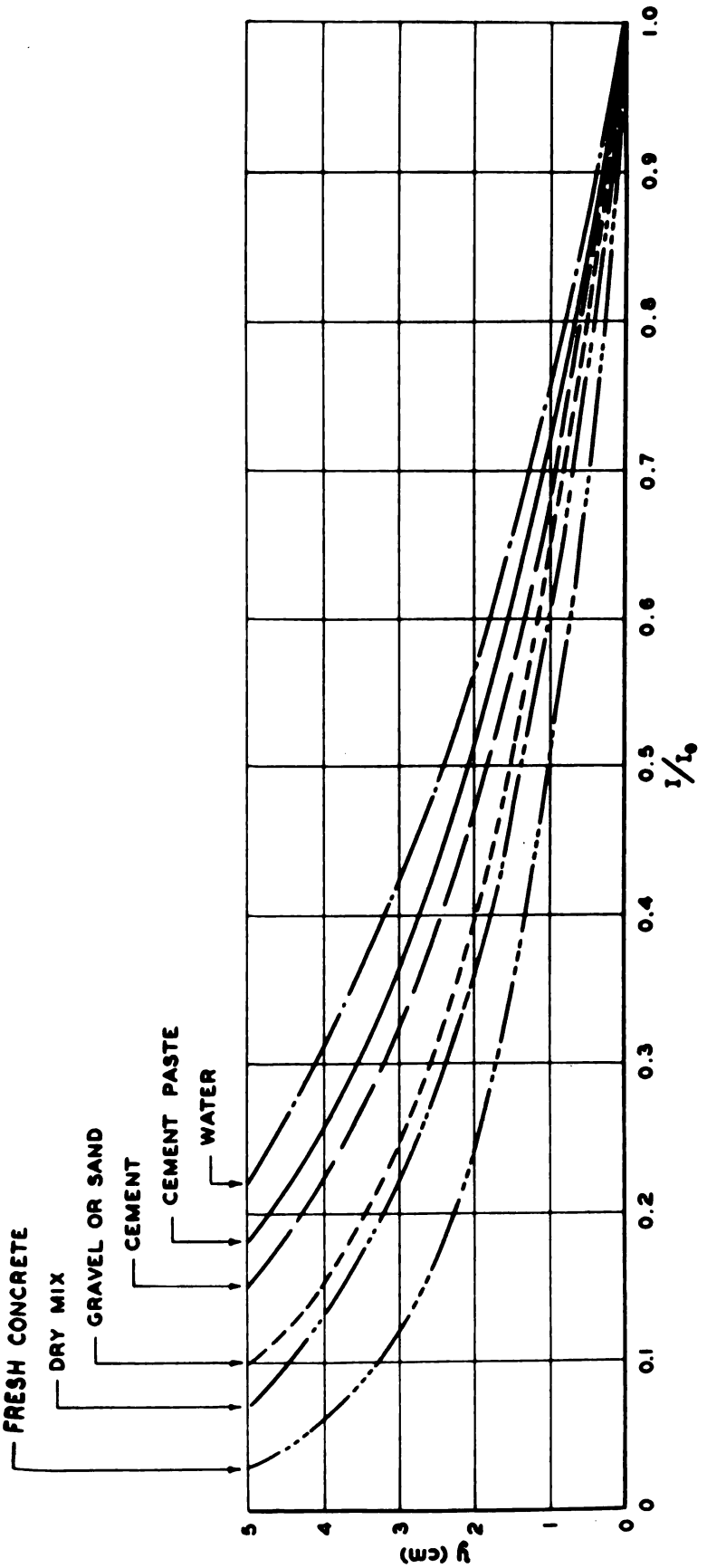


Figure 9. Attenuation factor as a function of absorber height for gamma-rays scattered through the concrete material.

EQUIPMENT AND MATERIALS

The essential features of the gamma-ray densitometer, as described here, are shown in Fig. 10.

1. Scintillation Detector Model DS5, Nuclear-Chicago Corp.

This device can be used for detecting and measuring the energy of alpha, beta, or gamma radiation. For counting gamma rays only a crystal of sodium iodide (thallium activated) is adapted as a main accessory for such detection. The energy of the incident gamma-ray photons is converted into a proportional amount of visible-light energy. The final multiplied output pulse is proportional to the energy of the incoming radiation.

2. Oscillograph, Double-Channel, Direct Inking, Model BL-202, Brush Development Co.

This instrument is designed for making instantaneous, permanent chart records of a wide variety of electrical phenomena. It provides a chart drive mechanism for pulling radially ruled paper at constant speed under the point of a pen resulting in a record showing variation of the phenomenon under study with time.

3. Universal Analyzer Model BL-320, Brush Development Co.

This instrument is a self-contained a.c. Wheatstone bridge, voltage amplifier, discriminator, and d.c. power amplifier. It is used with the direct-inking oscillograph.

4. Count Ratemeter, Model 1620B, Nuclear-Chicago Corp.

This ratemeter is designed to convert random pulses received from an external radiation detector into an average count rate for presentation on a panel meter and an optional external recorder.

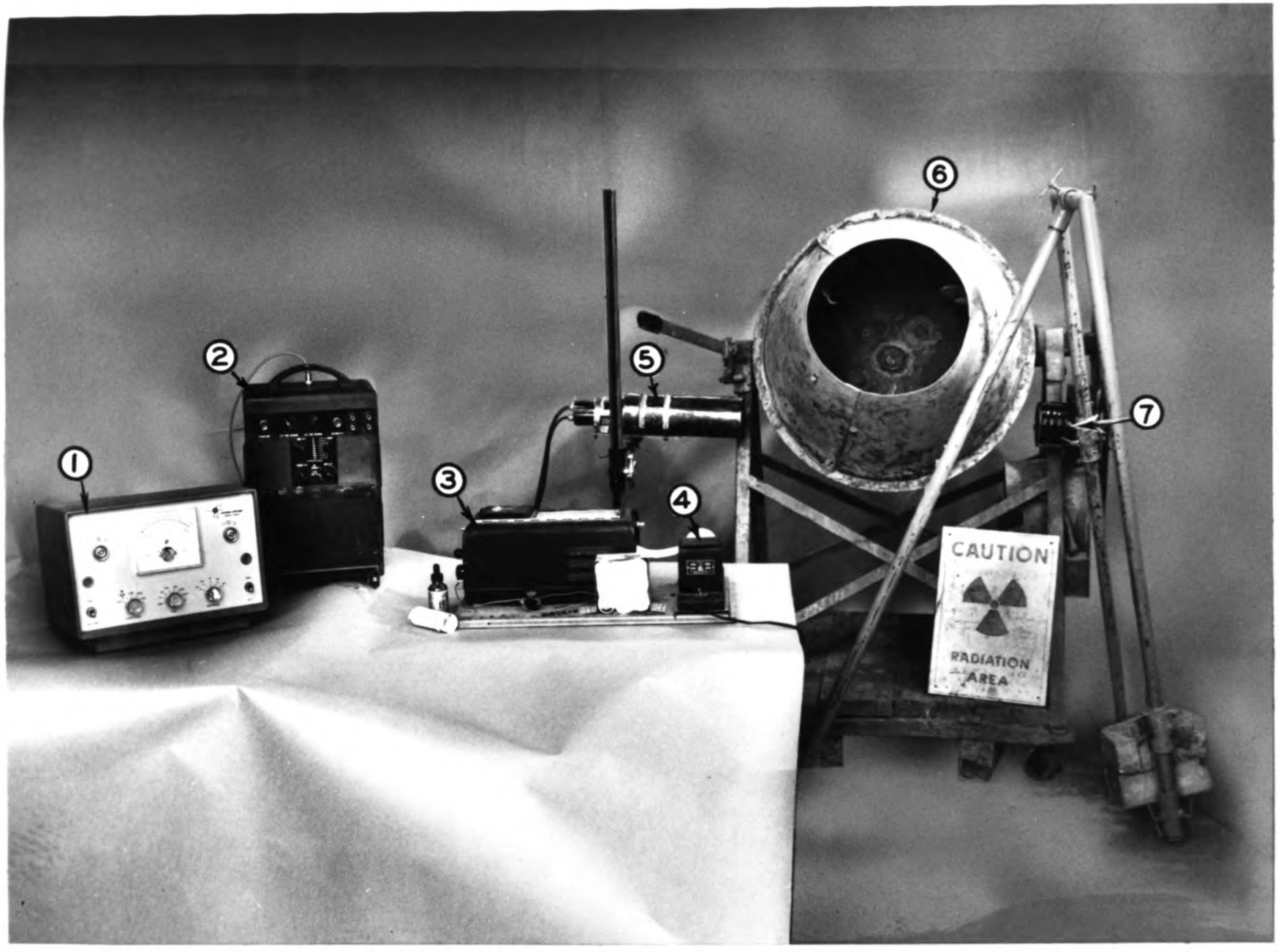


Figure 10. Equipment included (from left): 1) count ratemeter, 2) universal analyzer, 3) oscillograph, 4) chart drive, 5) scintillation detector, 6) mixer, and 7) radiation source.

5. Portable Scaler, Model 2800, Nuclear-Chicago Corp.

The scaler is a self-contained electronic scaler and power supply for use with nuclear radiation detectors. It may be used with power furnished from the storage battery in its case, or it may be used as an a.c.-operated instrument.

6. Chart Take-up Drive, Model BL-933, Brush Development Co.

This take-up drive is used with the double channel Brush oscillograph to reel recorded chart paper into a form which is readily stored.

7. Safety Equipment:

a. A radiation monitor surveys the radiation intensity in the working area. For persons who are exposed to small-intensity radiation from external sources, a tolerance dosage of 0.3 $\dot{\kappa}$ per week is permissible.

b. A film badge provides a permanent record of exposure to radiation by measuring accumulated dosage over one or two week periods.

8. Radiation Sources:

a. Five millicuries of Cesium 137 with a half-life of 33 years, results in about 2 percent loss in activity and count rate per year. This loss may be corrected for by use of a calibration curve. The source is enclosed in a hermitically-sealed metal capsule and stored in a portable lead-lined case, which absorbs most of the gamma rays produced. The lead case and capsule are sufficiently small and light to be transported readily.

b. Forty-five millicuries of Radium 226 and Beryllium with a half-life of 1620 years so that no correction for source decay is necessary. The sealed source is also stored in a lead-lined case.

EXPERIMENTAL PROCEDURES AND RESULTS

It has been mentioned that these investigations are concerned with two important factors which are involved in practically every mixing process: 1) to trace the uniformity of concrete by detecting significant variations during the mixing process, and 2) to find, if possible, the optimum mixing time while the blending operation is in progress. In an attempt to meet these objectives, a new technique was selected under the assumption that the combined effect of local changes in bulk density of the mixing materials and mixer design could be traced continuously in a simple gamma ray densitometer as described previously (Fig. 6). Thus, the various stages involved in the experimental work are discussed in the following order:

a. Concrete materials, mixing conditions, and a specific mixer for laboratory experiments.

b. Proper selection of radiation source, detector, and collimated arrangements related to the geometry of the proposed measuring system.

c. Attenuation properties of concrete materials as a function of their density and absorption coefficients.

d. Main features of the resulting gamma-ray trace as a function of mixing time.

e. Other techniques to verify those results obtained with the gamma ray densitometer. This stage includes a photographic study of the mixing process, a mixing time study with sodium chloride, and ASTM methods for compressive strength, air content, and slump tests.

The fresh concrete used throughout these laboratory experiments had the following composition:

	lb
Air-entrained portland cement	23.5
Natural sand (dry)	64.0
Gravel:	
a) Coarse: 3/4 in. to 1/2 in.	23.3
b) Medium: 1/2 in. to 3/8 in.	23.3
c) Fine: 3/8 in. to N-4	23.3
Water	11.8
Total weight	169.2
Total volume	about 1.15 cu ft
Unit weight (density)	about 147 pcf

Thirty concrete batches with this composition were tested after a mixing time of 1.5 minutes in a standard drum type mixer of 1.5 cu ft capacity, in terms of within-batch variations in unit weight, slump, air content and compressive strength. The following results were obtained in tests conducted according to ASTM methods:

Slump	2 to 3 in.
Air content	3 to 6 percent by volume
7-day compressive strength	2500 to 3000 psi
Unit weight	145 to 147 pcf

A commercial batch mixer was used in this study (Fig. 10). It has three steel paddles placed in the drum to aid in the mixing operation. The mixer is designed to run by electric power and to operate at 24 rpm.

In planning the mixing operation a standard procedure was desirable in order to form a basis for comparative observations and also to check the results. The following technique was used:

1. The weighted amount of sand and gravel was charged into the mixer and blended for about 5 seconds.

2. The measured quantity of cement was added and all the dry concrete materials mixed for 5 additional seconds.

3. After introducing necessary water, the revolving continued until a mixing time of 1.5 minutes had elapsed.

In mixing concrete materials at least two important features deserve particular attention:

a) The mixer design, which causes local changes in bulk density of the materials before the mixing water is being thoroughly distributed; this is the period of mechanical clumping that is characteristic at the beginning of the mixing cycle.

b) The large volume of air voids or spaces between aggregate particles that must be almost completely filled by the cement paste in order to achieve the qualities desired in a properly designed concrete mix.

These continuous changes in the physical characteristics of the mixture during the blending process were exposed to a collimated beam of gamma rays. Impulses picked up by the scintillation counter were fed into a ratemeter, then to an amplifier, and from there to a recorder (Fig. 6).

An ideal gamma source for this study should decay mono-energetically in the range of 0.3 to 1.5-mev, have a long half life, and be available at low cost. Cesium 137 and Cobalt 60 are good radiation sources and are available at reasonable prices. Cesium 137 has a radioactive half-life of 33 years and emits monoenergetic radiation of 0.66 mev. Cobalt 60 decays with a half life of 5.3 years, and for all practical purposes may be considered to emit mono-energetic radiation with a mean energy of 1.25 mev.

An encapsulated, collimated 5-millicurie Cesium-137 source and a scintillation counter equipped with a crystal of sodium iodide (thallium activated), were used for laboratory investigations. A scintillation counter was chosen because of its versatility and high gamma ray sensitivity. This detector can be quickly adapted also to count alpha rays (zinc sulphide crystal) or beta rays (antracene crystal).

Collimation was possible by inserting the source capsules as far as possible into a 1/2-in. hole drilled axially in a lead cylinder to within 2 in. of the bottom, holding the capsules near the bottom of the hole by inserting paper stuffing, corking the hole, and maintaining the cork in position with friction tape. A cone of gamma rays rather than a parallel beam was thus produced, its intensity being very high along the axis in front of the cork, and falling off rapidly at increasing angles from the axis.

Similarly, the solid angle of acceptance of the scintillation counter was collimated from its normal 2 pi steradians (50 percent of the total angle) to as narrow a cone as possible equivalent to approximately 0.5 steradians. This was done by wrapping five thicknesses of 1/8-in. lead sheet around the tube, projecting approximately 5 in. beyond the crystal. A lead circular plate with five 1/4-in. holes was then inserted in front of the collimated tube. In this way, the effect of scattered radiation associated with the geometry of the concrete mixer was greatly reduced and the overall performance of the measuring system was satisfactory.

The critical dimensions of this gamma absorption apparatus are shown in Fig. 11. These dimensions were established after a careful series of preliminary observations in the laboratory.

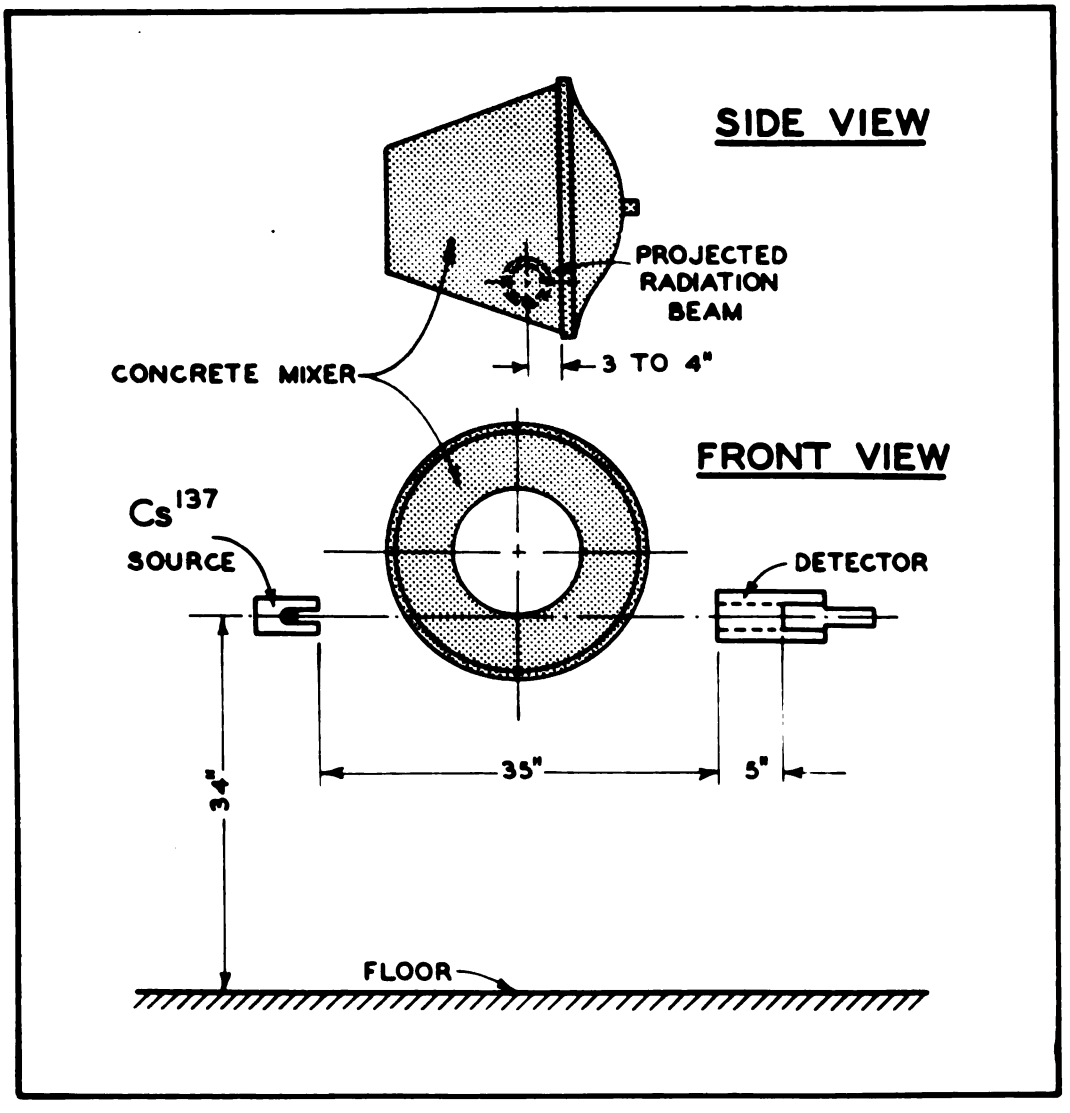


Figure 11. Critical dimensions of the gamma absorption apparatus.

To check the overall performance of this system, the radiation source was placed at various known distances from the counter and a set of averaged readings were taken at each position. The ratemeter and the continuous chart recorder were used simultaneously during the measurements. The resulting calibration curve is shown in Fig. 12. The same readings corrected for background radiation and based on the definition of a milliroentgen as described in the appendix can be used to check instrument readings against calculated intensities.

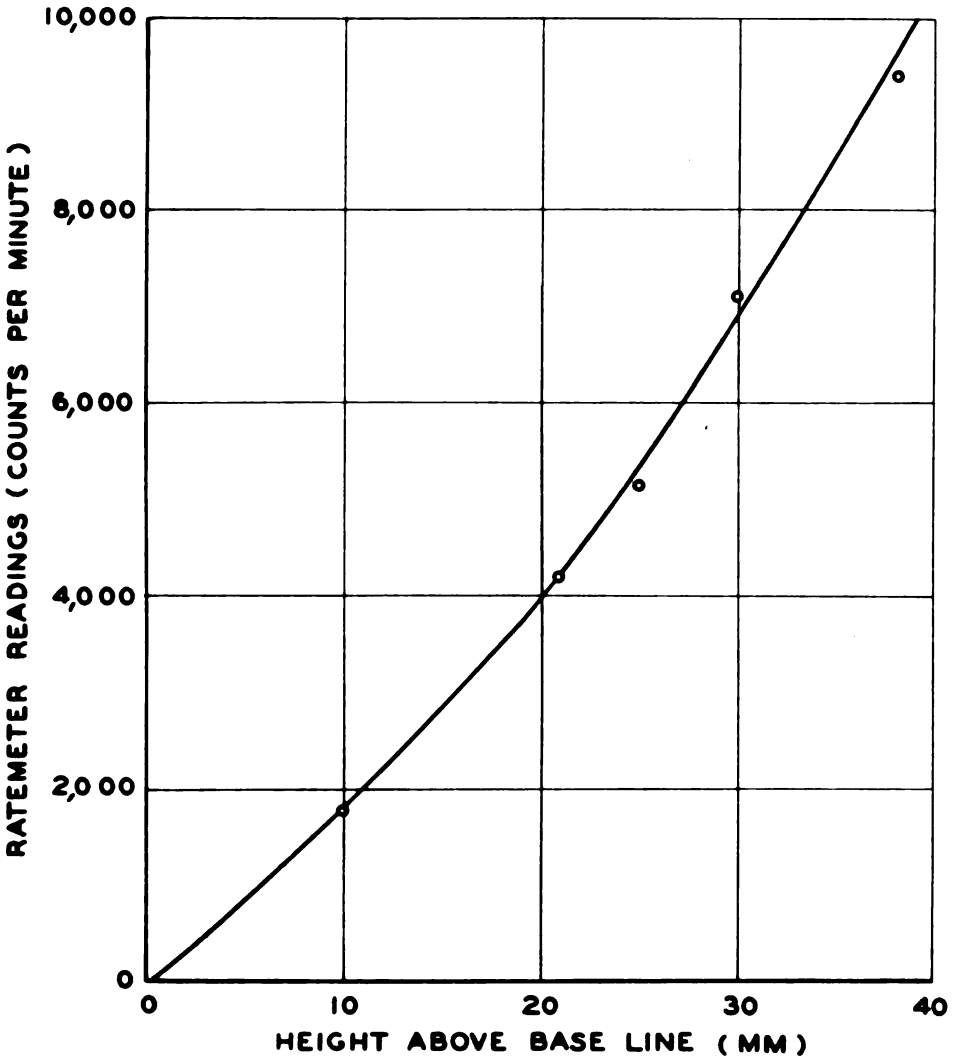


Figure 12. Laboratory calibration curve for ratemeter readings as a function of height above base line on a trace.

DENSITY CALIBRATION CURVE

As stated before, quick changes in bulk density of concrete materials take place at the beginning of the mixing cycle. Consequently, according to Equation 3, the linear attenuation coefficient μ should either decrease or increase as the absorbing material becomes less or more dense, respectively. So, after the measuring instruments were adjusted and put in good operating condition, the first step was to establish a density calibration curve for the concrete materials. This was done by placing each weighed ingredient separately in a sheet metal container of known volume, and laying the absorbing material between the source and the detector. Intensity of radiation was measured before and after the collimated beam of gamma rays passed through a thickness of 24 cm of absorber. The transmitted radiation was measured in counts per minute by using a standard portable scaler in conjunction with the scintillation counter. The actual readings corrected for background radiation are listed in Table III and plotted as a function of density in Fig. 13. The bulk density was computed from the given amount of material used and the known volume of the container.

From these data and with the aid of Equation 2 the linear absorption coefficients, μ, for the concrete materials were computed. The results are presented in Table IV and plotted in Fig. 14.

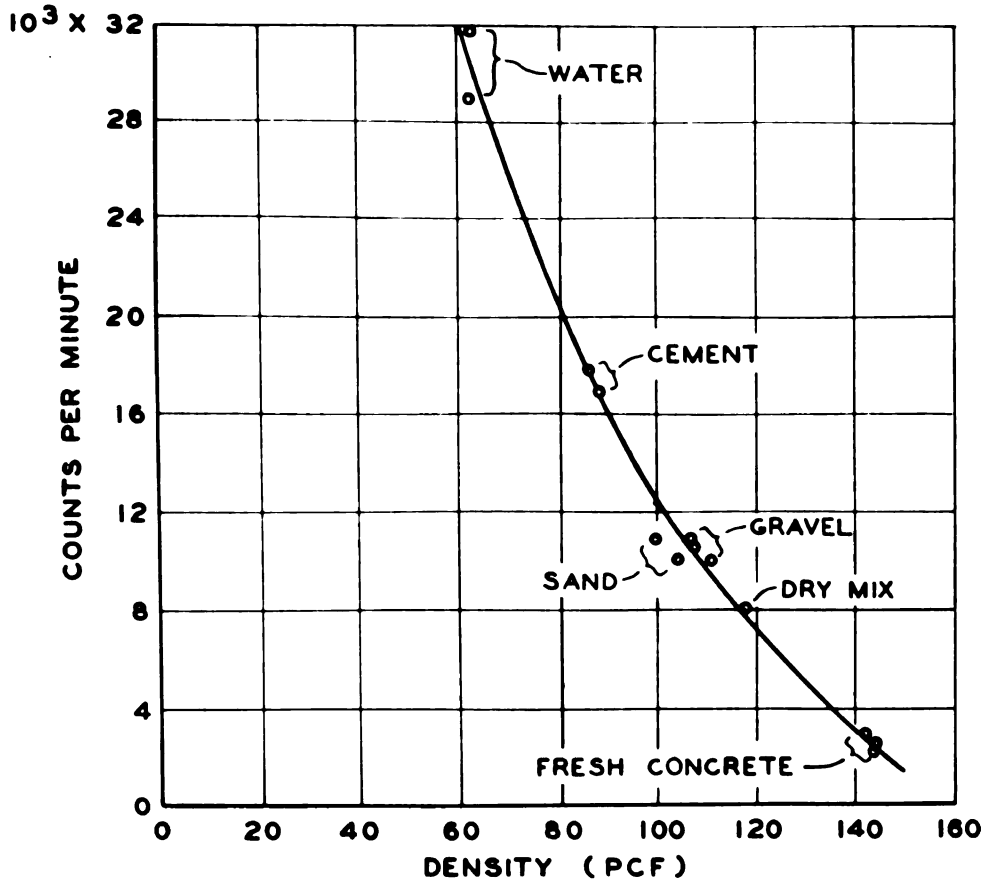


Figure 13. Density of concrete material versus counts per minute.

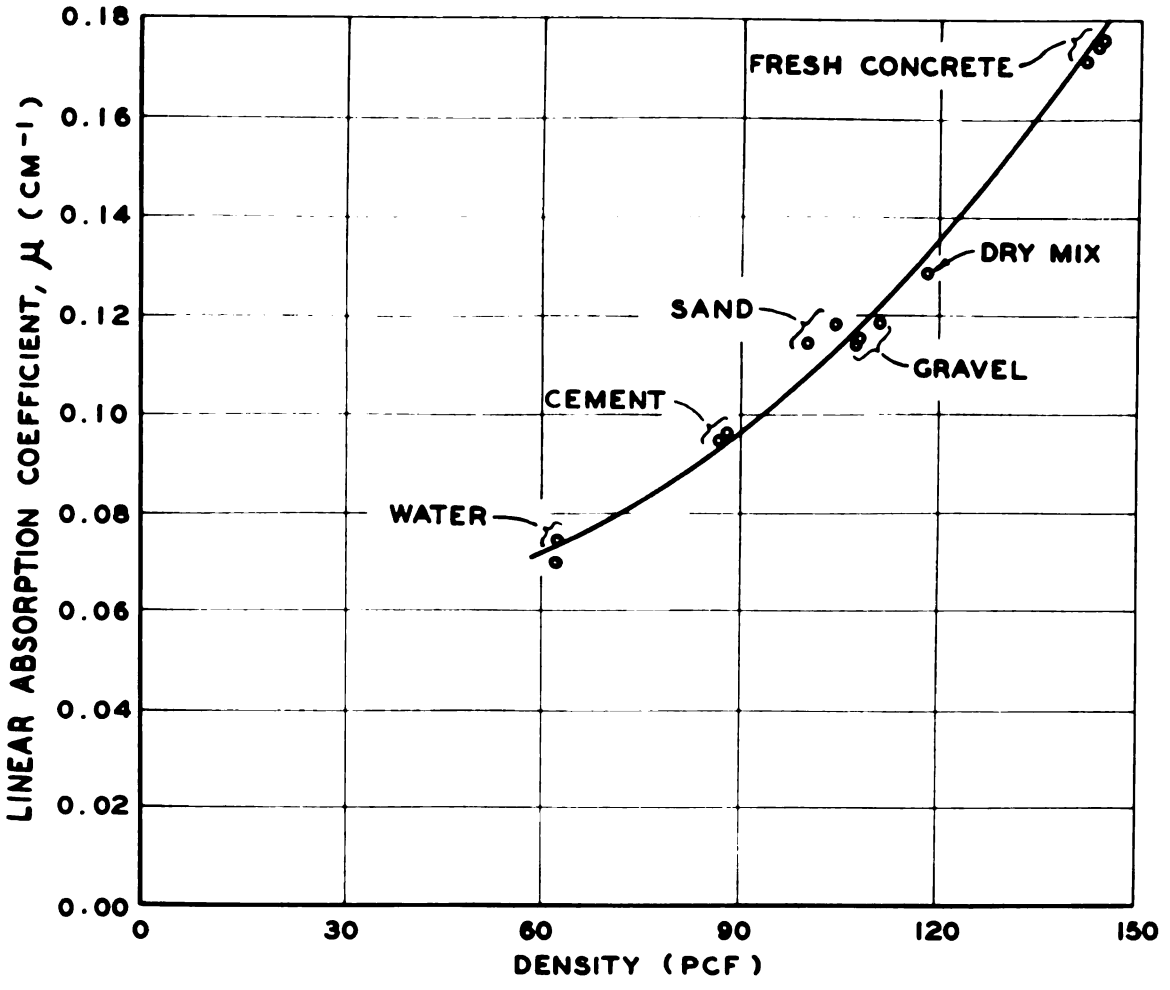


Figure 14. Linear absorption coefficient versus density of the concrete material.

TABLE III
GAMMA-RAY ABSORPTION DATA
FOR CONCRETE MATERIALS*

Material	Reading (counts per minute)				Mean	
	No. 1	No. 2	No. 3	No. 4	$\bar{X}$	$\bar{X}-1_b$
Water	30,429	30,238	30,121	30,091	30,220	28,920
	33,125	32,939	33,055	33,201	33,080	31,780
Cement	19,428	19,079	19,046	19,018	19,143	17,843
	18,902	18,071	18,159	18,173	18,326	17,026
Sand	11,453	11,301	11,625	11,651	11,508	10,208
	12,057	12,315	12,366	12,251	12,247	10,947
Gravel	11,431	11,224	11,566	11,341	11,391	10,091
	12,029	12,162	12,196	12,242	12,157	10,857
	11,361	11,251	11,424	11,467	11,376	10,076
	11,915	12,119	12,001	12,221	12,064	10,764
	12,104	11,934	12,069	11,975	12,020	10,720
Dry Mix (cement, sand, and gravel)	9,262	9,449	9,331	9,385	9,357	8,057
Fresh concrete	4,309	3,993	4,132	4,015	4,112	2,812
	3,542	3,575	3,501	3,399	3,504	2,204
	3,782	3,728	3,812	3,894	3,804	2,504
	3,935	3,981	3,963	3,804	3,921	2,621

* Average initial intensity, I_o = 174,000 counts per minute; average background radiation, I_b = 1300 counts per minute.

TABLE IV
LINEAR ABSORPTION COEFFICIENTS
AND DENSITIES OF VARIOUS MATERIALS*

Material	Linear Absorption Coefficient, μ (cm-1)	Density, ρ (pcf)
Water	0.071 0.074	62.4
Cement	0.095 0.097	86.7 88.0
Sand	0.118 0.115	104.0 100.0
Gravel	0.118 0.115 0.118 0.116 0.116	110.9 107.5 111.0 108.0 108.0
Dry Mix (cement, sand, gravel)	0.128	117.9
Fresh concrete	0.172 0.182 0.176 0.175	142.0 144.0 144.0 143.5

* Densities obtained by weighing 0.58 cu ft of absorbing material.

THE GAMMA RAY TRACE

Since these gamma-ray-absorption measurements, after being conducted in a laboratory batch mixer under controlled conditions, were also applied in the field while large concrete batches were produced continuously, each stage will be discussed separately.

Laboratory Tests

As described previously, while the mixing operation was in progress, changes in the physical characteristics of the absorbing media were continuously exposed to a collimated beam of gamma rays. These changes were converted into electrical signals, and then detected and amplified to produce a trace or continuous record of the variable which was changing with time. A typical gamma-ray trace obtained in the present investigations is shown schematically in Fig. 15.

At Point 1, all the dry ingredients were charged into the mixer and were intercepting the radiation beam to reduce its intensity to approximately 8000 counts per minute. The base line represents zero counts per minute.

At Point 2, the weighed amount of water was added and consequently its effect was to increase the transmittance (Fig. 13). This increase in transmittance would indicate less bulk density than at Point 1. At Point 3, the curve not only rises markedly, but the amplitude of the needle swings increases greatly, both reaching a maximum at Point 4. At Point 5, the count rate and amplitude have both returned to about where they were at Point 3. Point 4 is invariably closer to Point 3 than to Point 5. Now the amplitude continues to decrease gradually and steadily until the end of the mixing period. A series

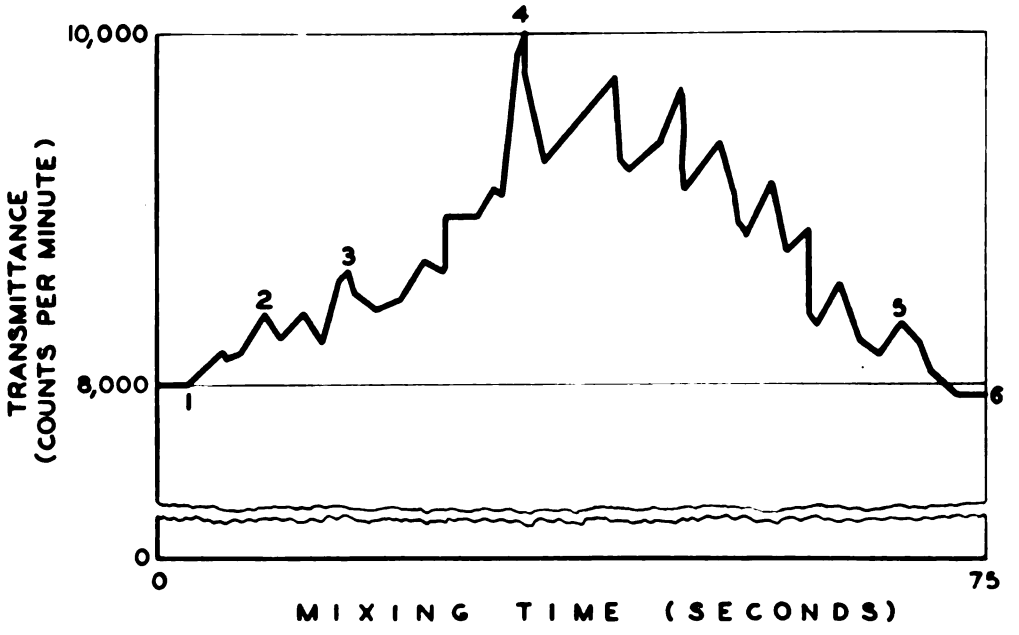


Figure 15. Schematic of a typical gamma-ray trace.

of 25 traces were obtained under similar mixing conditions according to those procedures described before for laboratory experiments.

At least two main features deserve particular attention. First, the remarkable manner in which the traces resemble each other almost exactly. They all follow the same pattern and they all show at least a full minute of mixing before the fluctuations recorded on the trace smooth down. Second, the temporary rise in count rate between Points 3 and 5 which has been tentatively ascribed to that period of mechanical clumping. As explained previously, the mix water before being thoroughly distributed forms local pockets of low density between discrete "clods" of somewhat higher density. Obviously, if before mixing is complete, large portions containing more than their designed quantities of cement, water, gravel, sand, or air, should pass through the beam, their effect would be to cause an increase in transmission due to lesser average bulk density of the mixture (Fig. 13).

Three of the 25 gamma ray traces obtained in the laboratory are shown in Fig. 16.

Field Tests

The field concrete plant consisted of three compartments with automatic scales to weigh separately the required amount of sand, gravel, and cement, prior to charging the large-size stationary mixer. The dry ingredients were carried on a belt-conveyor and discharged into the mixer. The duration of charging was about 20 seconds when the automatic equipment was operating under normal conditions. Water was weighed separately and gradually sprayed over the dry materials in the drum. After the proper mixing time had elapsed,

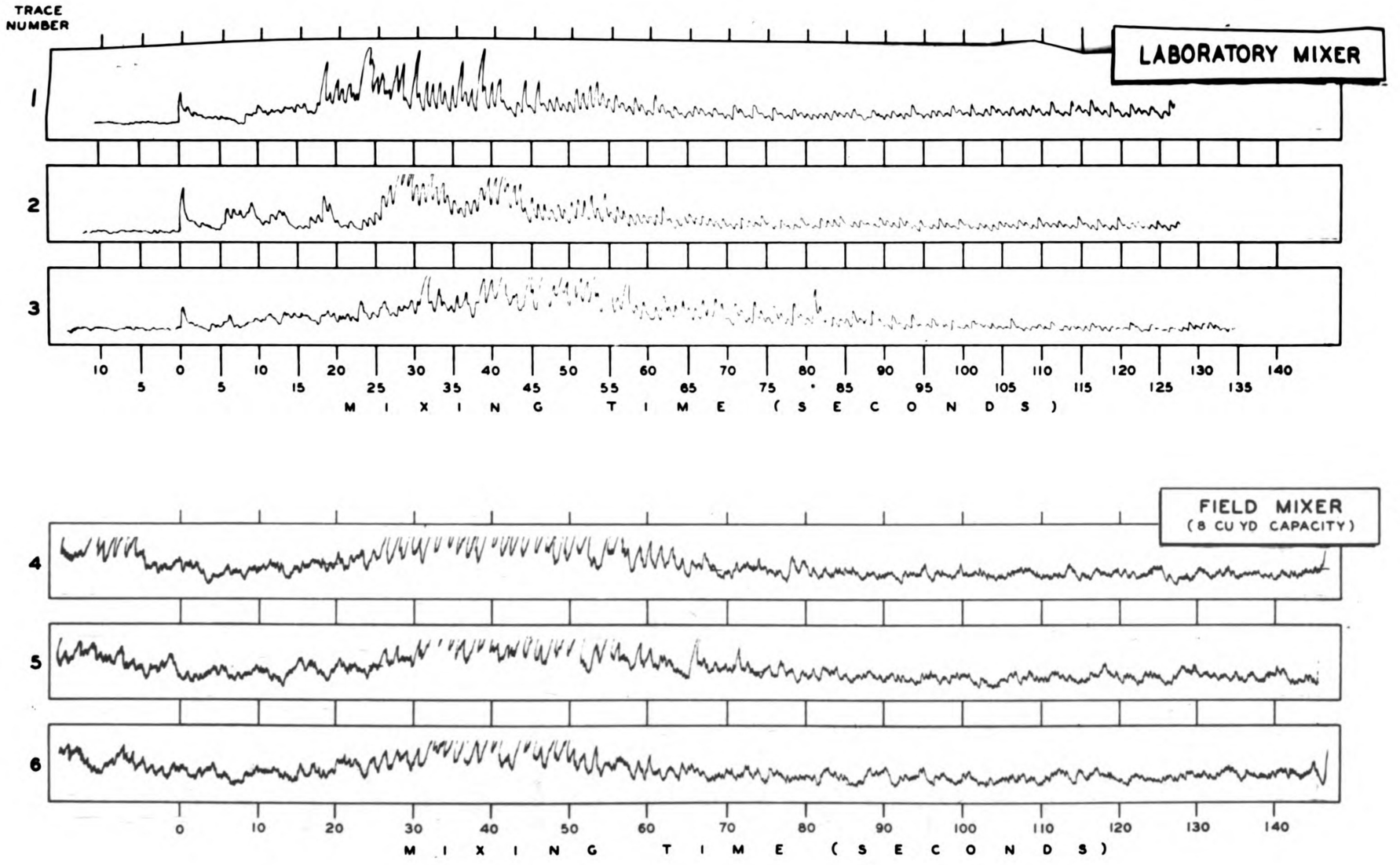


Figure 16. Typical gamma-ray traces.

the fresh concrete was deposited in a hopper and then discharged in trucks. Most of this operation was automatic but there was a separate control the operator could use to stop or lengthen the mixing cycle. A large mixer discharging concrete and a general view of the concrete mixing plant are shown in Fig. 17 and Fig. 18, respectively.

The field installation of the gamma ray densitometer had to meet special requirements with regard to radiation safety and normal concrete production. In this case, obviously a stronger radiation source was needed to penetrate the mixer's steel wall and the concrete material being mixed. On the other hand, the installation had to be done without interferring with the continuous operation of the plant. Since a 45 mc, Radium 226-Beryllium source was available, the main task was to find according to Equation 6 the proper radiation path L (i.e., $\alpha x = \mu L$) to optimize the recorder response (maximum signal-to-noise ratio). In the laboratory this was done by placing several hardened concrete slabs between a source and a detector until a transmittance of about 10,000 counts per minute was recorded. A thickness of 30 in. of concrete was found to provide a satisfactory recorder response. Finally, the apparatus was installed permanently in a location selected for safety without interference with the normal operation of the concrete plant. No attempt was made to correlate the gamma-ray trace's results with any ASTM test due to the extreme difficulty of conducting them in field conditions. The results of field concrete mixing with mixers having a capacity of 8 and 3 cu yd are shown in Figs. 16 and 19, respectively. These traces were selected from 700 similar traces obtained in the field mixing operation.

Figure 17. Mixer discharging concrete.

Figure 18. General view of mixing plant.

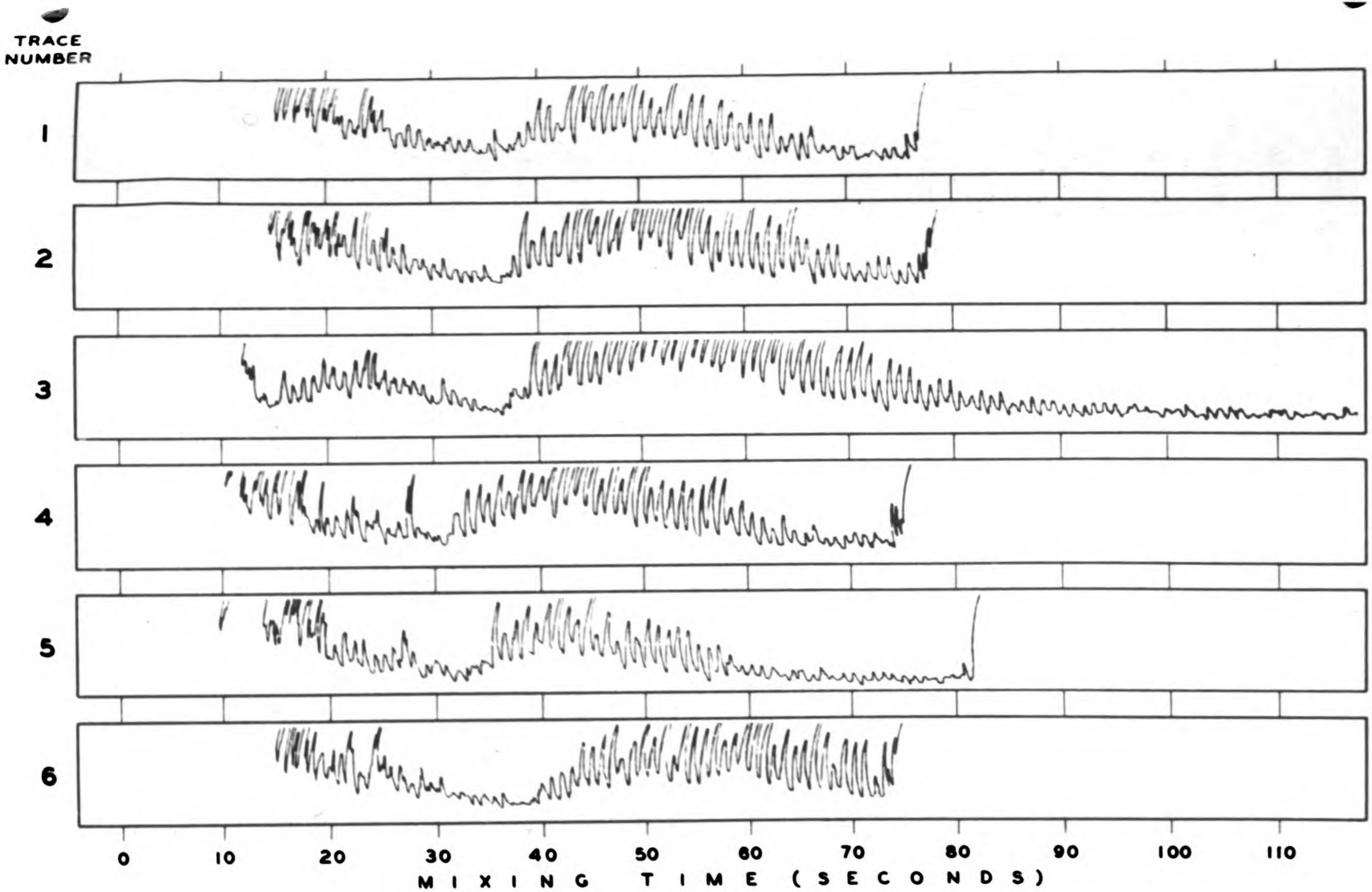


Figure 19. Field gamma-ray traces from a mixer with 3 cu yd capacity.

An outstanding characteristic of these field traces is the wide variability of the clumping period. Since many variables associated with the properties of concrete materials are involved in the clumping process, it is reasonable that neither the duration nor the effect of this period should be precisely the same from batch to batch. This is indeed the case as shown in Fig. 19. The duration of the clumping period between Points 3 and 5, as shown schematically in Fig. 15, range from 20 to 70 seconds. From the end of this period (Point 5) to the end of the mixing time, the fresh concrete attained the typical characteristics of a plastic fluid and all subsequent changes were very gradual and very moderate in amount.

Other features can be seen within the so-called "clumping period." For instance, in the last three traces of Fig. 16, changes in bulk density of concrete materials were so remarkable that the recording needle was carried off the paper. In the fifth trace of Fig. 19 this period was unusually brief, and in the third trace the period was unusually long. Finally, the sixth trace shows that the mixing operation was still in progress when the concrete batch was discharged.

PHOTOGRAPHIC STUDY OF THE MIXING PROCESS

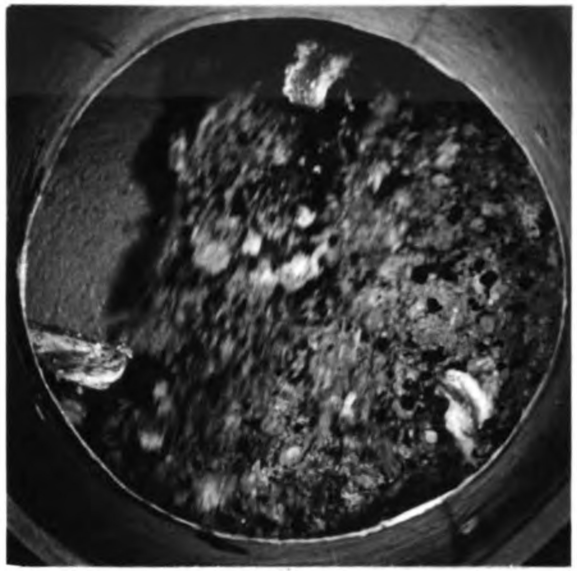
Although the results obtained by the gamma-ray absorption technique were promising for realization of the present objectives, a new technique had to be used to correlate the main features of the gamma-ray traces with the important variables involved in the concrete mixing process. As stated before the main objectives concerned the testing of uniformity of concrete and optimum mixing time.

A photographic study was made of the several stages of the mixing operation under normal conditions. Sharp and clear black and white pictures were obtained, but they did not provide any useful information concerning uniformity of mixing as a function of time. As a result some changes were introduced in the standard composition of the concrete materials as listed in the laboratory experimental procedures. Portland white cement was used instead of the regular air-entrained cement and the normal gravel was sprayed with a commercial Krylon black enamel. Two thin coats were used to cover the gravel. After drying and weighing the concrete materials as described previously, a new series of photographs was taken at 5-second intervals throughout the entire mixing period (Fig. 20).

Careful study of these pictures showed that the mixing process could be traced in its successive steps during the first 45 seconds of the entire blending cycle. But from that time on not much improvement was observed in the degree of uniformity of the mixture.

Sand, black gravel, and white cement ready to be mixed.

After rotating 5 sec, before adding weighted amount of water.



Appearance after 15 sec of mixing operation.

Appearance after 30 sec of mixing operation.

Appearance after 45 sec of mixing operation.

Appearance after 60 sec of mixing operation.

Figure 20. Batch-type drum-mixer at six stages in mixing process.

MIXING TIME STUDY WITH SODIUM CHLORIDE

Using standard laboratory equipment and mix materials, at least 1 min of mixing is required to assure workable and durable concrete, according to conventional tests. However, because the photographic study just described indicated that workable concrete could be produced in a shorter time, further investigation was undertaken.

In addition to the regular concrete ingredients which have already been mentioned, 200 g of dry sodium chloride was added. Then adding the required amount of water, the mixing operation proceeded as usual, with fourteen samples per batch taken at selected time intervals from a fixed point in the mixer. The rate of hardening of the fresh concrete was retarded by dissolving 50 g of sugar in the mixing water before it was added to the mixture. In this way, each sample was weighed and then easily diluted in 2500 ml of distilled water. After filtering the mother liquor, 20 ml of solution was pipated and titrated with 0.098 N silver nitrate according to a standard analytical procedure (47).

The actual average value of the 200 g of sodium chloride added to the concrete batch was equivalent to 4.8 ml of 0.098 N silver nitrate per 1000 gm of concrete sample. The results from three concrete batches are shown in Table 5 and plotted in Fig. 21.

In comparing these results with those obtained in the gamma ray traces, certain definite analogies were observed:

1. Initially, the silver nitrate-titration values scatter widely, approaching a limiting average value of 4.80 ml of silver nitrate. After 75 seconds of mixing, the dispersion is greatly reduced, falling within an experimental error

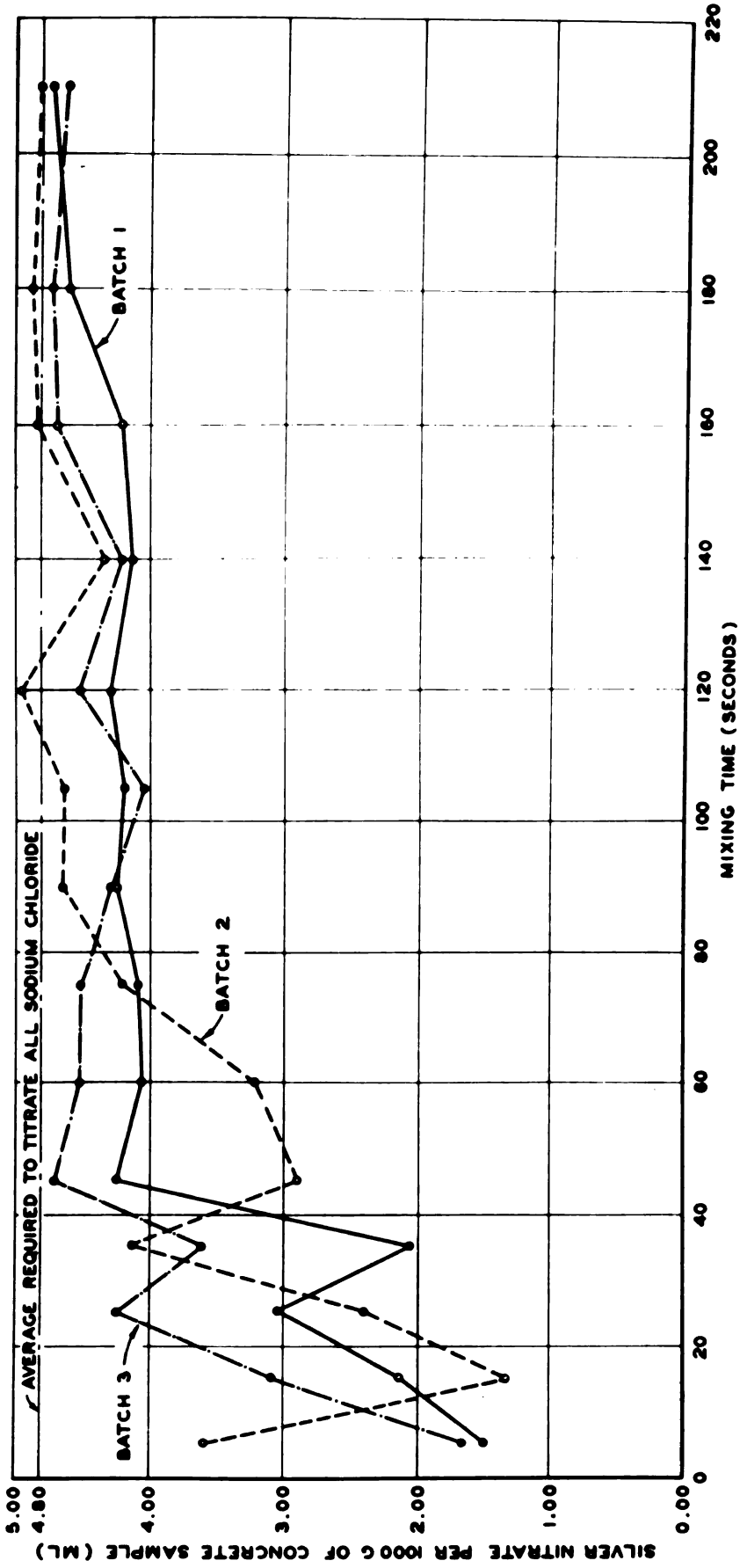


Figure 21. Mixing time study with sodium chloride.

TABLE V
MIXING TIME STUDY WITH SODIUM CHLORIDE*

Mixing Time (seconds)	Batch No. 1	Batch No. 2	Batch No. 3
5	1.50	3.60	1.65
15	2.15	1.33	3.10
25	3.05	2.40	4.25
35	2.05	4.15	3.60
45	4.25	2.89	4.70
60	4.05	3.23	4.53
75	4.10	4.23	4.53
90	4.25	4.67	4.30
105	4.20	4.64	4.05
120	4.30	4.98	4.52
140	4.15	4.34	4.21
160	4.20	4.82	4.69
180	4.60	4.87	4.72
210	4.75	4.82	4.64

*Readings in ml of 0.098 N of silver nitrate per 1000 g of concrete sample.

region with an average value of 4.5 ml of silver nitrate. This general variability of the titration values follows a definite regularity very similar to that found for the clumping period.

2. Fig. 21 shows that the beginning of the experimental error region falls between 75 to 85 seconds of mixing time. This range is close to the end of the clumping period, which is between 60 and 70 seconds in the gamma ray trace.

ASTM METHODS

These conventional tests were conducted to evaluate concrete uniformity in terms of within-batch variations in unit weight, slump, air content, and compressive strength, according to ASTM methods and specifications. The fresh concrete tested was composed of the regular ingredients which were used throughout this research program, except in field testing operations. These tests were carried out for the purpose of correlating the results with those obtained with the gamma ray absorption technique.

Air content of fresh concrete was determined by the pressure method (43). This is based on the principle of Boyle's Law ($P_1V_1 = P_2V_2$) in which a known pressure is applied to a given volume of concrete and the change in volume determined. The pressure device is shown schematically in Fig. 22.

The first step is to fill completely with fresh concrete sample the measuring bowl B of the pressure meter. This measuring bowl is accurately calibrated for volume. The bowl containing the sample of concrete is weighed in order to compute the unit weight in pounds per cubic foot (46). The same specimen is used to determine air content by the pressure method.

The upper part, A, of the pressure device is filled with water and a pressure of 15 psig is applied. At this point a reading is taken on scale D. After releasing the pressure another reading is taken at zero pressure. The difference in readings is expressed as percent of air content by volume. This test indicates the degree of workability and durability of the concrete.

The second step is to measure the consistency of the fresh concrete mixture by the slump test (45). The concrete sample is placed in a galvanized metal mold formed in a cylindrical cone (Fig. 23).

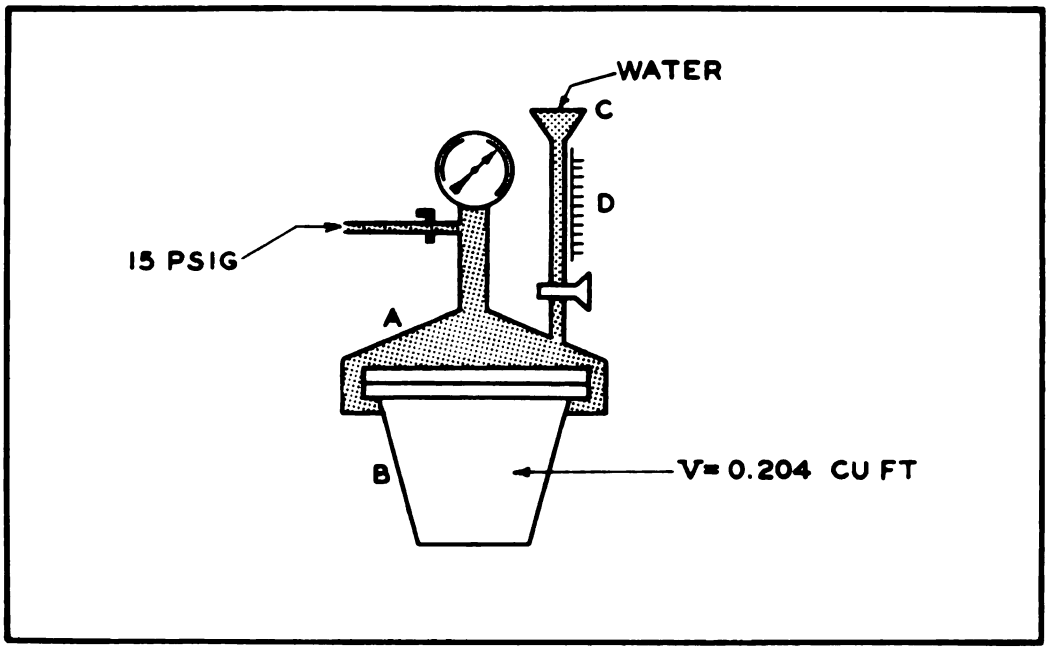


Figure 22. Pressure device for air content measurement.

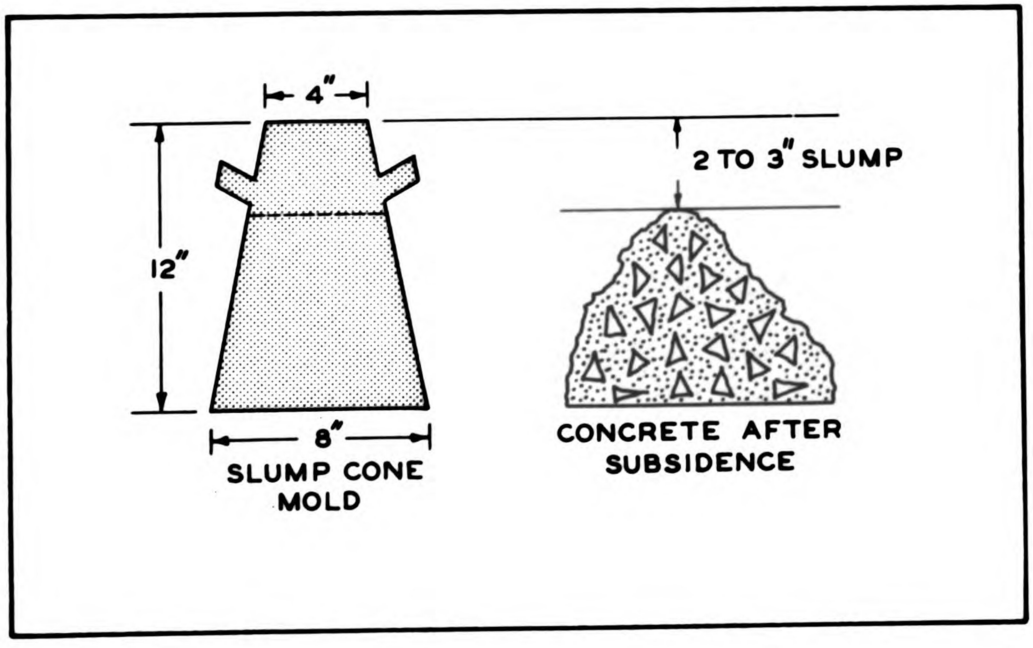


Figure 23. Slump test.

After rodding the sample and striking off the top layer even with the top of the mold, the mold is raised vertically away from the concrete. The concrete mass subsides, and its height is measured immediately after settling. The difference between this height and the height of the mold is the slump.

The final test is for compressive strength, made on cylinders of 4-in. diam and 8-in. height. After moist-curing the concrete specimens for seven days the samples are subjected to compressive strength testing according to the standard method (44).

The results of slump and air content tests as functions of mixing time are shown in Fig. 24. Under present laboratory conditions and for concrete to be used in pavements the ASTM specifications require 2 to 3 in. slump. According to these limits, a concrete with acceptable consistency would have been produced in a mixing time of 100 to 170 seconds.

The required air content is generally from 3 to 6 percent of the total volume. Based on this requirement a durable and workable concrete would have been obtained with a maximum mixing time of 120 seconds.

The results of unit weight and compressive strength tests are also shown in Fig. 24. Referring to the compressive strength curve, a striking result deserves particular attention. The curves indicate that anywhere between 50 to 70 seconds of mixing time, the concrete reached a maximum compressive strength. This corresponds almost exactly to the end of the clumping period as shown in the gamma ray trace.

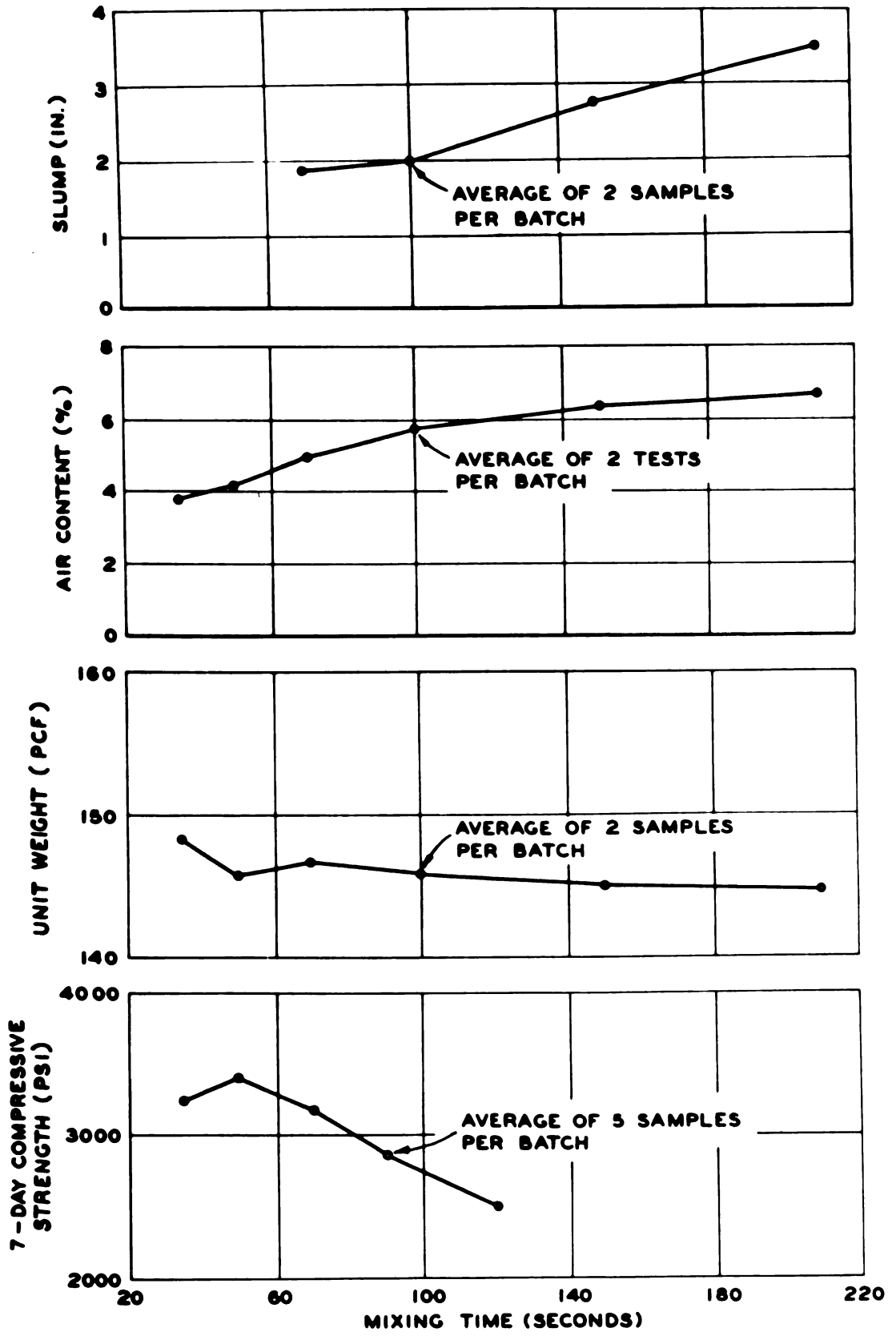


Figure 24. Conventional concrete tests.

DISCUSSION OF RESULTS

In general, the present investigations have shown that the gamma-ray absorption technique is a practical means of evaluating mixing operations of any type, provided the density of the materials being mixed changes over a wide range of operating values. Such has been the case with the concrete mixing process as described here. This technique is capable of clearly tracing the changeable features of the mixture during the entire mixing cycle. Since changes in local densities are closely associated with variations in the distribution of the ingredients being mixed, the technique furnishes a procedure for evaluating the uniformity of the mixture throughout the blending period.

Turning first to the beginning of the mixing cycle, the mechanical action involved in this stage is illustrated in Fig. 20. This irregular agglomeration or clumping of materials throughout the batch while the mixing is taking place is clearly connected with the temporary rise in transmittance between Points 3 and 5, as shown schematically in Fig. 15 or in any typical gamma-ray trace. The end of this clumping stage ranged from 60 to 70 seconds as shown in the gamma-ray traces. This also appeared to be the end of the random variation of those values obtained with the sodium chloride technique (Fig. 21). In many respects, the general distribution of the sodium chloride values followed a definite regularity very similar to that found during the clumping period.

The results of compressive strength tests provided additional evidence of the usefulness of the gamma-ray method. The method seems to be capable of detecting the optimum mixing time when the blending process is based on compressive strength variation. In fact, Fig. 25 indicates that the concrete

reached a maximum compressive strength anywhere between 50 and 70 seconds of mixing time. As shown by the gamma-ray trace, this period corresponds almost exactly to the end of the clumping stage, which ranges from 60 to 70 seconds.

In this study the technique has uncovered unsuspected facts in connection with mixing processes in the field. For example, in the last three traces of Fig. 16, variations in bulk density of concrete materials were so remarkable that the recording needle was carried off the paper. This could have been caused either by adding more water during mixing or by overcharging the mixer. In the fifth trace of Fig. 19 the duration of the clumping period was short, indicating either that the concrete batch was mixed with insufficient materials or that the water-cement ratio was initially high. In the third trace the clumping period was unusually long. A possible explanation for this condition could be a delay during charging, which would increase the duration of mechanical clumping. Finally, the sixth trace shows that the clumping process was still in progress when the concrete batch being mixed was discharged. These examples are only a few of numerous instances in which the technique gave an accurate representation of the important features of the blending process.

SUMMARY

The present investigations were concerned essentially with two important factors involved in the concrete mixing operation: first, tracing the distribution of the materials being mixed by using a non destructive method, and second, using this method for detecting, if possible, the optimum mixing time while the blending operation was in progress. In an attempt to carry out these objectives, the gamma-ray absorption technique was selected under the assumption that the combined effect of mixer design and local changes in density of the concrete materials could be traced continuously with a simple gamma-ray densitometer as described here, with the following results:

The present non destructive technique can be applied efficiently to evaluate blending operations of any kind provided the density of the materials being mixed varies over a wide range of operating values.

Since variations in densities are associated with changes in the proportion of the concrete materials being mixed, the non destructive method provides a procedure for evaluating the uniformity of the mixture throughout the blending period.

In many respects, these important findings were supported by the concrete mixing study with sodium chloride as also described here. In comparing both methods, at least two main features have been disclosed:

1. The general distribution of the experimental values obtained with sodium chloride followed a regularity very similar to that found in the gamma-ray trace, especially during the clumping period.

2. The end of this clumping period ranged from 60 to 70 seconds in the gamma-ray traces. This also appeared to be the end of the variability of sodium chloride values before falling within the range of experimental error.

Additional supporting evidence that the gamma-ray technique is useful in concrete mixing studies was provided by the compressive strength tests. These results indicated that anywhere between 50 and 70 seconds of mixing time the concrete reached a maximum compressive strength. This was very similar to the end of the clumping period in the gamma-ray trace. On the basis of the maximum compressive strength of the concrete, the non destructive method was capable of detecting the optimum mixing time.

Many examples were described here in which the gamma-ray technique gave an accurate record of the changeable features of field concrete mixing operations. This ability of the non destructive method could be used for quality control of concrete as it is being produced.

A photographic study of the concrete materials being mixed showed that the blending operation could be traced partially during the first 45 seconds of the mixing period. From then on, the pictures did not show any significant change in the mixing process.

Gamma-ray absorption properties of the concrete materials were established by a density calibration curve. These results were used to calculate linear absorption coefficients and some factors related to the design of the gamma-ray densitometer. These results were of considerable assistance for evaluating and predicting the overall performance of the gamma-ray densitometer.

Finally, the fresh concrete composed of the regular ingredients used in this research work was tested for compressive strength, slump, air content, and unit weight according to ASTM methods and specifications. By these standards, the results showed that the concrete was durable and workable and had the consistency required.

CONCLUSIONS

The gamma-ray absorption technique can be applied as a practical method for assessing blending operations of all types, provided the densities of the materials being blended vary over a sufficiently wide range.

Since changes in density are associated with variations in the distribution of the ingredients being blended, the technique furnishes a non destructive procedure for evaluating the uniformity of the mixture throughout the blending period.

This non destructive, simple, and rapid technique is capable of giving an accurate record of the changeable features involved in concrete mixing operations. This could be of real value in quality control of the product.

If the desired quality of fresh concrete is based on compressive strength, the technique is capable of detecting the optimum mixing time in situ.

SUGGESTIONS FOR FURTHER WORK

In planning further experiments with the gamma-ray absorption technique, it would be desirable to investigate:

1. How well the measuring system, especially the amplifier and the recorder, responds to quick changes of the quantity measured, and to find the limit beyond which the apparatus is unable to keep up with such changes.

2. The response of different arrangement of the gamma-ray densitometer such as a double-beam ratio recording with a synchronized selector switch.

3. Simultaneous testing between the gamma-ray technique and the ASTM methods as a function of mixing time.

4. The effect of different types of commercial mixers and other variables involved in mixing operations such as mixing speed, loading, degree of uniformity desired, and physical and chemical properties of the components to be mixed.

5. Different water content and water distribution throughout the concrete batch, relating these conditions with a moisture calibration curve. The measurements of moisture content may be carried out by a standard moisture probe containing a BF_3 slow neutron detector and a radium-beryllium fast neutron source.

6. A rapid method of optimizing the overall performance of the gamma-ray densitometer associated with different geometries of the absorbing system.

APPENDIX

COMPUTATIONS

A. Decay Activity Per Year of Cesium 137

From the fundamental law of radioactive disintegration:

$$N = N_o e^{-\frac{0.69t}{t_{1/2}}}$$

where N = decayed intensity in mc
N_o = original intensity = 5 mc
$t_{1/2}$ = half-life of 33 years
t = elapsed time since irradiation = 1 year

Hence,

$$N = 5 e^{-\frac{0.69}{33}} = 4.90 \text{ mc}$$

That is, the original Cs^{137} source of 5 mc has decayed to 4.9 mc in a year.

This corresponds to 2 percent loss in activity and count rate per year.

B. Amount of Radioisotope Required to Provide 5 mc of Activity

From the fundamental equation:

$$-\frac{dN}{dt} = \left(\frac{0.69}{t_{1/2}}\right) N = \left(\frac{0.69}{t_{1/2}}\right)\left(\frac{6.02 \times 10^{23}}{m}\right) \quad w = 4.17 \times 10^{23} \frac{w}{t_{1/2}\, m}$$

Hence,

$$\frac{w}{t_{1/2}\, m} = \frac{w'}{t'_{1/2}\, m'} \text{ or } w' = \frac{m' w t'_{1/2}}{m t_{1/2}}$$

where w, w' are weights and m, m' are atomic weights of radioactive materials:

m = 226 (atomic weight of radium)
m' = 137 (atomic weight of Cesium)
w = 1g of radium
$t_{1/2}$ = 1600 years, half-life of radium
$t'_{1/2}$ = 33 years, half-life of Cesium

Hence:

$$w' = \frac{(137)\,(1)\,(33)}{(226)\,(1600)} = 1.25 \times 10^{-2} \text{ g}$$

Since this quantity is equivalent to 1c of radioactivity, therefore for 5 mc: (1.25×10^{-5}) (5) = 6.35×10^{-5} g or 0.06 mg of Cs^{137} is required.

C. Required Safe Distance from Radiation Source

In the study of nuclear instruments two aspects of radiation require measurement--intensity and dosage. The intensity is the amount of radiant energy emitted at a given location per unit time and may be expressed in any convenient unit, such as roentgens per day, milliroentgens per hour, counts per minute, etc. The dosage or exposure is a cumulative term, expressing the quantity of radiation received by an object or person during a given time.

By definition, a roentgen (ℛ) is the radiation received in one hour from a 1-g source of radium at a distance of 1 yd or 3 ft. Since radiation intensity is inversely proportional to the square of the distance between the point under exposure and the radiation source, then by definition:

$$I = \frac{w}{s^2}$$

where I = intensity in (mℛ) per hour
w = amount of radium in milligrams or an equivalent activity of any other radioactive substance
s = the distance expressed in yards (42)

For persons often exposed to radiation a tolerance dosage has been established at 120 mℛ per week or 3 mℛ per hr. Now 1.25×10^{-2} g Cs^{137} is equivalent to 1 g of radium and 6.35×10^{-5} g Cs^{137} (5 mc) is equivalent to 5.08×10^{-3} g of Ra. Therefore:

$$s = \sqrt{\frac{w}{I}} = \sqrt{\frac{5.08}{3}} = 1.3 \text{ yd}$$

Since the Cs^{137} source used in these investigations was hermitically sealed in a metal capsule and stored in a portable lead-lined case, no serious hazard problems were involved.

RADIOACTIVE DISINTEGRATION

Radiation hazard comes from the particles or rays emitted from radioactive substances. There are three principal kinds of radiations designated as alpha rays (α), beta rays (β), and gamma rays (γ). They are distinguished principally by the manner in which they interact with matter (Fig. 25). Alpha particles consist of doubly charged helium ions moving with considerable velocity (about 20,000 miles per sec) but they are incapable of penetrating thin layers of materials such as paper or human skin. Beta particles are merely fast-moving electrons with more penetrating power than alpha particles, but can be stopped by metal sheets such as aluminum of 1/4-in. thickness. Very few beta particles (depending upon their energy) penetrate as much as 0.5 in. of tissue. Gamma rays are not particles at all and carry no electrical charge. They are very penetrating photons. Consequently, a serious injury may occur to human tissue continuously exposed to such radiation.

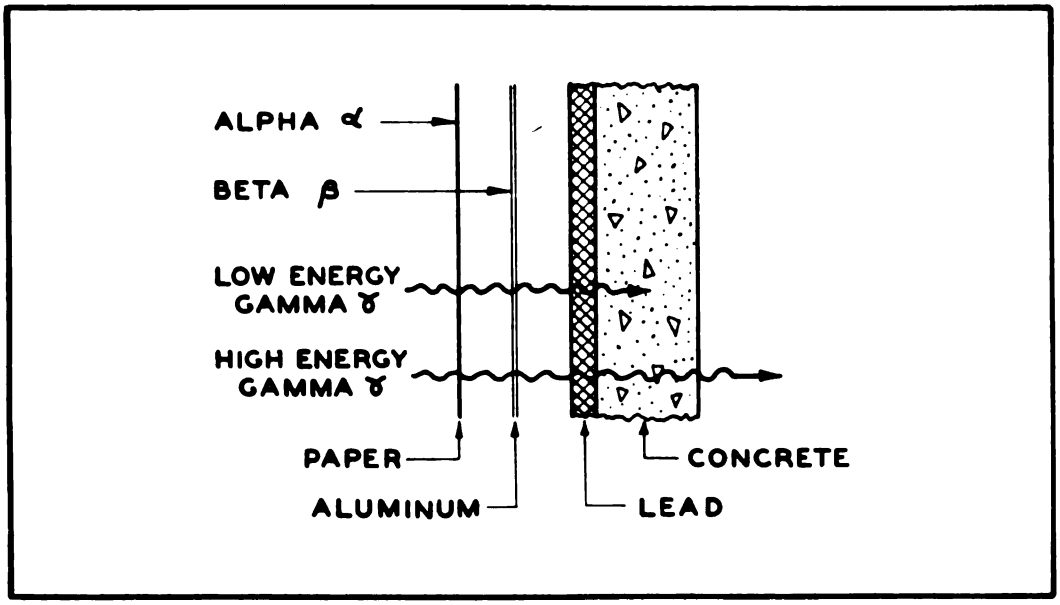


Figure 25. Radiation attenuated by different materials.

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