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THE WATER CONTENT OF HARDENED CONCRETE

By
H. HILSDORF

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SUMMARY

An estimate of the shielding effectiveness of concrete against neutron radiation requires a sufficiently accurate knowledge of the water content of concrete. However, the water content of concrete may vary over a wide range. It depends primarily on the original mix proportions of the concrete, the dimensions and the age of the concrete member and environmental conditions. In this report the various parameters affecting the water content of concrete are discussed, and relationships are deduced which allow a conservative estimate of the water content of various types of concrete.

The water content of fresh concrete is controlled primarily by the required workability of the concrete mix. When concrete hardens, the water is either chemically bound to the cement, adsorbed in the pores within the cement gel or present as free water in larger capillary cavities. Additional water may be held within the aggregates. When a concrete member is subjected to drying it loses water and approaches an equilibrium water content which depends mainly on the relative humidity and temperature of the surrounding air as well as on the amount of cement and the pore structure within the concrete. The drying of concrete follows a very slow diffusion process, and under normal temperatures the inner portions of thick concrete sections have a water content considerably above the equilibrium water content even after many years of drying.

In the final sections of this report a procedure is described to estimate the water content of a concrete member (a) if the initial mix proportions and the exposure conditions of the concrete are known, and (b) if the previous history of the concrete is unknown. Numerical calculations are given to demonstrate the application of this procedure. Finally, values of the water content of concrete are tabulated depending on climatic conditions and age as well as type and size of the concrete member.

FOREWORD

The author gratefully acknowledges the assistance he obtained from Dr. A. B. Chilton, Professor of Civil Engineering and Nuclear Engineering, who also initiated this investigation. This report is based upon experimental work carried out elsewhere. The outstanding contributions by T. C. Powers from the Portland Cement Association, Chicago, on the properties of cement paste and by S. E. Pihlajavaara from the Finish State Institute for Technical Research on the drying of concrete deserve special mention.

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1. Introduction

Concrete is considered an excellent and economical shielding material against nuclear radiation because it contains both light and heavier elements and is comparatively cheap. The light elements which are present in concrete, especially hydrogen, are important for slowing down fast neutrons to the thermal region where they can be absorbed. Heavier elements are necessary for attenuating gamma rays and partially slowing down very high energy neutrons.

An accurate knowledge of the composition of concrete is necessary, both for the design of a concrete shield and for the evaluation of the shielding effectiveness of existing structures: Concrete density controls gamma ray shielding; the hydrogen content of concrete is the most important variable in determining the neutron shielding effectiveness. Hydrogen is present in concrete predominantly in the form of water which has been added to the concrete during the mixing process. However the water content of concrete gradually decreases with time and may vary over a range from 50 kg/m^3 to 250 kg/m^3 depending on original mix proportions, age and dimensions of the concrete as well as the environmental conditions to which the concrete is exposed.

It is the object of this paper to develop a procedure which allows moderately accurate, though somewhat conservative, estimates of the water content of various types of concrete subjected to various environmental conditions.

In the first sections of this report the parameters affecting the water content of concrete are discussed and relationships for estimating the water content are deduced. For the benefit of the shielding engineer, these relationships are summarized in the final sections and their practical application is demonstrated by sample calculations. There, distinciton is made between two cases: (a) the original mix proportions of the concrete are known, and (b) the previous history of the concrete is unknown.

No experimental work has been carried out for this report. All data used herein have been reported elsewhere.

Throughout this report the metric system of units is used since this is common practice in nuclear engineering. In order to avoid inconsistencies in units of equations, the metric system also has been used in areas of concrete mix design. The equivalents to the U.S. system are summarized in Appendix I on page 49 of this report and are given throughout the text and figures.

A list of notations used in this report is given in Appendix II on page 50 of this report.

2. State of Water in Concrete

Fresh concrete contains approximately 125 to 250 kg/m^3 (25 to

50 gal/yd^3) of free water, 200 to 500 kg/m^3 (4 to 11 bags/yd^3) of cement and 1200 to 1900 kg/m^3 (2400 to 3700 lbs/yd^3) of aggregates. These values correspond to a volume distribution of 15 to 25 volume percent of water, 7 to 20 volume percent of cement and 50 to 75 volume percent of aggregates. Only part of the original water is necessary for the hydration of cement. With increasing age of the concrete an increasing amount of water is chemically bound to the concrete. Part of the free water gradually penetrates to the surface of the concrete and evaporates, but some free water is held in the pore system of the cement paste and the aggregates. In addition, some water may be chemically bound to the minerals in the aggregates. Thus, concrete may contain water in the following ways:

a) Chemically bound water within the hydration products of the cement,
b) Water within the pore system of the cement paste,
c) Free water in the pores of aggregates,
d) Crystal water or chemically bound water within the minerals forming an aggregates.

3. Water Content of Fresh Concrete

3.1 Mixing Water

Water in concrete is required to ensure sufficient workability of the fresh concrete mix, and to ascertain hydration of the cement, which in turn is necessary to develop sufficient strength and durability of the hardened concrete.

Generally, the workability of fresh concrete increases with increasing water content. The amount of water necessary to obtain a certain workability can be associated with the specific surface of the aggregate in a concrete mix: The larger the specific surface the higher the required water content of the mix for a given workability. If the gradation of the aggregates is continuous, then the average specific surface for a given volume of aggregates decreases with increasing maximum aggregate size. It is, therefore, common practice in concrete technology to relate the amount of water required for a given workability to the maximum size of the aggregates used in the mix.

Strength and durability of hardened concrete can be related to the ratio between the weight of water and the weight of cement in a concrete mix. A decrease of this water cement ratio results in a strength increase, or the strength increases if for a given cement content the water content is reduced. If, however, a certain workability of the fresh concrete is required, then a minimum water content has to be maintained, Then both the water and the cement content have to be adjusted accordingly in order to fulfill the strength requirements.

Thus, the water content of an economically designed mix can be solely related to the required workability, and to the specific surface of aggregates expressed in terms of the maximum aggregates size used in the mix. These relationships are presented in Figure 1 (1,2,3)*. According to this diagram the amount of mixing water of concrete generally ranges from 125 to 250 kg/m^3 (25 to 50 gal/yd^3) and decreases with increasing maximum aggregate size.

The relationships given in Fig. 1 can be approximated by the following equation:

$$W_o = a_1 - b_1 \lg_{10} S_a \tag{1}$$

if

W_o = content of mixing water in kg/m^3

S_a = maximum aggregate size of concrete in cm

a_1 b_1 = coefficients given in Table 1 for various consistencies of the fresh concrete

The coefficients a_1 and b_1 are not dimensionless, and Eq. 1 is only the result of a curve fitting procedure. Its mathematical form has no physical significance.

Since a certain water cement ratio has to be maintained in order to obtain a given strength and durability of the concrete, a reduction of the water content also allows a reduction of the cement content, and thus of the over-all costs of the concrete. Therefore, in an economically designed concrete mix, the water content is always kept as low as possible.

The use of air entraining agents results in a substantial increase of the workability of fresh concrete, and thus allows a reduction of the water content of fresh concrete by 20 to 26 kg/m^3 (4 to 5 gal/yd^3) of concrete. The corresponding coefficients for Eq. 1 when air entrainment is used, are given in Table 1.

3.2 Water Content of Aggregates

Water or hydrogen may be present in aggregates either chemically bound to the minerals, i.e., non-evaporable, or as free water in the pores of the aggregates. In Table 2 the content of non-evaporable water of minerals commonly found in concrete aggregates is summarized (4). According to Table 2, aggregates may contain from 0 to 4 percent of water by weight of aggregates; but even for a given mineral this percentage varies over a wide range depending on the origin of the particular type of

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*Numbers in paranthesis refer to the corresponding entries in the List of References on page 45 of this report.

aggregate.

The amount of mixing water W_o as given in the preceeding section is valid under the assumption that all aggregates are in a saturated but surface dry condition, i.e., all aggregate pores are filled with water but no excess water is on the aggregate surface. If the aggregates are in a moist or dry state different from saturated surface dry, then the mixing water has to be adjusted accordingly. Typical values of the water absorption of naturally occurring normal weight aggregates are given in Table 3. They may range from 0.2 to 8 percent by weight of aggregates (5 to 8). The values given in Table 3 are valid only for natural aggregates. Some artificially made light weight aggregates exhibit considerably larger absorption capacity.

3.3 Total Water Content of Fresh Concrete

According to the foregoing discussion the water content of fresh concrete is

$$W_{of} = W_o + W_a + W_{an}$$

if

W_{of} = total water content of fresh concrete

W_o = mixing water from Fig. 1 or Eq. 1

W_a = free water in aggregates

W_{an} = non-evaporable water in aggregates

Since the aggregate content of a normal concrete is up to 75 percent of the total volume of concrete, even a small amount of non-evaporable water in the aggregates constitutes a substantial contribution to the hydrogen content of concrete. However, unless exact information about the particular kind of aggregate is available or a certain type of aggregate has been chosen because of its known high water content, the content of non-evaporable water in the aggregates should be neglected. For the free water in aggregates, a lower limiting value of 0.5 percent by weight may be assumed (see Table 3). However, since the pores in the aggregates generally are much larger than the pores in the hardened cement paste, only a small fraction of the water absorbed by the aggregates may be present in dried concrete. For a conservative estimate of the water content of hardened concrete it, therefore, is advisable to neglect both W_a and W_{an}. Then $W_{of} = W_o$.

3.4 The Water Cement Ratio and the Cement Content of Concrete

It will be shown in the following sections that for an estimate of the water content of hardened concrete, its water-cement ratio and cement content have to be known.

As it was pointed out earlier, the amount of water in fresh concrete is governed by workability considerations. Strength and durability requirements are met by a proper choice of the water cement ratio. In Fig. 2 the relationship between concrete compressive strength after 28 days and the water cement ratio is presented for two types of cement, and concrete with and without air entrainment (1,2). These are conservative estimates and are recommended for use in concrete mix design. Under controlled conditions the actual concrete strength for a given water cement ratio may be considerably above the values given in Fig. 2. Recommended maximum water cement ratios to insure durability of concrete are given in Table 4 (1,2).

By combining the required water cement ratio for strength and durability and the required amount of mixing water for workability of the fresh concrete, the cement content can be determined. Figure 3 shows the relationships between cement content and required concrete strength for two types of cement and for fluid and stiff consistency of the fresh concrete. The dependence of the cement content on the maximum aggregate size is shown in Fig. 4. According to these diagrams the dominating parameter affecting the cement content of concrete is the required strength. The use of air entrainment has little effect on the cement content; since air entrainment reduces the compressive strength of concrete, a lower water cement ratio has to be chosen to develop a required compressive strength. Consequently, the cement content has to be increased. However, the required water content for a given consistency of the fresh concrete can be reduced if air entrainment is used and thus the cement content can also be decreased. Therefore, for a given consistency and strength the cement content of air entrained concrete is approximately equal to the cement content of non-air-entrained concrete.

The relationships between the water cement ratio and the required strength as given in Figure 2 can be approximated by the following expression

$$f'_c = \frac{a_2}{W_o/C + b_2} - c_2$$

or

$$C = W_o \frac{f'_c + c_2}{a_2 - b_2(f'_c + c_2)} \qquad (3)$$

If C = cement content in kg/m^3

f'_c = compressive strength of concrete after 28 days in kg/cm^2.

W_o = water content of fresh concrete in kg/m^3

a_2, b_2, c_2 = coefficients depending on type of cement and air entrainment of concrete as given in Table 5.

Values for the water content of concrete W_o can either be taken from

Figure 1 or computed from Equation 1 in Section 3.3.

4. Water Content of Hardened Concrete

4.1 The Structure of Hardened Cement Paste

Most of the water in concrete is held within the cement paste. Consequently, the water content of concrete is strongly related to the properties of the cement paste. In this section, the structure of cement paste is described briefly. More details are given in references such as (9 to 12).

Unhydrated cement consists mainly of a fine powder of calcium silicates, calcium aluminates and calcium aluminoferrites with an average specific surface of approximately 3,000 cm^2/g. When mixed with water, these compounds hydrate at first violently and then at a decreasing rate. The hydration products are mainly calcium-hydroxide crystals and submicroscopic irregular and needle or plate like crystals whose chemical compounds are similar to tobermorite. The individual particles are not interconnected but separated from each other by small, mostly water filled "gel pores" with an average diameter of approximately 20 Å. Because of their small size, the hydration products are colloidal, and the hydrated cement paste is considered a gel of the limited swelling class. Significant characteristics of the cement gel are its very large specific surface of approximately 2×10^6 cm^2/g and a porosity of approximately 26 percent.

When cement and water are mixed, initially a system is formed which consists of a solid phase of unhydrated cement and comparatively large capillary pores filled with water. As hydration progresses, water is taken up from the capillary pores and is gradually replaced by the cement gel. Thus with increasing hydration the volume of capillary pores decreases while the volume of gel pores increases. It will be shown later that normally some capillary pores are left even if the cement is completely hydrated.

Not all of the water in the cement gel is chemically bound. The gel pores also contain a considerable amount of water. Because of the high specific surface of the hydration products and the small diameter of the gel pores, most of the gel water is adsorbed and has a mobility lower than that of free water. Thus, neglecting large cavities due to imperfect compaction, hardened cement paste contains 2 types of pores: (a) Capillary pores, and (b) gel pores. Water may be present in cement paste in either of the following three states: (a) free water in the capillary pores (capillary water), (b) chemically bound water in the hydration products, and (c) adsorbed or physically bound water in the gel pores (gel water).

In numerous experiments, Powers and Brownyard (9) investigated the pore structure of the cement paste quantitatively. Later on these tests were extended and reinterpreted by various investigators (10 to 16).

In these experiments no precise distinction could be made between water in the various states. The pore size distribution in the cement paste is continuous, and consequently there is no sharp transition from capillary to gel water. Within the hydration products the water is bound to the cement particles in different ways and with different degrees of fixation. Therefore, in general a distinction is made between evaporable and non-evaporable water at a given pressure and temperature. The non-evaporable water is more or less arbitrarily defined as that water which is held by the cement paste after the paste has been dried to a constant weight at a temperature of 105°C. The water content of a given cement paste at a 105°C is approximately the same as the water content of the paste at 20° and zero relative vapor pressure. The predominant portion of this "non-evaporable" water can be considered as chemically bound water (type b). At normal temperatures up to a relative vapor pressure of 0.40, all of the water in excess of the non-evaporable water is adsorbed water (type c). The cement paste contains also free water (type a) at a relative vapor pressure beyond 0.40.

Powers and Brownyard (9) found that in the process of hydration the weight of non-evaporable water can be very well expressed as a constant percentage of the weight of hydrated cement:

$$W_n = 0.24\ mC \tag{4}$$

if W_n = weight of non-evaporable water

C = total weight of cement

m = maturity factor = ratio of weight of hydrated cement to total weight of cement.

For a saturated paste the weight of the absorbed water or gel water can also be expressed as a percentage of the weight of hydrated cement:

$$W_g = 0.18\ mC \tag{5}$$

if W_g = weight of gel water

From these observations, it has been concluded that the physical properties of the hydrated cement gel are independent of the age of cement at which they have been formed (9).

The volume taken up by the cement gel is larger than the initial volume of the non-hydrated cement, but it is less than the sum of the original volume of cement and the non-evaporable water: The non-evaporable water is "compressed" and its specific volume is reduced from 1.0 to approximately 0.75. However, the specific volume of the gel water deviates little from 1.0 (14). From these values the volume of the cement gel can be estimated as follows:

$$V_g = \underset{\substack{\text{original}\\ \text{volume of}\\ \text{hydrated cement}}}{mCv_c} + \underset{\substack{\text{volume of non-}\\ \text{evaporable water}\\ \text{(chemically bound)}}}{0.24mCv_{wn}} + \underset{\substack{\text{volume of}\\ \text{gel water}\\ \text{(adsorbed)}}}{0.18\,mCv_w} \qquad (6)$$

If V_g = Volume of cement gel

C = total weight of cement

v_c = specific volume of cement, generally in the range of 0.318 to 0.333

v_w = specific volume of evaporable water

v_{wn} = specific volume of non-evaporable water

m = maturity factor = ratio of weight of hydrated cement to total weight of cement.

With $v_c = 0.318$; $v_w = 1.0$ and $v_{wn} = 0.75$

$$V_g = 2.13\, mCv_c \qquad (6a)$$

With increasing hydration the volume of the cement gel increases, and for complete hydration, i.e., $m = 1$, the volume of the gel is approximately 2.1 times the original volume of the cement. From Eq. 6 and 6a, a characteristic porosity of the cement gel of approximately 26 percent of the volume of the gel can be computed.

The volume of the capillary pores can be determined from the difference between the initial volume of water and cement, and the volume of hydrated cement gel and unhydrated cement particles.

$$V_{cp} = C \times v_w \left(\frac{W_o}{C} - 0.36m\right) \qquad (7)$$

If V_{cp} = volume of capillary pores

W_o = initial weight of water added to the mix

C = total weight of cement

v_w = specific volume of evaporable water

m = maturity factor.

The volume of capillary pores decreases with increasing maturity and decreasing water cement ratio. For complete hydration, i.e., $m = 1$, and a water cement ratio of 0.36, the volume of capillary pores is zero. Complete hydration becomes impossible for W_o/C ratios < 0.36.

Since the non-evaporable water in the hydrated cement gel is "compressed" not all of the volume of water taken up from the capillary pores will be filled with hydrated cement gel. Therefore, the cement paste "dries" internally even if evaporation of water is prevented, and the water content of a paste which is kept saturated is larger than its initial water content:

$$W'_o = W_o + 0.24mC \left(\frac{v_{wn} - v_w}{v_w}\right) \tag{8}$$

With $v_{mn} = 0.75$ and $v_w = 1.0$

$$W'_o = W_o + 0.06\ mC$$

if

W_o = initial water content

W'_o = water content of saturated, hydrated cement paste

C = total weight of cement

m = maturity factor

4.2 The Maturity Factor of Concrete

The maturity factor, m, indicates which portion of the cement in a concrete mix is hydrated at a given time. For complete hydration, m = 1. Whether cement does completely hydrate is a controversial matter. It is thought that the gel surrounding non-hydrated cement particles may prevent free water from penetrating to the non-hydrated cement. However, it may be assumed, that cement eventually hydrates completely, if the portion of cement particles having mean diameters larger than approximately 50 microns is small, if the water cement ratio is larger than about 0.45 and if the paste remains sufficiently saturated with water. Hydration generally ceases if the relative humidity within the cement paste is less than 80 percent (9).

The principal parameters affecting maturity of concrete are time, chemical composition of the cement, size of the concrete members and environmental conditions. Minor parameters, which have not been considered in the following are the water cement ratio and the specific surface of the cement. A reduction of the water-cement ratio and a decrease of the specific surface of the cement decreases the maturity of cement at a given time.

Rapidly reacting cements (type III cement) obtain a given degree of maturity after a shorter period of time than slower reacting cements (type I cement). The effect of size of the concrete member and environmental conditions cannot be separated easily: if the relative humidity of the surrounding air is less than 80 percent, then the concrete dries and its internal relative humidity eventually drops below 80 percent. Consequently, the concrete ceases to hydrate. Since the drying of concrete is a very slow diffusion process, at least the internal parts of a concrete member continue to hydrate even after the surface of the concrete is allowed to dry. The amount of additional hydration during the drying period depends on the size of the concrete member. It will be shown in Section 4.4 that drying is accelerated with an increase of the surface to volume ratio of the member. Therefore, small members dry faster than large ones, and the average maturity which concrete can develop after the initial moist curing period decreases with decreasing specimen size.

In Figs. 5a and 5b maturity factors are given for type I and type III cements and for different specimen sizes and drying conditions. In these diagrams the values for continuously moist cured concrete have been deduced from measurements of non-evaporable water (9) under the assumption that the weight of non-evaporable water is 24 percent of the weight of hydrated cement.

The maturity factors for drying concrete as given in Figs. 5 are average values for a specimen of a given size. They have been computed on the basis of the diffusion theory which will be discussed in Section 4.41. The computations are based upon the following assumptions:

(a) Prior to drying, the concrete is moist cured over a period of 7 days.

(b) At an internal humidity between 85 and 100 percent, the concrete hydrates at the same rate as moist cured concrete. As soon as the internal relative humidity of a certain part of the concrete drops below 85 percent, this portion of the specimen ceases to hydrate.

(c) The drying of concrete can be predicted on the basis of the diffusion theory assuming a constant diffusivity coefficient of $k = 10^{-11}$ m^2/sec.

(d) The concrete has a water cement ratio of 0.50 and a cement content of $C = 340$ kg/m^3.

(e) The effect of size and shape on the drying of concrete can be taken into account by using the "equivalent" thickness $\bar{\ell} = 2V/S$, if V = volume of the specimen and S = drying surface of the specimen (See Section 4.41).

These computations were carried out as follows: The concrete member has a total area of A. After a given period, the concrete dried so far that the area of concrete which has a relative humidity above 85 percent is reduced to $A_d = nA$. From the diffusion theory that period of time t, can be computed after which $A_d = n_1 A$. It depends upon the "equivalent" thickness of the drying member $\bar{\ell}$ (Section 4.41 and Fig. 10). During the drying period t, an additional maturity, Δm, has been developed which can be taken from the time-maturity relationship given for continuously moist cured concrete. If the maturity at the beginning of drying is m_o then the average maturity factor after t, days of drying is for small increments of n:

$$m_{t1} = m_o + \Delta m_1 \frac{1-n_1}{2}$$

After additional $t_2 - t_1$ days of drying the maturity factor is

$$m_{t2} = m_{t1} + \Delta m_2 \frac{n_1 - n_2}{2}$$

or

$$m_{ti} = m_{t(i-1)} + \Delta m_i \frac{n_{i-1} - n_i}{2} \qquad (9)$$

Equation 9 was evaluated on the basis of the sssumptions stated above and for increments of $n_i - n_{i-1} = 0.10$. The equivalent thickness was varied between $\bar{\ell} = 0.050$ m and $\bar{\ell} = 0.20$ m. According to Figs. 5a and 5b thick concrete members can develop almost complete hydration even if moist cured only for seven days. Small sections may reach a maturity factor of not more than 0.60.

The maturity factor depends also on the temperature of the ambient atmosphere. With a decrease of temperature the rate of hydration decreases and at a temperature below -10°C, cement ceases to hydrate. The maturity factors given in Figures 5a and b are valid for temperatures fo 20 to 25°C (68 to 77°F). If the concrete temperature deviates considerably from this value over an extended period of time, then the maturity factor can be taken from Figs. 5a and b by adjusting the corresponding age of concrete according to the following empirical expression (19):

$$d_e = \frac{\Sigma \Delta d\ (T + 10)}{30} \qquad (10)$$

If

d_e = age of concrete at which equal maturity under a curing temperature of 20°C would have been developed

Δd = days under temperature T

T = curing temperature in °C

4.3 Water Content of Hardened Concrete at Moisture Equilibrium

When a concrete member is exposed to drying, its surface attains a relative humidity equal to the humidity of the surrounding atmosphere within a short period of time, usually less than 24 hours. However, because of the low permeability of the concrete the inner fibers dry at a much slower rate and the water content at a given time increases with increasing distance from the drying surface. Only after very long drying periods is the entire concrete member in moisture equilibrium with the surrounding atmosphere. This equilibrium moisture content of concrete, which will be discussed in the following section, corresponds to the minimum water content of concrete under given environmental conditions.

The following is based on research work by Powers and Brownyard (9) who studied, in an extensive investigation, the water content of hardened cement paste at various degrees of hydration, for various types of cement and various relative vapor pressures.

Sorption isotherms from (9) for moist-cured cement pastes made of type I cement with a water-cement ratio of 0.44 and different degrees of maturity are given in Fig. 6. There, the total water retained by the paste as a fraction of the total cement content W_e/C is given for various values of relative vapor pressures φ at a constant temperature of 25°C. (The relative vapor pressure is identical with the relative humidity). Values for W_e/C at a relative vapor pressure of zero represent the non-evaporable water. The values at $\varphi = 1.0$ correspond to the water content of a saturated paste.

As discussed in the preceeding paragraphs the maturity factor increases with increasing age of concrete, and the weight of non-evaporable and evaporable water increases accordingly. As mentioned earlier the water content at saturation also increases with increasing maturity because the non-evaporable water is "compressed" and the space in the capillaries initially taken up by free water will not be completely filled with cement gel.

In Fig. 7 isotherms from (9) for two types of cement, water cement ratios and maturities are given in a somewhat different way. There, the ratio of the equilibrium water content to the amount of hydrated cement, W_e/mC, is given as a function of the relative vapor pressure φ. Identical curves have been obtained for pastes made of different cements and tested at various ages. This coincides with the statement made earlier that the hydration products formed at any stage are identical.

For relative vapor pressures below 0.40 the ratio W_e/mC is independent of the water-cement ratio. From this observation it has been concluded (9) that for $\varphi < 0.40$ the paste contains only non-evaporable water and gel water. According to Eqs. 4 and 5 the total weight of non-evaporable and gel water is:

$$W_n + W_g = 0.42mC$$

or

$$\frac{W_n + W_g}{mC} = 0.42$$

However the water content at $\varphi = 0.4$ according to Fig. 7 is $\frac{W_e}{mC} = 0.34$. Therefore, some of the gel water must have evaporated already at $\varphi > 0.4$, indicating again that the distinction between capillary and gel pores is somewhat arbitrary.

For a relative vapor pressure above 0.40, capillary condensation takes place and the water content increases with increasing volume of the larger capillary pores which in turn is dependent on the water cement ratio. Therefore, the water content of the paste increases with increasing water cement ratio.

At saturation, i.e., $\varphi = 1$, the water content of the cement paste is larger than the initial water content W_o. It is, according to Eq. 8

$$W'_o = W_o + 0.006mC$$

or

$$\frac{W'_o}{C} = \frac{W_o}{C} + 0.006m$$

At relative vapor pressures $\varphi < 1.0$, parts of the gel water and capillary water evaporate. If the ratio between the weight of gel water at a given value of φ and the weight of gel water at saturation is designated with X and the corresponding ratio for the capillary water is Y, then according to Eq. 4, 5 and 7 the equilibrium water content of the cement paste at any relative vapor pressure can be expressed as follows:

$$W_e = \underbrace{0.24mC}_{\text{non-evaporable water}} + \underbrace{X\,0.18mC}_{\text{gel water}} + \underbrace{YC\left(\frac{W_o}{C} - 0.36m\right)}_{\text{capillary water}}$$

or

$$\frac{W_e}{C} = m\,(0.24 + 0.18X) + Y\left(\frac{W_o}{C} - 0.36m\right) \qquad (11)$$

The coefficients X and Y were evaluated from the isotherms reported in (9) for various water cement ratios and types of cement. By definition X = 0 for $\varphi = 0$ and X = 1 for $\varphi = 1.0$. Since for $\varphi < 0.4$ all capillary water has evaporated, Y = 0 for $\varphi < 0.40$. For complete saturation at $\varphi = 1.0$, Y is equal to unity.

It should be pointed out here that the choice of the limiting values for X and Y is somewhat arbitrary, similar to the distinction which has been made between gel pores and capillary pores.

The coefficients X and Y are given in Fig. 8 as functions of φ. They are independent of the water cement ratio and the type of cement. The coefficient Y decreases slightly with decreasing maturity, indicating that at a particular relative humidity the amount of capillary water decreases with decreasing maturity. This is not unreasonable, considering the fact that the diameter of pores within the capillary pore system is variable. It is likely that for a low degree of hydration the average size of the capillary pores is larger and consequently the amount of water held in this system is smaller.

In Fig. 9 sorption isotherms for various types of cement, water cement ratios and maturities are presented. They have been computed according to Eq. 11 and are compared to experimental data reported in (9). The maturity factor, m, has been taken from Figs. 5a and 5b. The agreement between experimental data and computed values is satisfactory.

The experiments (9) on which the foregoing discussion is based, correspond to the lower bound values of the equilibrium water content of cement paste. In Powers' and Brownyards' tests the cement paste samples at first had been dried and then were brought back to moisture equilibrium at a given relative vapor pressure. Thus adsorption rather than desorption isotherms were obtained. Cement paste exhibits a desorption-adsorption hysteresis, i.e., the water content of cement paste at a given relative humidity is higher for the pastes which initially were saturated than for pastes which initially were dry. The difference between adsorption and disorption isotherms dimenishes with increasing temperature (20) and disorption curves approach the initial adsorption curve for cyclic wetting and drying (9, 17). Under normal temperatures the difference between adsorption and desorption curves is small enough to justify the assumption that the equilibrium water content of hardened cement paste can be sufficiently described by adsorption isotherms.

In the following sections it will be assumed that the water content of aggregates of concrete is negligible. Then the equilibrium moisture content of concrete corresponds to the water content of the cement paste as computed from Eq. 11. As has been shown by Menzel (17) this assumption is not entirely correct but it appears necessary for a safe lower bound estimate. The pores in most concrete aggregates are much larger than the pores in the cement paste. Therefore an appreciable amount of free water will be held by the aggregates only at relatively high vapor pressures. If the non-evaporable water content of aggregates used for a particular type of concrete is known, then it can be considered in estimating the equilibrium water content of concrete:

$$W_{ea} = C \left[m(0.24 + 0.18X) + Y \left(\frac{W_o}{C} - 0.36m\right) + \frac{W_{an}}{A} \cdot \frac{A}{C} \right] \qquad (11a)$$

If

W_{ea} = equilibrium water content of concrete containing aggregates with non-evaporable water

$\frac{W_{an}}{A}$ = non-evaporable water content of aggregates per unit weight of aggregate

$\frac{A}{C}$ = aggregate-cement ratio

4.4 The Water Content of Drying Concrete

The water content of concrete at equilibrium as discussed in the preceeding chapter constitutes only a minimum value which the drying concrete approaches at a very slow rate. Especially thick concrete sections will reach this state only after many years, and for an estimate of the water content of concrete it would in many instances be too conservative to take only the equilibrium water into account. In the following sections the various parameters affecting the process of drying will be discussed, and a method will be given to estimate the average water content of a drying concrete section at a given time.

It has to be realized, however, that the theoretical background for the drying of concrete has not been sufficiently developed as yet and experimental data are scarce. The method presented here allows a rough estimate. It does not eliminate the urgent need of further studies, both experimentally and theoretically.

4.41 The Diffusion Theory

It has been shown by Sherwood (21) and later by Newman (22) and other investigators, that the movement of water in porous media can be considered as a problem similar to the transfer of heat. Transfer phenomena generally are expressed in the following way:

$$\frac{\partial P}{\partial t} = \text{div}\,(k\ \text{grad}\ P) \qquad (12)$$

if

P = Potential

t = time

k = transfer coefficient

If the transfer coefficient is a constant, then Eq. 12 simplifies to

$$\frac{\partial P}{\partial t} = k\ \text{div grad}\ P = k\nabla^2 P \qquad (13)$$

Applied to the drying of a porous material, Eq. 13 can be written as

$$\frac{\partial U}{\partial t} = k\left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} + \frac{\partial^2 U}{\partial z^2}\right) \qquad (14)$$

If, x, y, z = rectangular coordinates of the point in question

t = time

U = liquid concentration at a given location and time

k = diffusivity coefficient or moisture conductivity in $\frac{(\text{unit of length})^2}{\text{time}}$

The moisture conductivity k is defined as the amount of liquid kg per hour which flows across an area of 1 m^2 if the concentration of the liquid has a gradient of 1 kg per m^3 over a length of 1 m in the direction of the flow.

In a drying process the material may have a certain initial liquid content W_o. As drying proceeds this liquid content decreases and the material approaches a state in which it is in moisture equilibrium with the surrounding atmosphere. The corresponding moisture content at equilibrium is W_e. Then the liquid concentration is:

$$U = \frac{W_{ti} - W_e}{W_o - W_e}$$

If W_{ti} = moisture content at a given point at time t

W_o = initial moisture content

W_e = equilibrium moisture content

Thus, in a drying process the liquid concentration at a given point and at a given time is the ratio of the amount of liquid in excess of the equilibrium moisture content, to the total amount of liquid which can be lost in the process of drying. At the beginning of drying, $U = 1$; at the end of drying, $U = 0$.

Various solutions of Eq. 10 for cylinders, spheres, slabs or prismatic bars have been given by Newman (22) using Fourier series and Bessel functions. They are also reported e.g. in textbooks (24) and (25). In these solutions the liquid concentration U is presented as a function of the Fourier number Fo

$$U = f\,(Fo) = f\left(\frac{k\ t}{\ell^2}\right) \tag{15}$$

where ℓ = characteristic thickness of the drying member.

For a cylinder, ℓ is equal to the radius, for a slab drying in two directions ℓ is equal to the half-thickness of the slab. If for a given member with a characteristic thickness ℓ_1 a certain liquid concentration U_1 will be reached after drying time t_1, another member whose characteristic thickness is ℓ_2 will reach the same liquid concentration after

$$t_2 = t_1 \left[\frac{\ell_2}{\ell_1}\right]^2$$

In Fig. 10 solutions of the diffusion equation (from 26) are given for an infinitely long slab drying in two directions. There, the liquid concentration U is given as a function of x/ℓ for various values of $Fo = k\ t/\ell^2$, if ℓ is the half thickness of the slab and x is the distance of the point in question from the center line of the slab.

By integrating U over the cross section of the drying member the average liquid concentration can be obtained:

$$\bar{U} = \frac{1}{\ell}\int_0^\ell U \, dx$$

or by definition:

$$\bar{U} = \frac{W_t - W_e}{W_o - W_e} \qquad (16)$$

if W_t = average moisture content at a given time

W_o = initial moisture content

W_e = equilibrium moisture content

The average moisture concentration for various types of drying members is given in Fig. 11 as a function of kt/ℓ^2. From these relationships it can be seen that a member dries faster the smaller its volume/surface ratio. As an approximation, drying of a member of arbitrary cross section can be calculated according to the diffusion theory using the relationship for an infinitely long cylinder as given in Fig. 11, if the term ℓ is replaced by the "equivalent" thickness $\bar{\ell}$

$$\bar{\ell} = \frac{2V}{S} \qquad (17)$$

If this procedure would be an exact solution, then drying of a cylinder of radius ℓ and a bar of rectilinear cross-section 2ℓ by 2ℓ should be identical. It can be seen from Fig. 11 that this is not the case. Nevertheless this approximation gives sufficiently accurate results.

Unfortunately, the assumption of a constant moisture conductivity can depict the drying of porous materials only if the difference between the initial moisture content W_o and the equilibrium moisture content W_e is small. However better agreement between theory and actual behavior could be achieved by assuming a variation of k with the liquid concentration:

$$k = k_e \, (1 + bU^n) \qquad (18)$$

if k_e = basic moisture conductivity = const

U = liquid concentration

b,n = coefficients

Solutions of the diffusion equation with linearily varying values of k are e.g. presented by Crank (25). Pihlajavaara and Vaisanen (26) developed nomograms for the drying of infinitely long slabs and a linearly varying moisture conductivity. Other relationships $k = f(U)$ such as an exponential variation also have been reported by Crank (25). Further and more detailed discussions on the diffusion theory can be found in textbooks by Crank (25) or Carlslaw and Jaeger (24).

4.42 Application of the Diffusion Theory to the Drying of Concrete

Carlson (28), Pickett (29) Campbell-Allen (30)*, Waters (31)* and Rostasy (32) applied the diffusion theory to the drying of concrete assuming constant values for the moisture conductivity. Values of k ranging from 10^{-9} to 10^{-11} m^2/sec best fit the test results, but with the exception of Rostasy's tests the agreement between drying of concrete and the diffusion theory assuming a constant moisture conductivity was poor though rated "satisfactory" by the authors.

The most extensive studies on the drying of concrete in recent years have been carried out by Pihlajavaara (20,23,26,27). He gave an excellent description of the problem and detailed reviews of literature on drying of concrete. Pihlajavaara also carried out numerous experiments mainly with the objective of verifying the diffusion theory in such a way that it sufficiently represents the drying of concrete. However, despite the scientific value of his work, Pilajavaara's data do not answer the very practical question of the water content of structural concrete mainly because his specimens were moist cured over extended periods of time so that no appreciable amount of hydration took place during the drying period. This is, in general, not true for structural concrete.

Pihlajavaara (20) showed that the assumption of a constant moisture conductivity allows a good estimate of the average liquid concentration $\bar{U}$ if the difference between the relative humidity of the surrounding atmosphere and of the concrete at the beginning of drying is small, i.e., in the order of 15%. The drying of concrete from 100 percent to approximately 70 percent relative humidity can be fairly well predicted assuming a linear variation of the moisture conductivity k with the liquid concentration U:

$$k = k_e (1 + bU)$$

Furthermore, he showed experimentally that the moisture conductivity in general varies with the liquid concentration according to Eq. 18, i.e., the moisture conductivity decreases with decreasing moisture content.

This tendency is in accordance with the findings of Rose (33, also discussed in 20) who distinguishes between six different types of moisture transfer in a porous solid depending on the internal relative humidity:

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*References 30 and 31 could not be located. They are discussed in Ref. 20 and 23.

(a) At relative humidities below 10 percent even vapor flux does not take place until the surfaces of the pores are covered with layers of adsorbed water.

(b) At humidities around 20 percent unimpeded vapor movement takes place while the vapor behaves like an inert gas.

(c) In the third stage at a relative humidity of approximately 50 percent the water is in a liquid stage only within the small gel pores. Vapor is being transferred at a somewhat higher speed compared to (b).

(d) If the relative humidity increases to 70 to 80 percent then, in addition to vapor transfer, also liquid water flows in thin layers along the surface of the pores.

(e) For high relative humidity above 90 percent unsaturated liquid transfer takes place and vapor makes only a minor contribution to the total water movement.

(f) At 100 percent relative humidity there is saturated liquid flow.

The moisture conductivity will vary as the moisture transport enters another stage. However, in a drying concrete member all types of flow may occur simultaneously depending on the location of the point in question with respect to the drying surface (20).

In addition, the moisture conductivity of concrete will depend on its degree of hydration. With increasing maturity, the number of capillary pores decreases while the number of gel pores increases. Consequently, the permeability and also the moisture conductivity decreases with time. Also the amount and pore structure of the aggregates will have a major effect upon moisture conductivity of concrete, dense aggregates of low permeability resulting in a lower moisture conductivity. Thus it is not at all surprising that the diffusion theory assuming a constant moisture conductivity does not sufficiently describe the drying of concrete.

4.43 Experimental Results

In the following paragraphs the principal parameters affecting the water content of drying concrete will be discussed and the test results compared with solutions given by the diffusion theory. The principal characteristics of the sited tests are summarized in Table 6. Unfortunately the number of experimental data is limited. Nevertheless some general relationships can be given.

In the following presentation the terms describing the water content of concrete are defined in the following way:

$\bar{U} = \frac{W_t - W_e}{W_o - W_e}$ = average liquid concentration at time t

W_o = total initial water content, i.e., mixing water

W_t = total water content at the time t including the non-evaporable water

W_e = equilibrium water content including non-evaporable water at the time t

These definitions have been chosen for practical reasons, since in this report an estimate of the total water content of concrete is required. It would be more consistent with the diffusion theory if only the evaporable water would be considered in determining the average liquid concentration $\bar{U}$, and in fact a slightly better agreement between experimental results and diffusion theory can be achieved if $\bar{U}$ is defined accordingly. Both definitions, however give identical values if the specimen is cured such that it does not lose or gain weight during the moist curing period and if no additional hydration takes place during the drying period. Then the equilibrium moisture content does not change during drying.

(a) Specimen Size

In connection with studies of shrinkage of concrete, Thiel (3) reported weight changes of drying concrete specimens of various sizes. All specimens had equal length, however their cross-section varied from 7 by 7 cm to 20 by 20 cm. After one day of moist curing the specimens were exposed to a relative humidity of 50 percent at a temperature of 20°C. In Fig. 12 the weight loss given as a percentage of the initial weight is plotted versus $t/\bar{\ell}^2$, if t is the drying time and $\bar{\ell}$ is the equivalent thickness of the specimens as defined in Eq. 17. According to Fig. 12 the drying specimens of various sizes can be represented by a unique relationship. Thus the "model law" of the diffusion theory is affirmed which indicates that the average moisture concentration $\bar{U}$ can be described by a parameter independent of the specimen size:

$$\bar{U} = f(d \frac{t}{\bar{\ell}^2})$$

A similar observation has been made by Jain and Kesler (35). The distribution of the relative humidity across drying cylinders of various diameters was measured using an electrical hygrometer (46). Some of the results of this investigation are shown in Fig. 13. Jain and Kesler showed that the variation of the relative humidity of cylindrical specimens of various diameters can be presented in a form as given in Fig. 14. There, the desiccation, H

$$H = \frac{\text{Initial Humidity - Humidity at a Given Time}}{\text{Initial Humidity - Final Humidity}}$$

is plotted as a function of

$$R = \frac{t}{r_o^2}$$

if t = drying time

r_o = radius of cylinder

If the location of a point within a drying cylinder is expressed as its relative distance from the center

$$\theta = \frac{r}{r_o}$$

where r_o = radius of cylinder

r = distance of point in question from axis of cylinder,

then the desiccation of this point is independent of the size of the drying specimen.

(b) Water Cement Ratio

The water cement ratio of concrete affects both the pore structure of the cement paste and the equilibrium moisture content. Therefore, it is likely that the moisture conductivity of the concrete is also a function of the water cement ratio, high values of W_o/C resulting in a higher moisture conductivity. In Fig. 15 the average liquid concentration $\bar{U}$ of concrete cylinders 20 cm in diameter and 80 cm long with a water cement ratio W_o/C of 0.45; 0.55; and 0.65 is given as a function of drying time. The specimens were moist-cured for seven days and dried at 65 percent relative humidity. The original data have been obtained from a study of Hummel et.al. (36). The average liquid concentration was assumed to vary with time and was computed on the basis of the discussion presented in Section 4.3 using the maturity factors as given in Fig. 5a. According to Fig. 15, the average liquid concentration at a given time decreases with increasing W_o/C-ratios. In Fig. 15 solutions of the diffusion theory are also given assuming various constant values of the moisture conductivity. Only up to 100 days of drying can the theory represent the drying behavior of concrete. Figure 16 shows the values of a constant moisture conductivity k which would have to be assumed in order to determine the average moisture concentration at a given time. For a given concrete, k varies almost by an order of magnitude. In Fig. 17 a linear variation of the moisture conductivity as proposed by Pihlajavaara was assumed (Eq. 18). The agreement with the actual behavior of concrete is improved, however, the deviation between theory and test results still is considerable.

(c) Relative Humidity

An increase of the relative humidity of the ambient atmosphere results in an increase of the "driving force" of drying. Consequently, the average liquid concentration of a specimen of given size and mix proportions after a given period of drying should be smaller the lower the relative humidity. This can be clearly seen from Fig. 19. There, test results reported by L'Hermite and Grieux (37) are presented.

Concrete specimens 7 by 7 by 28 cm were moist cured for one day and then subjected to drying at relative humidities of 35, 50 and 75 percent, respectively. In Fig. 19 the experimental curves are compared to an approximate analytical procedure which will be discussed in Section 4.44.

(d) Maturity and Type of Concrete

The problem of drying of concrete becomes even more complicated by the fact that concrete may continue to hydrate even after it has been exposed to drying. Then the equilibrium moisture content and the amount of non-evaporable water increase with time. The additional hydration which takes place during the drying period depends on the size of the specimen and the relative humidity of the ambient atmosphere as has been discussed in 4.2.

It appears to be a reasonable assumption that for a given relative humidity the rate of loss of water or of the decrease of average liquid concentration would be larger the lower the maturity of concrete at the beginning of drying. L'Hermite and Grieux (37) reported tests on specimens 7 by 7 by 28 cm made of type I cement with a W_o/C-ratio of 0.57 which were exposed to drying at a relative humidity of 50 percent after 2;7;28 or 90 days, respectively. The variation of the average liquid concentration of these specimens with time is presented in Fig. 20: A decrease of curing time results in a decrease of the liquid concentration at a given time.

Further test results from Ref. (38) are presented in Fig. 21. Cylindrical specimens 20-cm in diameter and 80-cm long were exposed to drying at a relative humidity of 65 percent after 1, 3, 7, 28 and 90 days respectively. The W_o/C-ratio of the concrete was 0.55 and type III cement was used. In these tests the difference in the average liquid concentration between specimens of different maturity at the beginning of drying is much less pronounced than it is for the data presented in Fig. 18. After 200 days of drying the specimen attained an average liquid concentration which is almost independent of their maturity at the beginning of drying. The two test series presented in Fig. 20 and 21 differ in two major respects: the specimen from Fig. 20 had a cross-section of 7 by 7 cm while the specimens from Fig. 21 were cylindrical with a diameter of 20 cm. The first test series was made of type I cement, the second test series of type III cement. Thus the specimens from the second group had a much higher maturity at the beginning of drying. Because of their comparatively large dimensions and the higher relative humidity of the ambient atmosphere they could continue to hydrate during drying and may eventually have reached almost complete hydration. It thus appears that the degree of hydration at the beginning of drying affects the moisture content of concrete only in the first days of drying. At some later date, however, the final degree of hydration is the governing factor for the average liquid concentration.

In Fig. 22, the effect of type of cement upon drying of concrete is demonstrated (36). Cylindrical specimens 20 by 80 cm made of Type I and Type III cement, respectively, were moist cured for seven days and dried at a relative humidity of 65 percent. There is a marked difference between the drying of the two types of concrete. This is somewhat contradictory to the statements made above. Because of their large size the specimens from both series of tests will eventually reach almost identical maturity. Therefore, their average moisture concentration should approach each other with increasing drying time. However, it should also be mentioned that the specimens made of type III cement and reported in Figs. 22 were in all controllable respects identical to the specimens reported in Ref. (38) and shown in Fig. 21. Nevertheless, there is a significant difference in moisture content after extended periods of drying, indicating the scatter which has to be expected even under controlled conditions.

(e) Other Factors

In preceeding paragraphs only the major parameters affecting the water content of drying concrete have been discussed. Numerous other factors may influence the liquid concentration of concrete at a given time: A decrease of the permeability of the aggregates may increase the water content of concrete at a given time. However, tests reported in (8) show that the loss of water of concrete specimens made of six different types of "normal" aggregates after 200 days of drying differed by less than 10 percent. But, if highly permeable light weight aggregates are used a considerably faster rate of drying has to be expected. Also the relative proportions of aggregates and cement will affect the rate of drying. However, no experimental results on these subjects could be found.

Also the amount of air voids in the concrete may affect its drying behavior. Air entrained concrete may lose its water at a faster rate compared to non-air entrained concrete. In addition poorly compacted concrete will dry faster than well-compacted concrete.

It was shown by Pihlajavaara (20) that the wind velocity of the surrounding air affects drying of concrete only during the first hours while the concrete surface is still wet. It has little influence on the water content of concrete at a later date.

4.44 An Approximate Method to Estimate the Water Content of Drying Concrete

It has been shown in the preceeding sections, that the diffusion theory in its simple form assuming a constant or a linearly varying moisture conductivity does not sufficiently describe the drying of concrete. Better agreement between actual behavior and theory can be accomplished only if the diffusion theory is further modified and if additional assumptions for the variation of the moisture conductivity are made. An "exact" solution would be obtained only if these assumptions are based on thermodynamics and the physical properties of hardened cement paste. However, this is not yet possible on the basis of our present knowledge. Empirical adjustments of the diffusion theory are not much beyond the stage of curve fitting, and thus it appears to be justified, especially in view of the practical applications of the present paper, to abandon the diffusion theory for the time being and to base the prediction of drying of concrete on empirical relationships which best fit the available test results.

The data presented in Figs. 15 to 22 can be very well approximated by the following relationship:

$$\bar{U} = \exp\left[-a\left(\frac{t}{\bar{\ell}^2}\right)^{1/3}\right] \tag{19}$$

if $\bar{U}$ = average liquid concentration

t = drying time

$\bar{\ell}$ = $2V/S$ = equivalent half thickness of drying member

α = coefficient

A similar approach has been used by L'Hermite and Grieux (37). In Eq. 19, $\bar{U}$ is given as a function of $t/\bar{\ell}^2$ rather than t in order to take the effect of the size of the concrete member into account.

In Figs. 18 through 22 the relationship given by Eq. 19 is compared to the experimental results. For each series of tests the coefficient α was chosen such that an optimum agreement with the test data was obtained. In the following, relationships for the coefficient α will be developed on the basis of the main parameters affecting the drying of concrete:

The coefficient α will be governed by two principle factors, (a) The relative humidity φ of the ambient atmosphere as a measure of the "driving force" of the diffusion process, and (b) the permeability of the concrete P_c.

Therefore,

$$\alpha = f(\varphi) \cdot f(P_c) \tag{20}$$

According to the results from Fig. 19 the effect of relative humidity can be approximated by

$$f(\varphi) = K_1 \sqrt{1-\varphi} \tag{21}$$

if K_1 = coefficient

φ = relative humidity

For $\varphi = 1$, $\alpha = 0$ and $\bar{U} = 1.0$, i.e., no drying takes place.

Powers (9) reported that according to Kozeny and Carman the coefficient of permeability K_p of a porous body can be expressed by

$$K_p = k_1\, \epsilon\, M^2 = k_1 \frac{\epsilon^3}{S_p^{\,2}} \tag{22}$$

if k_1 = material constant

ϵ = ratio of pore volume to total volume

$M = \dfrac{\epsilon}{S_p} = \dfrac{\text{pore volume}}{\text{surface of pores}}$

According to Eqs. 5 and 7 the pore volume of the cement paste including capillary and gel pores is

$$V_p = C \cdot v_w \left(\frac{W_o}{C} - 0.18m\right)$$

and

$$\epsilon = \frac{V_p}{V} = \frac{v_w\left(\frac{W_o}{C} - 0.18m\right)}{v_c + \frac{W_o}{C} v_w}$$

if V_p = pore volume of cement paste

V = total volume of cement paste

v_w = specific volume of water

v_c = specific volume of cement

W_o = weight of mixing water

C = weight of cement

m = maturity factor

According to Powers (9), the total surface of capillary pores can be neglected compared to the total surface of the gel pores. Since the total surface of the gel pores is proportional to the amount of hydrated cement

$$S_p \approx k_2 \cdot \frac{m}{v_c + \frac{W_o}{C} \cdot v_w}$$

Then, the coefficient of permeability of cement is according to Eq. 22

$$K_p = k_1 \frac{\epsilon^3}{S_p^2} = \frac{\frac{W_o}{C} - 0.18m}{\left(\frac{W_o}{C} + v_c\right) m^2} \cdot K_2 \qquad (23)$$

if $K_2 = \dfrac{k_1}{k_2}$

Assuming proportionality between α and the coefficient of permeability K_p, we obtain from Eq. 20, 21 and 23

$$\alpha = K_1 K_2 \sqrt{1-\varphi} \frac{\frac{W_o}{C} - 0.18m}{\left(\frac{W_o}{C} + v_c\right) m^2} \qquad (24)$$

In most practical cases of drying of concrete the maturity factor m is not a constant but increases during the drying period. Therefore, in evaluating Eq. 24, m was replaced by m_a, where m_a is the average value between m_o at the beginning of drying and the maximum value m_∞ which would be obtained after an infinitely long drying period:

$$m_a = \frac{m_o + m_\infty}{2}$$

Equation 24 indicates the same tendencies as shown by the test results: the coefficient α increases with increasing water-cement ratio and decreasing maturity. However, Eq. 20 overestimates the effect of maturity and underestimates the effect of the water cement ratio. This may be due to various reasons: (a) As has been pointed out by Powers (9) and others, Eq. 22 does not completely describe the permeability of cement paste since equal weight is given to the capillary and the gel pores. In reality the smaller pores will be less effective in the transmission of water than larger pores. (b) In Eq. 24 no attention has been paid to the over-all properties of the concrete: At high water cement ratios early shrinkage and bleeding of the cement paste may result in large voids or cracks around the aggregates increasing the permeability of the concrete much more than expressed by Eq. 24. On the other hand, for very low water-cement ratios the permeability of the cement paste may be lower than the permeability of the aggregates. Then the permeability of the concrete will be governed mainly by the properties of the aggregate and further reduction of the water cement ratio has little effect on the permeability of the concrete. Finally, concrete of a low water cement ratio generally results in a dry and less workable mix. This may lead to insufficient compaction and thus to an increase of concrete permeability.

Since it was not possible to incorporate all these factors into Eq. 24, an empirical relationship between α_1, m_a and the water cement ratio was developed:

$$\alpha = K_3 \sqrt{1-\varphi} \frac{1 + 15\left(\frac{W_o}{C} - 0.40\right)^2}{m_a} \times 10^{-2} \qquad (25)$$

A coefficient $K_3 = 1.75$ was determined from Fig. 23. Equation 25 de-emphasizes the effect of variations in the water cement ratio for low values of W_o/C while the effect of high water cement ratios is more pronounced compared with Eq. 24. In Table 6 the average liquid concentration $\bar{U}$ after 200 days of drying was computed from Eqs. 19 and 25, and is compared to the experimental results in Fig. 24. Considering all uncertainties in the deviation of Eq. 25, the agreement between theory and experiments is satisfactory.

4.5 The Effect of Carbonation Upon Water Content of Concrete

In the process of hydration of cement, calcium hydroxide is formed. However, concrete exposed to the atmosphere takes up a certain amount of carbon dioxide, which reacts with the calcium hydroxide in the hardened cement paste:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

Thus calcium carbonate is formed, and part of the originally non-evaporable water is freed and may eventually evaporate. The reactions with carbon dioxide are not limited to the calcium hydroxide crystals. The tobermorites may also carbonize (12).

The extent of carbonation of concrete may significantly effect various concrete properties. It does not only change the moisture content but also influences the pore structure, strength and shrinkage of concrete. In addition, carbonized concrete loses its high alkalinity which is necessary for protection of embedded steel against corrosion.

Verbeck (39) and Pihlajavaara (20) studied the carbonation process in concrete and found that the penetration of carbon dioxide follows a very slow diffusion process. The diffusivity constant is in the order of 10^{-12} to 10^{-13} m^2/sec (20). Verbeck (38) showed that the extent of carbonation depends upon the moisture content of concrete, very low or very high values resulting in reduced carbonation. Fortunately, the penetration depth of carbonation is small and normally only the outer layers of a concrete member are affected by carbonation. Pihlajavaara (20) derived a depth of penetration assuming a diffusivity constant of 10^{-12} m^2/sec:

$$L_{0.16} = t^{1/2} \text{ (cm)}$$

and

$$L_{0.89} = 0.1\, t^{1/2} \text{ (cm)}$$

if $L_{0.16}$ = distance from exposed surface in cm at which 16 percent of maximum carbonation took place

$L_{0.89}$ = distance from exposed surface in cm at which 89 percent of maximum carbonation took place

t = time of exposure to carbon dioxide in years.

Thus, after 10 years of exposure that distance from the surface at which carbonation virtually stopped is approximately 3 cm. This is a very conservative estimate since the diffusivity constant for carbonation generally decreases with time. Rehm and Moll (40) examined the depth of carbonation in old reinforced concrete structures using phenolphtaleine as an indicator. They found that even after periods of 30 years the carbonized zone of dense and well compacted concrete did not exceed 1 cm.

Thus carbonation of concrete is significant for experimental studies which are generally carried out on small specimens. However, for the water content of larger concrete sections it is of minor importance and can be neglected.

4.6 The Effect of Temperature Upon the Water Content of Concrete

In all of the foregoing discussions it was assumed that the various processes take place under "normal" temperatures, i.e., in a range of 10 to 30°C (50 to 87F). Since the present paper is primarily directed towards the water content of concrete with respect to weapons shielding this limitation is justified. However, for a more general application e.g. concrete for nuclear reactor vessels, temperature also has to be considered a major and important parameter.

An increase of the temperature generally increases the mobility of the water and thus decreases the equilibrium moisture content and the amount of non-evaporable water. Also the diffusion process and carbonation are accelerated. Unfortunately, conclusive experimental data on the effect of temperature on the water content of concrete are very limited. Pihlajavaara (20) investigated the effect of temperature upon the equilibrium water content of cement paste in the temperature range from 5 to 35°C (35-95°F). According to these tests temperature dependence of the sorption isotherms in this range is so small that it can be neglected in this discussion. No data are available on sorption isotherms for temperatures above 35°C (95°F).

Wilson and Martin (41) reported on the water content of cement paste specimens made of type I cement at temperatures up to 600°C (1112°F). The water-cement ratio and the age of the specimens prior to the temperature treatment were the major variables. Results from this investigation are presented in Fig. 25. There, the water content of the samples after heating exposure for at least 24 hours is given as a function of the temperature. At 600°C almost all of the water evaporated. There is a marked brake in the curves between 300 and 400°C, which is generally associated with a decomposition of calcium hydroxide in this temperature range. In these tests the specimens were dried in a container which was "ventilated by a slow stream of dry carbon-dioxide-free air brought to the oven temperature." The relative humidity is not reported, however, it appears to be a reasonable assumption, that at least above temperatures of 100°C the air was dry enough, so that the water content given in Fig. 25 can be considered the content of non-evaporable water at the given temperature.

In sections 4.1 and 4.3 it was pointed out that the equilibrium water content of hydrated cement paste at zero vapor pressure and 20°C corresponds to the amount of water held by the cement at 105°C under normal pressure conditions. According to Eq. 4 in Section 4.1 the amount of water at 105°C, or the "non-evaporable" water under lower temperatures is

$$W_n = 0.24mC$$

If the maturity factors for type I cement are chosen according to Fig. 5a to compute the amount of non-evaporable water W_n, then values are obtained which are 10 to 40 percent larger than the values shown in Fig. 25. There could be several reasons for this discrepancy: (a) the definition of the non-evaporable water content is not exactly correct (b) the tests reported by Wilson and Martin were carried out in 1929. At this time the fineness of cement was generally much lower than it is today. Therefore, the rate of hydration was slower and consequently the extent of hydration at a given time was below the values shown in Figs. 5a and 5b.

Despite this uncertainty, a general conclusion can be drawn from these tests: In Fig. 26 the ratio of the water content at a given temperature T, W_n^T, to the water content at 105°C, W_n^{105}, is shown as a function of the temperature T. A unique relationship can be given which is independent of the water cement ratio and the curing time prior to heating. This corresponds to previous statements about the structure of cement paste: During the process of hydration the same hydration products are formed at any time, however at different rates. The amount of hydrated cement is proportional to the amount of water held at a temperature of 105°C. Elevated temperatures cause a gradual decomposition of the hydration products. If the type of hydration products is independent of time and original water cement ratio then for a given temperature the same amount of water has to be released for a given amount of hydrated cement. Therefore, the ratio $\bar{T} = W_n^T/W_n^{105}$ has to be independent of water cement ratio, curing time and type of cement.

Since no complete sorption isotherms of concrete at elevated temperatures have been measured experimentally, it is suggested to determine the equilibrium moisture content of concrete at elevated temperatures in the following way:

At temperatures up to 35°C according to Eq. 11:

$$\frac{W_e}{C} = 0.24m + 0.18mX + Y\left(\frac{W_o}{C} - 0.36m\right)$$

At temperatures between 35°C and 105°C:

$$\frac{W_e}{C} = 0.24m + \sqrt{\frac{105-T}{70}}\left[0.18mX + Y\left(\frac{W_o}{C} - 0.36m\right)\right] \quad (26a)$$

above 105°C:

$$\frac{W_e}{C} = 0.24m\bar{T} \tag{26b}$$

Above 105°C it can be assumed that all capillary and gel water evaporates rapidly. Then, the equilibrium water content can be determined by reducing the amount of non-evaporable water at normal temperatures by the coefficient $\bar{T}$ which can be obtained from Fig. 26. There is no direct experimental or theoretical evidence for the equation given for the water content between 35°C and 105°C. Only the limiting values are known and it was assumed that the amount of capillary and gel water held at a given vapor pressure decreases parabolically with an increase of the temperature.

No relationships have been reported between the water content of drying concrete and time at various temperatures. There is little doubt that the rate of water evaporation increases with increasing temperature. For a conservative estimate of the water content of drying concrete at elevated temperatures it is suggested to take only the equilibrium water content into account, i.e., $W_t = W_e$.

The non-evaporable water content of aggregates also decreases with an increase of temperature. The most stable among the minerals with a high water content is serpentine which retains most of its water up to temperatures around 500°C.

In reactor shielding, the water content of a thick concrete member subjected to a temperature gradient may have to be considered. This may lead to a moisture distribution substantially different from the distribution in a concrete member under uniform temperature (50). Experimental evidence of this phenomenon is very limited and further discussion of this problem is beyond the scope of this report.

It has to be pointed out again, that the experimental basis for the relationships given in this section are weak. A thorough study both experimentally and theoretically is urgently needed.

5. Means of Maintaining High Water Content of Concrete

In order to increase the shielding effectiveness of concrete against neutron radiation it is desirable to maintain a high water content over long periods ot time. There are basically two ways to accomplish this:

(a) Ensure a high content of non-evaporable or chemically bound water.
(b) Minimize the evaporation of free water.

5.1 Non-Evaporable Water

A high amount of fixed water can be obtained in various ways. Some naturally occuring minerals exhibit a high hydrogen content. When used as aggregates they can substantially contribute to the fixed water content (4.43). Mostly hydrous ores are used for this purpose:

Type of Aggregate	Water Content in percent of Total Weight
Limonite	6-12%
Geothite	8-12%
Serpentine	10-13%

Limonite and Geothite lose most of their water at temperatures above 200°C. Serpentine is more stable and retains most of its water up to temperatures as high as 500°C.

According to Eq. 11 the amount of non-evaporable water held by the cement paste depends primarily upon the cement content and the maturity or degree of hydration: An increase of both factors results in an increase of non-evaporable water. Increased cement content may have a number of adverse effects. It decreases the economy of the concrete and causes high shrinkage and creep deformations. However, sufficient and prolonged curing of concrete resulting in a high degree of hydration is desirable since it not only ensures a high content of non-evaporable water but also improves other concrete properties such as strength, durability and volume changes. This is of special importance for small concrete members.

It can be seen from Eq. 11 that an increase of the initial water content without a simultaneous increase of the cement content has little effect on the amount of non-evaporable water. Only at a high relative humidity does an increase of the water cement ratio result in an increased amount of equilibrium water content. It has no effect on the water content at elevated temperatures. Generally, good quality has a reasonably high amount of non-evaporable water.

5.2 Minimum Evaporation

According to Eq. 25 in Section 4.44 the moisture conductivity expressed by the coefficient α decreases markedly with a decrease of the water cement ratio and an increase of the degree of hydration. Theoretically, the evaporation of water can be further slowed down by maintaining a high relative humidity of the ambient air and low temperatures of the concrete. However, these factors generally can not be controlled. Evaporation of free water can be reduced by coating the concrete surface with an impermeable layer. Concrete specimens coated with a thin layer of epoxy resin (44) lost 80 to 90 percent less than non-coated specimens. This would correspond to a reduction of the coefficient α in Eq. 25 by a factor of 0.2. A procedure in practical use is to coat concrete with a layer of linseed oil which allows a reduction of the coefficient α by a factor of 0.3 to 0.5. The use of coatings seem to be a promising means of reducing water evaporation. The type of coating used is subject to economical considerations.

6. Experimental Procedures to Determine the Water Content of Hardened Concrete

It has been shown in the previous sections that the water content depends on numerous parameters. Its prediction is difficult and subject to uncertainties even if all major parameters are known and well controlled. Therefore, if a vary accurate knowledge of the water content of concrete is necessary, experimental procedures still seem to be the most reliable approach. A description of various test methods is given in the following.

6.1 Direct Method

The most apparent procedure is to determine the water content of samples taken from the concrete in question. Concrete cores of various sizes may be drilled and the loss on ignition of the sample is an accurate measure of its water content. However, the sample may not necessarily be representative for the concrete of the structure: when drilling a sample, the core is usually cooled with water in order to avoid the development of high temperatures and thus evaporation of water. The cooling on the other hand increases the water content of the surface layers of the core. However, for a dense concrete the depth of penetration of the cooling water usually is less than a few millimeters. If small samples are taken from the surface of a structure then the moisture gradient of the structure is not being taken into account and the carbonation of the concrete fibers close to the drying surface may falsify the results. Therefore, this direct method can give reliable results only if the samples are comparatively large. Many structures therefore will not permit the application of this method (45).

6.2 Indirect Methods

6.21 Relative Humidity

An electrical resistance probe has been developed by Monfore (46) which allows the determination of the relative humidity inside a concrete specimen. In applying this procedure small holes with a diameter of approximately 5 mm, in which the gage may be inserted have to be drilled into the concrete. If these holes are drilled to different levels, the humidity distribution across a concrete member can be determined. The gage has to be calibrated in media of known humidity and its accuracy is 3 to 5 percent. However, the relationship between water content and relative humidity is not linear. In order to determine the water content of concrete, at least the maturity factor has to be estimated and then the water content may be calculated from Eq. 11 in Section 4.3. This procedure does not take into account the water content of aggregates.

6.22 Electrical Properties

Various attempts have been made to utilize the fact that the electrical conductivity of concrete increases with increasing water content (46). However, the electrical conductivity is also influenced by other factors than moisture content such as degree of maturity and type of aggregates so that no reliable procedures and instruments can be recommended at the present. The same holds true for attempts to relate variations of the dielectric constant of concrete to its water content.

6.23 Microwave Absorption

The extent to which electromagnetic waves with a wave length of a few centimeters are attenuated in concrete depends on the water content of concrete (47). However, since the attenuation is also affected by the mix proportions of the concrete, this procedure can be used only to measure variations of a particular type of concrete of known original composition.

6.3 Radiation Methods

Gamma radiation is sometimes applied to measure density of concrete. Since evaporation of water from concrete decreases its density, gamma ray transmission or gamma ray scattering can be used to measure the loss of water of a drying concrete. Obviously, this procedure is a good indication of the water content of concrete only if the original water content and the original density of the concrete (or original transmission factor) are known.

Neutron scattering techniques using fast neutron sources and a thermal neutron detector have been frequently used as a measure of the water content of concrete (48). A serious disadvantage of this procedure is that the results may be affected to some extent by other elements. The counting rate is also affected by the chemical bonding of the hydrogen atoms, because of the effect of the latter on thermal neutron cross-sections; and thus it is not always a true measure of the water content of concrete. Preiss and Grant (48) showed, however, that these difficulties may be minimized by covering the neutron detector with cadmium, which has a cut-off energy of 0.4 ev. Thus the effects of other elements and of the chemical bonding of the hydrogen atoms can be practically eliminated. Since neutron scattering is related to the hydrogen rather than to the content of free water this procedure will also cause inclusion of the hydrogen content of the aggregates. The neutron scattering technique can be successfully applied only if the distance between source and detector is less than 15 cm. Its application is therefore restricted to smaller concrete sections. Nevertheless, at the present it appears to be the most reliable experimental procedure for the determination of the hydrogen content of hardened concrete.

7. Summarized Presentation and Practical Application of a Method to Predict the Water Content of Hardened Concrete

In this section the various steps to estimate the water content of concrete are summarized. Distinction will be made between the following three cases:

(a) original mix proportions, curing and exposure conditions of the concrete are known.

(b) the exposure conditions of the concrete are known but the mix proportions are unknown.

(c) guiding values for a conservative estimate of the water content of concrete.

7.1 Estimate of the Water Content of Concrete for Given Mix Proportions and Environmental Conditions

The following <u>material properties</u> of the concrete should be known:

Type of Cement

W_o = original water content in kg/m^3

W_{an} = content of non-evaporable water of aggregates in kg/m^3

C = cement content in kg/m^3

$\frac{W_o}{C}$ = water-cement ratio

$\frac{W_{an}}{A}$ = water content of aggregate per unit weight of aggregate

$\frac{A}{C}$ = aggregate-cement ratio

$\bar{\ell} = \frac{2V}{S}$ = equivalent thickness of the drying concrete member

if V = volume of the concrete in m^3

S = drying surface of the concrete in m^2

For an infinitely long cylinder or square bar, $\bar{\ell}$ is equal to the radius or the half thickness of the body. For a slab drying in two directions, $\bar{\ell}$ is equal to the thickness of the slab.

The following <u>Exposure Conditions</u> of the concrete should be known:

d_c = period of moist curing prior to drying in days

If the temperature during the curing period deviates considerably from 20°C (68°F), then an equivalent curing period has to be computed from the following relationships:

$$d_e = \frac{\Sigma \Delta d(T + 10)}{30} \tag{10}$$

if d_e = equivalent curing period

Δd = days under temperature T_c

T_c = curing temperature in ^{o}C

φ = average relative humidity = relative vapor pressure of the air surrounding the drying concrete member

T = average temperature of the surrounding air during drying

7.11 Initial Water Content of Fresh Concrete

The water in fresh concrete, W_{of}, consists of the mixing water W_o, and of the water held by the aggregates which may be either evaporable (W_a) or non-evaporable (W_{an}):

$$W_{of} = W_o + W_a + W_{an} \tag{2}$$

or

$$W_{of} = C \left[\frac{W_o}{C} + \frac{W_a + W_{an}}{A} \cdot \frac{A}{C}\right]$$

For normal aggregates the amount of non-evaporable water W_{an} generally is small and therefore negligable. The evaporable water content of aggregates W_a consists of water in the pores of aggregates. For normal aggregates it ranges from 0.5 to 3 percent by weight of the concrete. Because of the high aggregate cement ratios of most concretes, the absorbed water W_a is considerable and has to be taken into account in mix design in order to assure the desired water cement ratio of the cement paste W_o/C. However, since in most cases the pores in aggregates are much larger than the pores in the cement paste, the amount of evaporable water held by the aggregates of hardened and drying concrete is small. Therefore, for a conservative estimate of the water content of concrete, only the mixing water W_o will be taken into account:

$$W_{of} = W_o$$

7.12 Water Content of Hardened Concrete at Moisture Equilibrium

Concrete exposed to an atmosphere of a given relative humidity dries until its internal moisture is in equilibrium with the surrounding atmosphere. This equilibrium water content of concrete, W_e, constitutes the minimum water content of concrete at a given age d and for given environmental conditions.

The equilibrium water content of the concrete can be computed from

$$W_e = C\left[m(0.24 + 0.18X) + Y\left(\frac{W_o}{C} - 0.36m\right)\right] \qquad (11)$$

if W_e = equilibrium water content of concrete at a given age, d, in kg/m^3

C = cement content of concrete in kg/m^3

X = ratio of weight of gel water in the cement paste at a given relative humidity, φ, to the weight of gel water at saturation

Y = ratio of weight of capillary water in the cement paste at a given relative humidity, φ, to the weight of capillary water at saturation

m = maturity factor at a given age, d.

For a given relative humidity, values for X and Y can be obtained from Figure 8. In Figures 5a and 5b the maturity factor m is given as a function of the age of concrete d, the equivalent thickness of the drying member, $\bar{\ell}$ and the relative humidity of the concrete, φ. In the derivation of the relationships in Figs. 5a and 5b it was assumed that the concrete was initially moist cured over a period of 7 days, i.e., $d_c = 7$. This is common practice in concrete construction. If the temperature during curing or during drying deviates considerably from 20°C then an equivalent age of concrete d_e should be computed according to Eq. 10.

7.13 Water Content of Hardened Concrete During the Drying Period

The average water content of a drying concrete member before it reaches a state of equilibrium, can be computed from the following expression

$$W_t = W_e + \bar{U}(W_o - W_e) \qquad (16)$$

if W_t = water content of concrete in kg/m^3 after t days of drying

W_e = equilibrium water content of concrete in kg/m^3 according to Eq. 11 at a given age d

W_o = initial water content of concrete, i.e., amount of mixing water in kg/m^3

$\bar{U}$ = average liquid concentration of concrete after t days of drying

The average liquid concentration $\bar{U}$ indicates how much of the water which is evaporable at a given relative humidity is still held by the concrete. At the beginning of drying $t = 0$, $\bar{U} = 1.0$ and $W_t = W_o$. After the concrete reached equilibrium with the surrounding atmosphere $\bar{U} = 0$ and $W_t = W_e$.

The variation of $\bar{U}$ with the drying time t can be approximated by the following exponential function:

$$\bar{U} = \exp\left[-\alpha \left(\frac{t}{\bar{\ell}^2}\right)^{1/3}\right] \qquad (19)$$

if t = duration of drying in days

$\bar{\ell} = \frac{2V}{S}$ = equivalent thickness in m

α = coefficient

The coefficient α depends on the water cement ratio, the relative humidity of the surrounding atmosphere and maturity factor during the drying period:

$$\alpha = 1.75 \times 10^{-2} \sqrt{1-\varphi}\, \frac{1 + 15\left(\frac{W_o}{C} - 0.40\right)^2}{m_a} \qquad (25)$$

if φ = relative humidity

$\frac{W_o}{C}$ = water cement ratio

$m_a = \frac{m_o + m_\infty}{2}$, where m_o = maturity factor at beginning of drying

m_∞ = maturity factor at end of drying

7.14 Effect of Elevated Temperatures

The equilibrium water content W_e decreases with increasing temperatures T. For $T < 35^\circ C$, W_e can be computed according to Eq. 11. For $35^\circ C < T < 105^\circ C$ the following relationship for W_e is proposed:

$$W_e = 0.24mC + \sqrt{\frac{105-T}{70}}\left[0.18mX + Y\left(\frac{W_o}{C} - 0.36m\right)\right] \qquad (26a)$$

if T = temperature in $^\circ C$

For temperatures above $105^\circ C$:

$$W_e = C \times 0.24m \times \bar{T} \qquad (26b)$$

The coefficient $\bar{T}$ depends on the temperature T and can be taken from Fig. 26.

Since elevated temperatures considerably accelerate the process of drying, it is suggested to assume for a conservative estimate of the water content of concrete at elevated temperatures that $W_t = W_e$.

7.15 Aggregates Containing Non-Evaporable Water

If special aggregates are used which contain an appreciable amount of non-evaporable water, then the equilibrium water content of the concrete is

$$W_{ea} = W_e + W_{an} + C \cdot \frac{A}{C} \cdot \frac{W_{an}}{A} \qquad (11a)$$

if W_{ea} = equilibrium moisture content of concrete containing aggregates with non-evaporable water

W_e = equilibrium moisture content of concrete without moisture content of aggregates (Eq. 11)

$\frac{W_{an}}{A}$ = non-evaporable water in aggregates per unit weight of aggregates

$\frac{A}{C}$ = Aggregate cement ratio

The water content at time t is

$$W_{ta} = W_{ea} + \bar{U}(W_o - W_e) \qquad (27)$$

The average liquid concentration $\bar{U}$ is independent of the moisture in the aggregates and can be computed from Eq. 19.

For $\bar{U} = 1$:

$$W_{ta} = W_o + W_{an}$$

For $\bar{U} = 0$:

$$W_{ta} = W_e + W_{an}$$

7.16 Practical Applications

Example I:

A concrete wall 20 cm thick is initially moist cured over a period of 7 days and then exposed to drying at an average relative humidity of 70 percent and at an average temperature of 20°C.

The following materials and mix proportions are given:

Type of cement: type I

Water-cement ratio: $W_o/C = 0.55$

Aggregate-cement ratio: $A/C = 5.0$

Cement content: $C = 340\ \mathrm{kg/m^3}$

Non-evaporable water in aggregates $\frac{W_{an}}{A} = 0.03$

Question 1: Estimate the water content of the concrete after 100 days and after 5 years of drying, respectively, if the water content of aggregates is neglected:

(a) characteristic thickness of member:

$$\bar{\ell} = \frac{2V}{S} = 0.20\mathrm{m}$$

(b) equilibrium water content:

from Figure 5a for $\varphi = 0.70$ and $\bar{\ell} = 0.20$
after 100 days: $m_{100} = 0.85$
after 5 years $m_{5\ years} = 0.95$
according to Figure 8 for $\varphi = 0.70$

$$x = 0.70;\ Y = 0.10$$

Then from Eq. 11, $W_e = C\left[m\ (0.24 + 0.18X) + Y\left(\frac{W_o}{C} - 0.36m\right)\right]$

after 100 days: $W_e = 340\left[0.85\ (0.24 + 0.18 \times 0.70) + 0.10\ (0.55 - 0.36 \times 0.85)\right]$

$= 114\ \mathrm{kg/m^3}$

after 5 years: $W_e = 126\ \mathrm{kg/m^3}$

(c) average liquid concentration $\bar{U}$ according to Eqs. 19 and 25:

$$\bar{U} = \exp\left[-\alpha\left(\frac{t}{\bar{\ell}^2}\right)^{1/3}\right]$$

and

$$\alpha = 1.75 \times 10^{-2}\sqrt{1-\varphi}\ \frac{1 + 15\left(\frac{W_o}{C} - 0.40\right)^2}{m_a}$$

if

$$m_a = \frac{m_o + m_\infty}{2}$$

From Figure 5a:

$$m_o = 0.55$$

$$m_\infty = 0.95$$

$$m_a = 0.75$$

$$\alpha = 1.75 \times 10^{-2} \sqrt{(1-0.70)} \frac{1 + 15\ (0.55 - 0.40)^2}{0.75} = 1.75 \times 10^{-2}$$

after 100 days: $\left(\frac{t}{\bar{\ell}^2}\right)^{1/3} = \left(\frac{100}{0.2^2}\right)^{1/3} = 15.8; \quad \bar{U} = 0.76$

after 5 years: $= \left(\frac{1820}{0.2^2}\right)^{1/3} = 34.77; \quad \bar{U} = 0.54$

(d) Water content W_t:

according to Eq. 16: $W_t = W_e + \bar{U}(W_o - W_e)$

after 100 days: $W_t = 114 + 0.76\ (187 - 114)$
$= 169\ \mathrm{kg/m^3}$

after 5 years: $W_t = 126 + 0.54\ (187 + 126)$
$= 159\ \mathrm{kg/m^3}$

Question 2: Estimate the water content of concrete after 5 years of drying if the content of non-evaporable water of aggregates is not neglected.

(a) equilibrium water content:

according to Eq. 11a $W_{ea} = W_e + C \cdot \frac{A}{C} \cdot \frac{W_{an}}{A}$

$= 126 + 340 \times 5.0 \times 0.03$

$= 177\ \mathrm{kg/m^3}$

(b) Moisture content W_{tn}

according to Eq. 27 $W_{tn} = W_{ea} + \bar{U}(W_o - W_e)$

$= 177 + 0.54\ (187 - 126)$

$= 210\ \mathrm{kg/m^3}$

Question 3: Estimate the water content of concrete if after 1 year of drying the temperature is increased to 200°C and the content of non-evaporable water of aggregates is not neglected.

Because of the accelerated drying process of high temperatures only the equilibrium water content will be considered. Then, according to Eq. 26b

$$W_e = C \times 0.24m \times \bar{T}$$

from Figure 5a: after 1 year $m = 0.93$
from Figure 23 at 200°C: $\bar{T} = 0.72$

$$W_e = 34- \times 0.24 \times 0.93 \times 0.72 = 55 \text{ kg/m}^3$$

according to Eq. 11a: $W_{ea} = 55 + 340 \times 5.0 \times 0.03 = 106 \text{ kg/m}^3$

If the amount of non-evaporable water in the aggregates is also temperature dependent, then a corresponding adjustment in the value for W_{an}/A has to be made.

7.2 Estimate of the Water Content of Concrete Whose Original Mix Proportions are Unknown

Even if the original mix proportions of the concrete are unknown, it is still possible to make a reasonable guess of the water content of a concrete member. However, it has to be assumed that good engineering practice has been maintained in manufacturing the concrete member.

The amount of mixing water W_o depends primarily on the required workability and the maximum aggregate size of the fresh concrete. It can be approximated by the following relationship:

$$W_o = a_1 - b_1 \cdot \lg_{10} S_a \qquad (1)$$

where W_o = mixing water in kg/m^3

S_a = maximum aggregate size of concrete in cm

$a_1; b_1$ = coefficients given in Table 1 for various consistencies of fresh concrete.

The consistency of a concrete mix usually is chosen according to the type of structure as shown in Table 7 (2).

The maximum aggregate size depends on the dimension of the concrete section and the presence and spacing of reinforcement: For reinforced concrete it shall not exceed one-fifth of the smallest dimension of the concrete member nor shall it be larger than three-fourths of the minimum clear spacing between reinforcing bars. For plain concrete it shall not exceed one-third of the minimum dimension of the structure. But consideration also has to be given to the available materials: In normal building construction the maximum aggregate size usually does not exceed 3.0 to 4.0 cm (1-1/2 in) even if the dimensions of the cross-section would permit this.

The water-cement ratio and the cement content of concrete are governed by strength and durability requirements. The relationship between strength and water-cement-ratio can be approximated by the following expression:

$$W_o/C = \frac{a_2}{f'_c + c_2} - b_2 \qquad (3)$$

if f'_c = compressive strength of concrete after 28 days in kg/cm^2

$a_2; b_2; c_2$ = coefficients depending on type of cement and air entrainment as given in Table 5

Unfortunately, the strength required for a certain type of structure or structural member may vary over a wide range. However, in many instances it will be possible to trace back the design strength of the structural member in question. Then, the water cement ratio can be calculated from Eq. 3.

It is likely that type III cement has been used in comparatively thin concrete sections when a high concrete strength was required already after a few days. Air-entrainment generally is being used when the concrete member is exposed to freezing and thawing. In this case the water-cement ratio of the concrete may be less than computed from Eq. 3. The maximum allowable values of the water-cement ratio to ensure sufficient frost resistance are given in Table 4.

If the design strength of the concrete member is unknown, then the water cement ratio of the concrete may be estimated from Table 8 depending on the type of the structural member and the exposure conditions. From this table it can be seen that water cement ratios above $W_o/C = 0.60$ are unlikely whenever the concrete member is exposed to a wide range in temperatures.

<u>Example II</u>

Determine the water content of an unreinforced concrete wall 20 cm thick 5 years after it has been cast. The design strength of the wall was 300 kg/cm^2 (4250 psi) and only mild temperatures and a moderately dry climate have to be expected during the life time of the structure.

(a) maximum aggregate size: $\frac{20}{3} = 6.7$ cm

assume 1.5 in. (3.8 cm)

(b) According to Table 7 the consistency of the concrete is stiff to plastic; no air-entrainment is used because of moderate temperatures.

(c) Amount of mixing water according to Eq. (1)

$W_o = a_1 - b_1 \lg_{10} S_a$

$S_a = 3.8$ cm

$a_1 = 208$ (from Table 1)

$b_1 = 83$

$W_o = 160$ kg/m^3

(d) Water-cement ratio from Eq. 3

$$W_o/C = \frac{a_2}{f'_c + c_2} - b_2$$

$f'_c = 300$ kg/cm^2 (4250 psi)

$a_2 = 500$ (From Table 5, assume Type I cement)

$b_2 = 0.34$

$c_2 = 225$

$W_o/C = 0.61$

$C = \frac{160}{0.61} = 262$ kg/m^3

(e) equilibrium water content

assume that the concrete was moisture cured for 7 days. The characteristic thickness $\bar{\ell} = \frac{2V}{S} = 0.20$m and $\varphi \sim 0.70$.

According to Figure 5a: $m_7 = 0.55$

$m_{5\ \text{years}} = 0.95$

From Figure 8 for $\varphi = 0.70$ $X = 0.70$; $Y = 0.10$

According to Eq. (7) $W_e = 254 \left[0.95(0.24 + 0.18 \times 0.70) + 0.10\,(0.61 - 0.36 \times 0.95)\right]$

$W_e = 95$ kg/m^3

(f) average liquid concentration from Eqs. 15 and 21

$$m_a = \frac{0.55 + 0.95}{2} = 0.75$$

$$\alpha = 1.75 \times 10^{-2} \sqrt{1-0.70}\, \frac{1+15(0.61-0.40)^2}{0.75} = 2.1 \times 10^{-2}$$

$$\left(\frac{t}{\ell^2}\right)^{1/3} = 34.77; \quad \bar{U} = 0.48$$

(g) Water content after 5 years according to Eq. 12

$$W_t = 95 + 0.48\,(160-95)$$

$$W_t = 126 \text{ kg/m}^3$$

7.3 Guiding Values of the Moisture Content of Various Types of Concrete Structures

If because of lack of information about mix proportions and environmental conditions of the concrete it is not justified to carry out detailed calculations of the water content of concrete, then conservative estimates may be taken from Table 9. The values given therein have been computed under the assumption that the concrete is exposed to temperatures less than 45°C (110°F) and that the water content of aggregates is negligible. For higher temperatures the user of this table is referred to the corresponding chapter of this report. If the content of non-evaporable water of aggregates is known it can be simply added to the values given in Table 9.

A distinction has been made between the following five climatic conditions:

	Climate	Temperature	Relative Humidity
(a)	Hot and Dry	20 to 45°C (68 to 100°F)	< 50%
(b)	Hot and Humid	20 to 45°C (68 to 110°F)	80 to 100%
(c)	Wide range in Temperatures - Moderately Dry	-25°C to 40°C (-10 to 100°F)	60 to 90%
(d)	Mild Temperatures Moderately Dry	15°C to 25°C (60 to 80°F)	60 to 90%
(e)	Mild Temperatures and Humid	15°C to 25°C (60 to 80°F)	80 to 100%

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APPENDIX I: METRIC UNITS AND THEIR EQUIVALENTS IN THE US-SYSTEM

1 kg = 2.20 lbs.

1 cm = 0.394 in.

1 m^3 = 1.31 yd^3

1 kg/m^3 = 0.001g/cm^3 = 2.02 lbs/yd^3

1 kg of water/m^3 = 0.202 gal/yd^3

water cement ratio kg/kg = 11.25 gal/bags of cement

1 kg/cm^2 = 14.2 psi

Temperature in ^{o}C = $\frac{^oF - 32}{1.8}$

APPENDIX II: NOTATIONS

The notations and symbols used in this report also have been defined in the text when first introduced.

a_1 = coefficients in Eq. 1

a_2; b_2; c_2 = coefficients in Eq. 3

d = age of concrete

d_c = age of concrete at end of curing

f'_c = compressive strength of concrete

k = moisture conductivity

k_e = basic moisture conductivity

k_1; k_2 = coefficients used in deriving Eq. 24

ℓ = half-thickness of drying member

$\bar{\ell}$ = $\frac{2V}{S}$ = equivalent thickness of drying member

n = A_{cd}/A_c

m = maturity factor = ratio of weight of hydrated cement to total weight of cement

r_o = radius of cylinder

r = distance of a point within a cylinder from center line of cylinder

t = drying time

v_c = specific volume of cement

v_w = specific volume of free water

v_{wn} = specific volume of non-evaporable water in cement paste

x; y; z = cartesian coordinates

A = aggregate content of concrete

A_c = total area of concrete member

A_{cd} = area of drying concrete member with relative humidity above 85 percent

C = total cement content of concrete

F_o = kt/ℓ^2 = Fourier number

H = Desiccation

K_1; K_2 = coefficients used in deriving Eq. 24

K_3 = coefficient used in deriving Eq. 25

P = potential

P_c = permeability of concrete

S = drying surface of concrete member

S_a = maximum aggregate size of concrete

S_p = surface of pores

T = temperature

$\bar{T}$ = coefficient to describe effect of temperature on non-evaporable water content of concrete

U = liquid concentration in drying member at a given time and at a given point

$\bar{U}$ = average liquid concentration

V = volume of concrete member

V_g = volume of cement gel

V_p = total pore volume of concrete

V_{pg} = volume of gel pores

V_{pc} = volume of capillary pores

W_a = free water in aggregates

W_{an} = non-evaporable water content of aggregates

W_e = equilibrium water content

W_{ea} = equilibrium water content of concrete containing aggregates with non-evaporable water

W_g = gel water content of cement paste

W_n = non-evaporable water content of cement paste

W_o = weight of mixing water in concrete

W'_o = water content of saturated cement paste

W_{of} = total water content of fresh concrete

W_t = average moisture content at time t

W_{ta} = average moisture content at time t of concrete containing aggregates with non-evaporable water

W_{ti} = moisture content at a given point at time t

X = ratio of weight of gel water at a given relative vapor pressure to weight of gel water at saturation

Y = ratio of weight of capillary water at a given relative vapor pressure to weight of capillary water at saturation

α = coefficient describing diffusion of moisture in concrete

ϵ = pore volume of porous medium

φ = relative humidity = relative vapor pressure

θ = r/r_o

Table 1: Mixing Water of Fresh Concrete, W_o.

Coefficients for Equation 1

$$W_o = a_1 - b_1 \cdot \lg_{10} S_a$$

W_o = Water content in kg/m^3

S_a = max. aggregate size in cm

	No Air Entrainment		Air Entrainment	
Consistency	a_1	b_1	a_1	b_1
stiff	208	83	188	88
plastic	230	93	206	90
fluid	234	97	218	93

Table 2: Content on Non-Evaporable Water of Minerals Commonly Found in Concrete Aggregates

Type of Mineral	Water Content in % by weight	Type of Mineral	Water Content % by weight
Limestone	0 - 4.0	Gabbro	0.1 - 0.9
Dolomite	0 - 0.5	Basalt	0.2 - 1.5
Sandstone	0.2 - 2.0	Diabase	0.2 - 1.5
Quartzites	0 - 1.0	Porphyrites	0.8 - 2
Granite	0 - 0.9	Slate	0.5 - 9
Gneiss	0.3 - 1.5	Limonite*	6 - 12
Syemite	0.2 - 2.0	Geothite*	8 - 12
		Serpentine*	10 - 13

*Hydrous ores, used as concrete aggregates only if a very high content of non-evaporable water is required.

Table 3: Absorption Capacity of Aggregates

Type of Aggregate	Water Content % by weight
Limestone	0.5 - 1.5
Sandstone	1 - 7
Quartzites	0.2 - 2.0
Granites	0.2 - 4.0
Basalts	0.1 - 0.7
Various River Gravels	0.6 - 5.0

Table 4: Maximum Water-Cement Ratios to Ensure Sufficient Durability of Concrete (from Ref. 2)

Water cement-ratio by weight
Exposure Conditions:

Type of Structure	Severe wide range of temperature			Mild temperatures, rarely below freezing		
	In Air	In Fresh Water	In Sea Water	In Air	In Fresh Water	In Sea Water
Thin reinforced concrete sections	0.50	0.45	0.40	0.55	0.50	0.40
Moderate sections such as retaining walls, abutments, girders, beams	0.55	0.50	0.45	≤0.80	0.55	0.45
Exterior portions of mass concrete	0.60	0.50	0.45	≤0.80	0.55	0.55
Concrete slabs laid on the ground	0.55	-	-	≤0.80	-	-
Concrete protected from weather such as in interior of buildings or below ground	≤0.80	-	-	≤0.80	-	-

Table 5: Cement Content of Concrete

Coefficients for Equation 3

$$f'_c = \frac{a_2}{W_o/C + b_2} - c_2$$

f'_c = compressive strength in kg/cm^2

W_o/C = water-cement ratio by weight

Type of Cement	No Air Entrainment			Air Entrainment		
	a_2	b_2	c_2	a_2	b_2	c_2
Type I	500	0.34	225	1220	0.79	660
Type III	570	0.37	250	1000	0.61	560

Table 6: Experimental Data from Tests on Drying of Concrete

Reference No.	Specimen Size		W_o/C	C	Type of cement	Length of curing period	Rel. Humidity φ	α 10^{-2}	$\bar{U}$ after 200 days	
	cross-section	length							measured	computed
	m	m	-	kg/m^3		days			-	-
36	Ø0.10	0.80	0.55	334	III	7	0.65	1.69	0.66	0.63
	Ø0.10	0.80	0.45	345	I	7	0.65	1.49	0.60	0.67
	Ø0.10	0.80	0.55	334	I	7	0.65	1.93	0.57	0.59
	Ø0.10	0.80	0.65	328	I	7	0.65	2.79	0.38	0.47
37	0.07/0.07	0.28	0.565	300	I	1	0.75	2.20	0.32	0.30
	0.07/0.07	0.28	0.565	300	I	1	0.50	3.46	0.18	0.15
	0.07/0.07	0.28	0.565	300	I	1	0.35	3.94	0.08	0.11
37	0.07/0.07	0.28	0.565	300	I	1	0.50	3.16	0.17	0.18
	0.07/0.07	0.28	0.565	300	I	2	0.50	2.46	0.23	0.26
	0.07/0.07	0.28	0.565	300	I	90	0.50	2.10	0.30	0.40
38	Ø0.10	0.80	0.55	337	III	1	0.65	2.18	0.66	0.55
	Ø0.10	0.80	0.55	337	III	3	0.65	1.85	0.70	0.60
	Ø0.10	0.80	0.55	337	III	7	0.65	1.70	0.72	0.63
	Ø0.10	0.80	0.55	337	III	28/90	0.65	1.43	0.73	0.68

Table 7: Consistency of Fresh Concrete

Type of Structure	Consistency
Reinforced foundation walls and footings	plastic
Unreinforced walls and footings	stiff to plastic
Reinforced slabs, beams and walls	plastic to fluid
Building columns	plastic to fluid
Pavements	stiff
Other slabs on the ground	plastic
Mass concrete	stiff

Table 8: Water Cement Ratio for Various Types of Structural Concrete Members

Type of Structure	Water Cement Ratio by Weight Exposure Conditions Severe wide range of temperature	Mild temperatures, rarely below freezing
Reinforced foundations walls and footings	0.45-0.55	0.60-0.80
Unreinforced foundations and footings	0.60-0.80	0.70-0.80
Reinforced slabs and beams in residential buildings	0.45-0.55	0.60-0.75
Slabs and beams in heavily loaded structures	0.40-0.55	0.40-0.60
Building columns heavily loaded	0.40-0.55	0.40-0.60
Reinforced walls	0.45-0.55	0.60-0.80
Pavements	0.40-0.60	0.50-0.70
Other slabs on the ground	0.50-0.55	0.70-0.80
Mass concrete	0.45-0.60	0.60-0.80

Table 9: Estimated Values of the Moisture Content of Concrete W_t in kg/m^3

Type of Structural Member	Size of Member	Hot and Dry		Hot and Humid		Wide range in temperatures, moderately dry		Mild temperatures rarely below freez., moderately dry		mild temp. and humid	
	$\bar{\ell}$ in (m)	after one year	Ten years	One year	Ten years	One year	Ten years	One year	Ten years	One year	Ten years
Foundations	0.20	110	90	160	140	150	140	130	110	160	140
	0.60	140	110	170	160	160	150	150	130	170	160
Moderately loaded slabs, beams and columns	0.10	140	110	170	160	160	150	140	130	170	160
	0.50	160	140	180	170	170	160	160	150	180	170
Heavily loaded slabs, beams and columns	0.10	150	130	170	150	160	150	150	140	170	160
	0.50	160	150	180	170	170	160	170	160	180	170
Walls	0.10	110	90	160	150	150	140	130	110	160	140
	0.50	140	110	170	160	160	150	150	140	170	160
Mass Concrete	1.00	120	100	140	130	140	130	130	120	135	130
	5.00	130	120	145	135	145	135	135	130	140	135

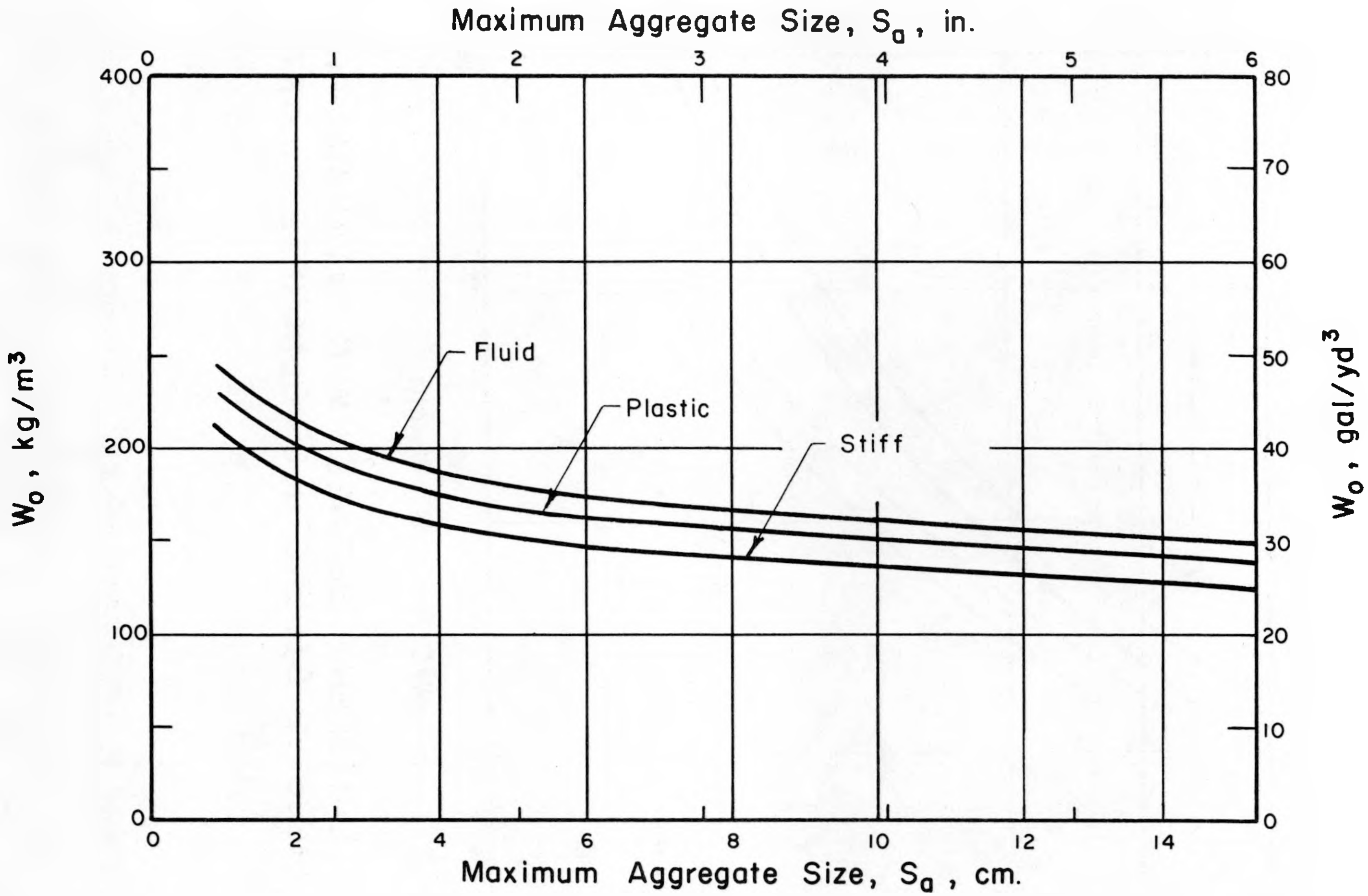

FIG. 1 MIXING WATER OF FRESH CONCRETE W_0 AS A FUNCTION OF THE MAXIMUM AGGREGATE SIZE. NON-AIRENTRAINED CONCRETE.

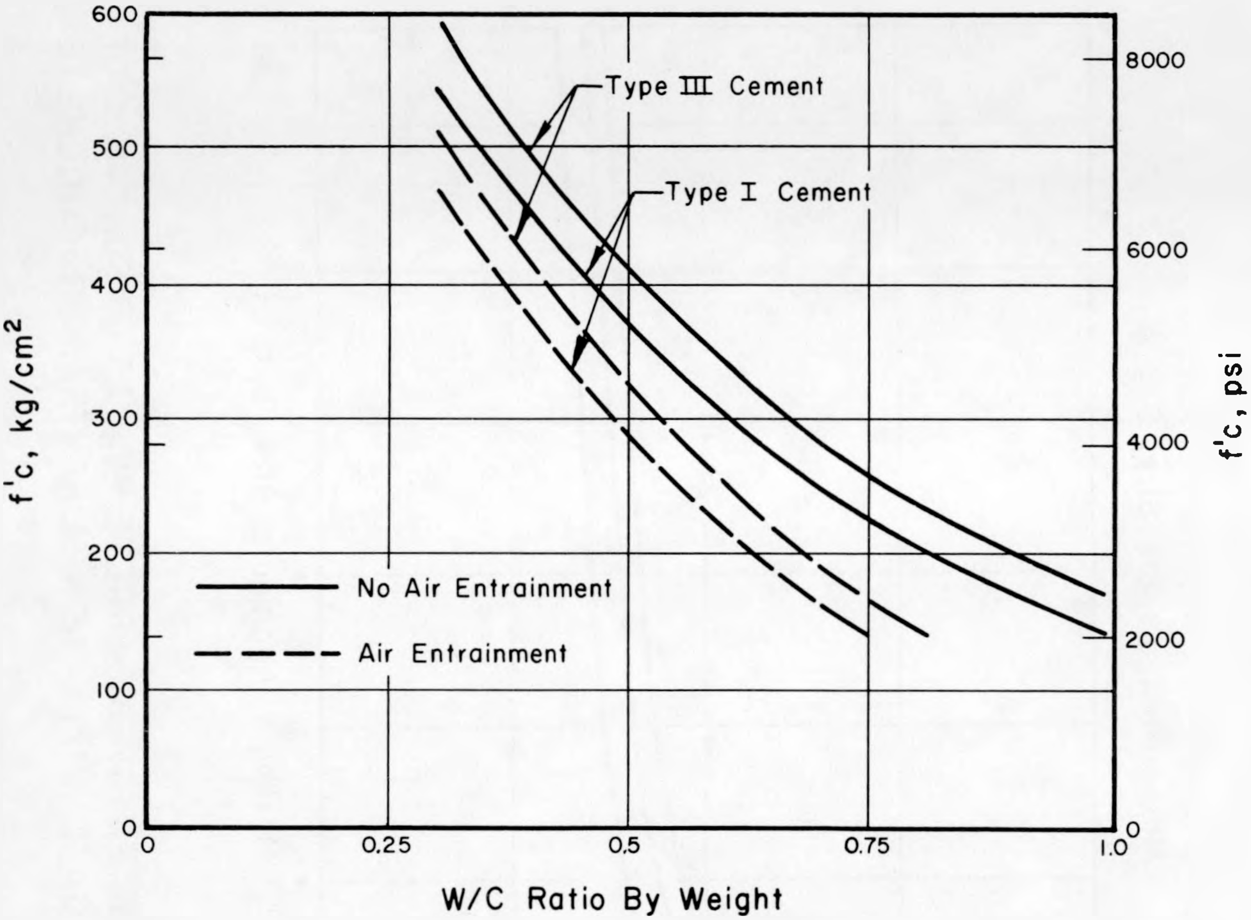

FIG. 2 RELATIONSHIP BETWEEN W/C RATIO AND COMPRESSIVE STRENGTH OF CONCRETE f'c AFTER 28 DAYS

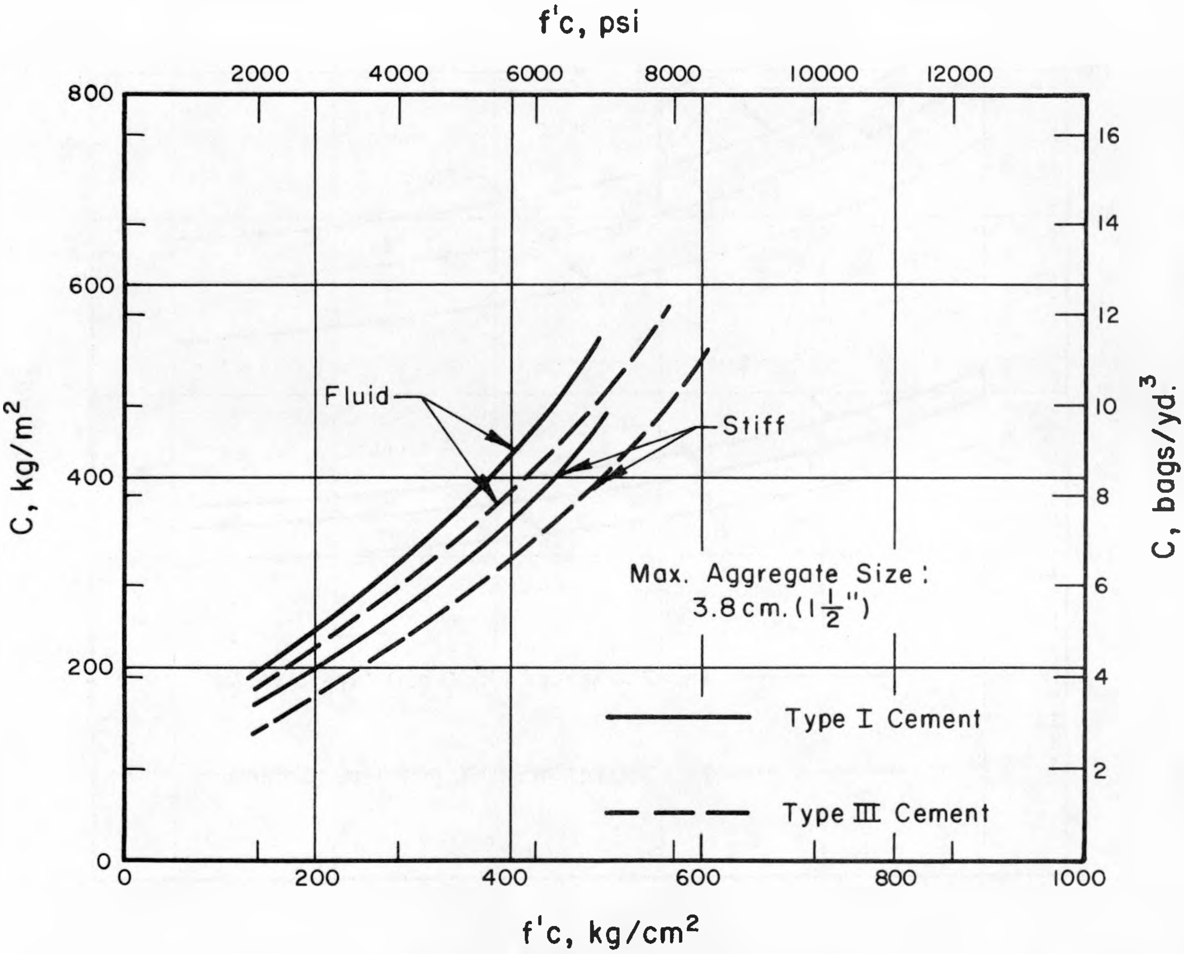

FIG. 3 CEMENT CONTENT, C, OF CONCRETE WITHOUT AIR ENTRAINMENT AS FUNCTION OF ITS COMPRESSIVE STRENGTH f'c AFTER 28 DAYS

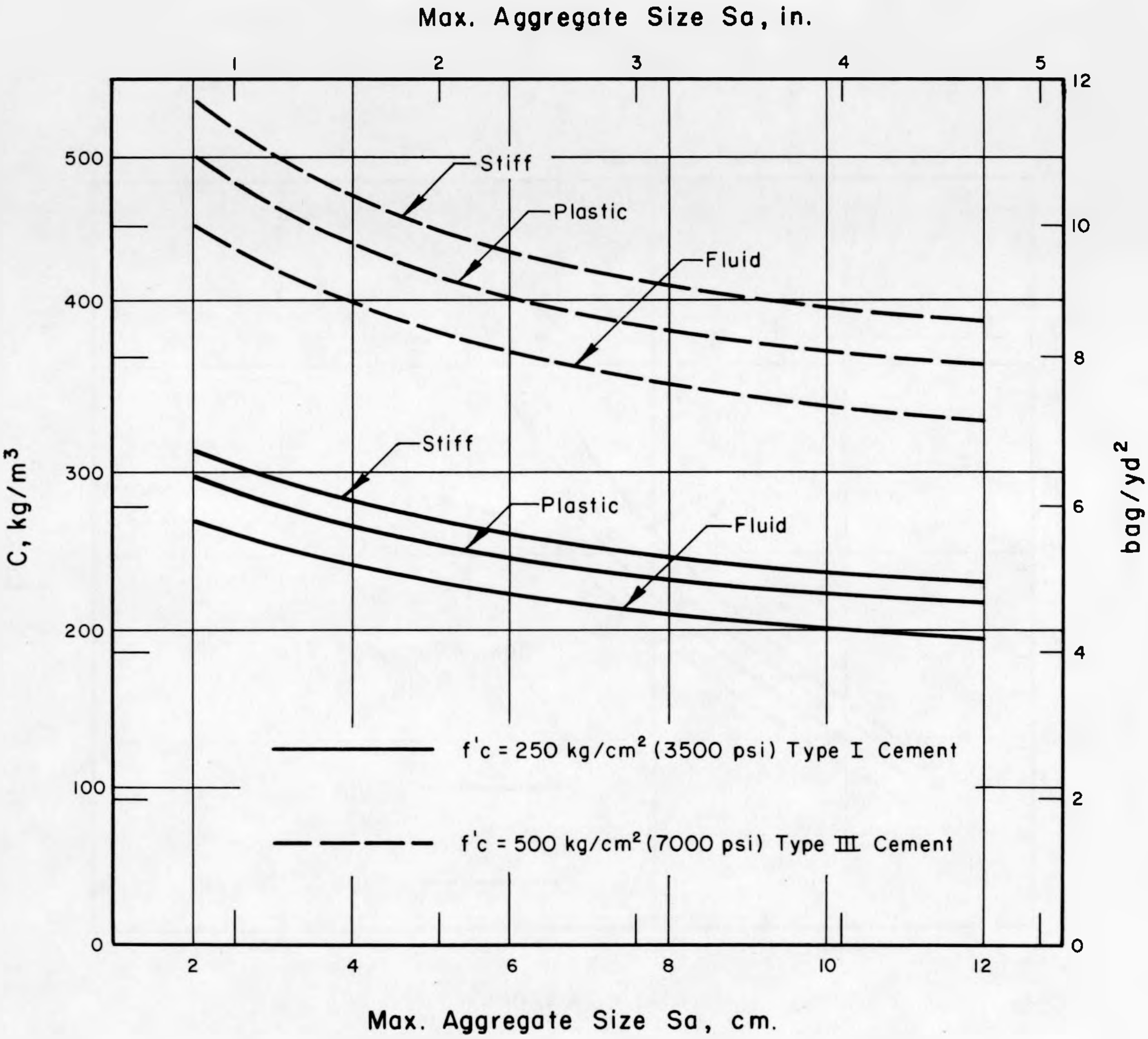

FIG. 4 CEMENT CONTENT, C, OF CONCRETE MIXES OF VARIOUS CONSISTENCY AND MAXIMUM AGGREGATE SIZE S_a

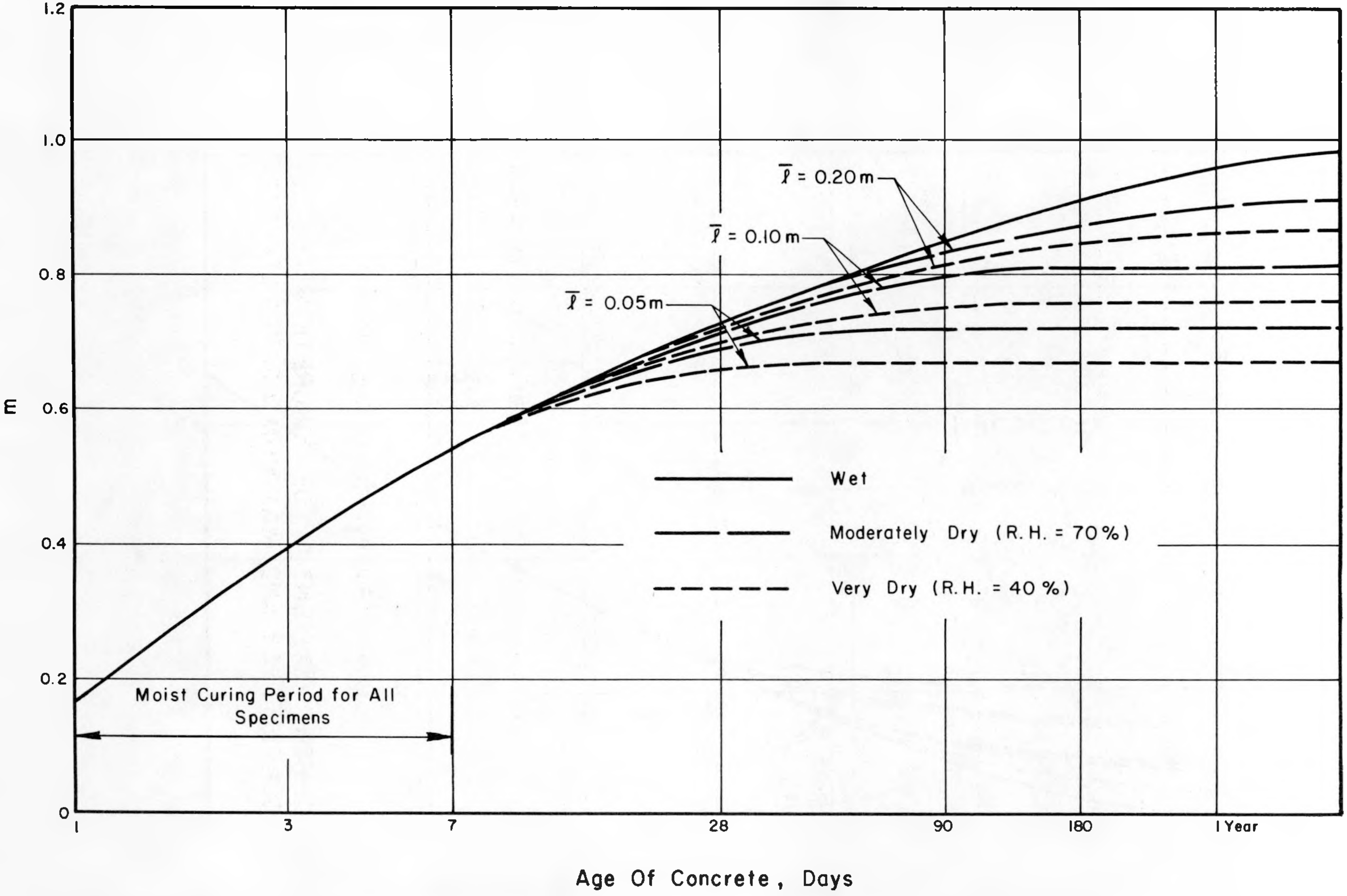

FIG. 5a AVERAGE MATURITY FACTOR, m, FOR SPECIMENS OF VARIOUS SIZE AND CURING CONDITIONS, TYPE I CEMENT

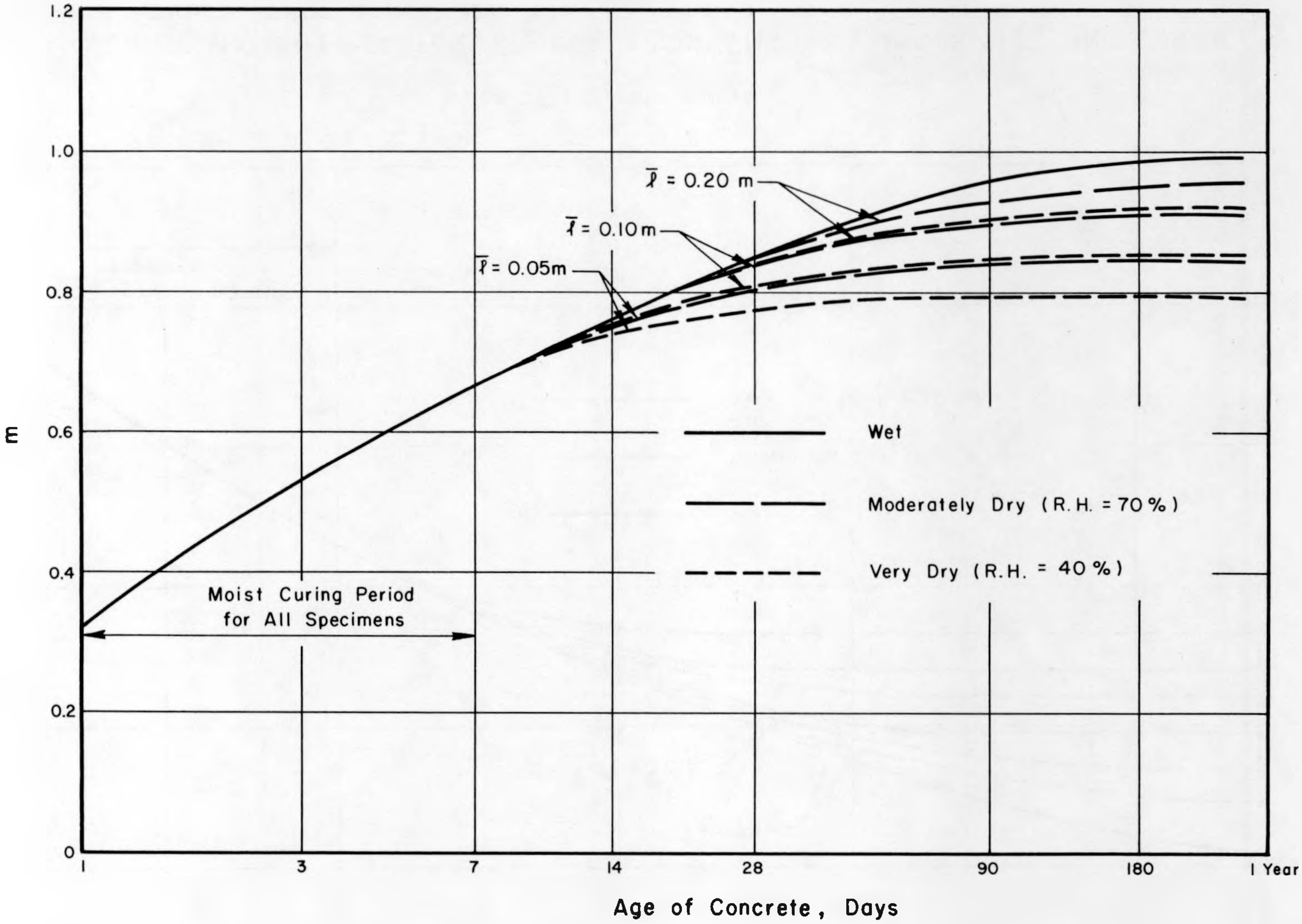

FIG. 5b AVERAGE MATURITY FACTOR, m, FOR SPECIMENS OF VARIOUS SIZE AND CURING CONDITIONS, TYPE III CEMENT

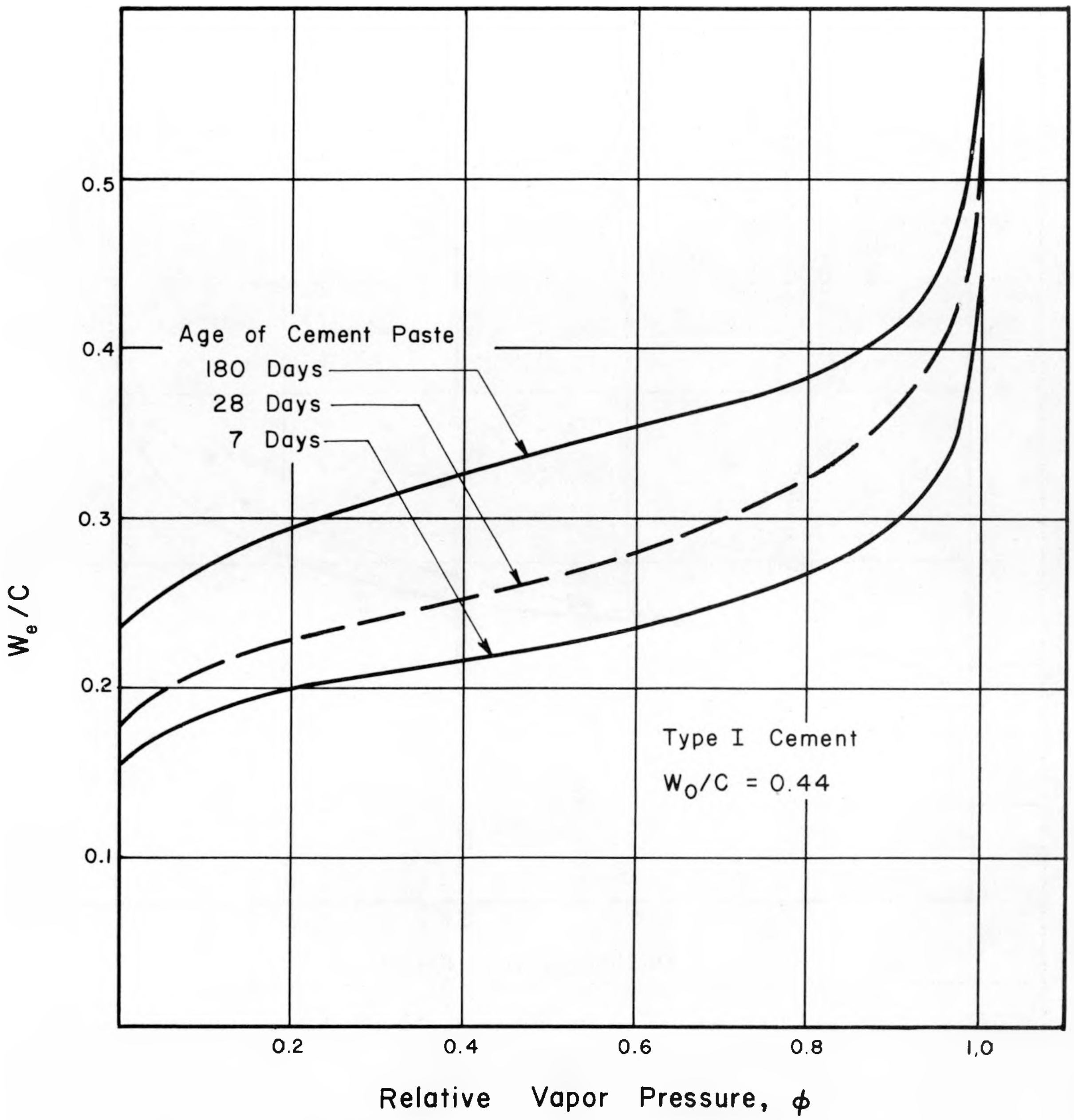

FIG. 6 EFFECT OF AGE OF CEMENT PASTE ON ITS EQUILIBRIUM MOISTURE CONTENT (From Ref. 9)

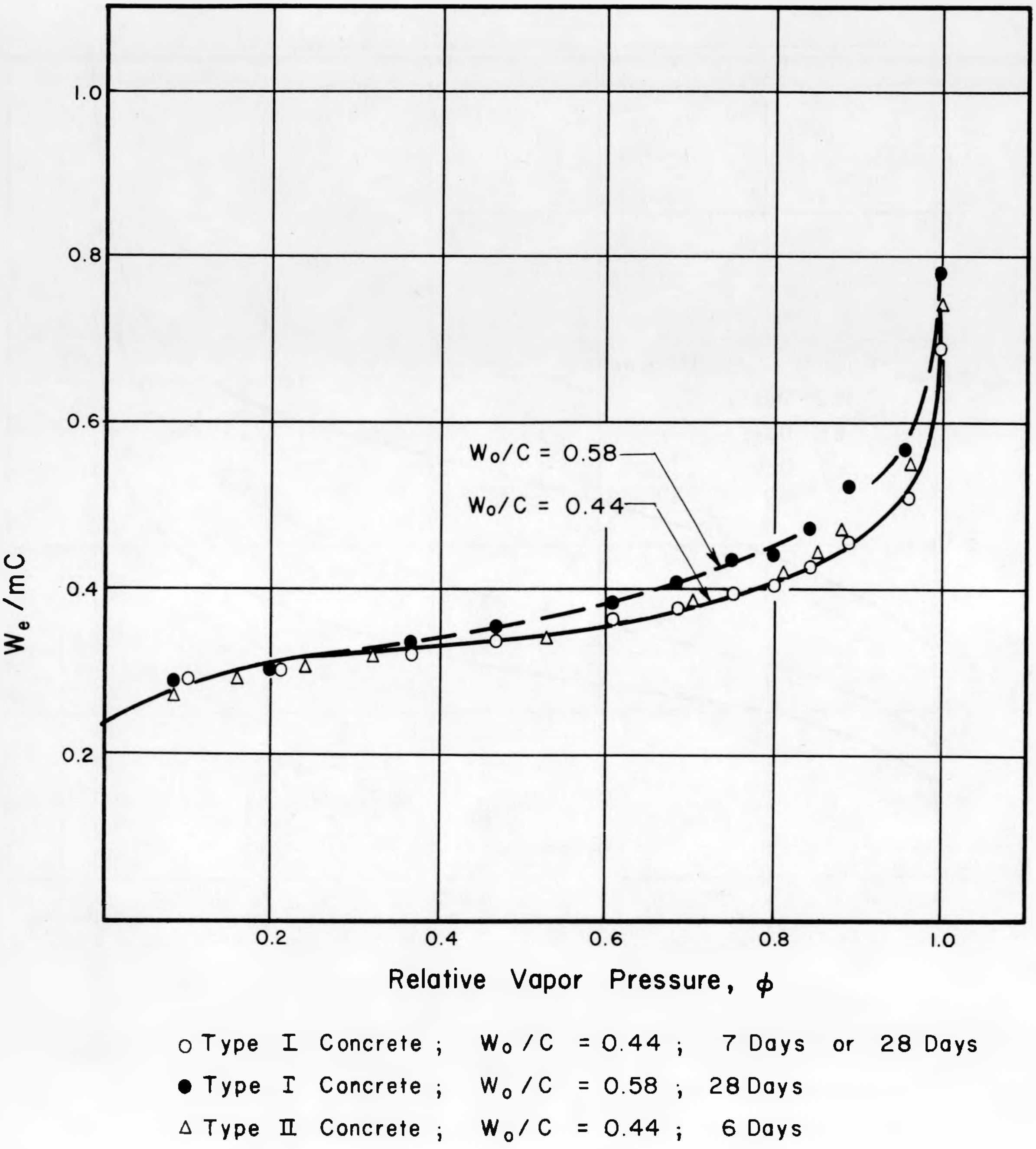

FIG. 7 EFFECT OF WATER-CEMENT RATIO OF CEMENT PASTE ON ITS EQUILIBRIUM MOISTURE CONTENT (FROM REF. 9)

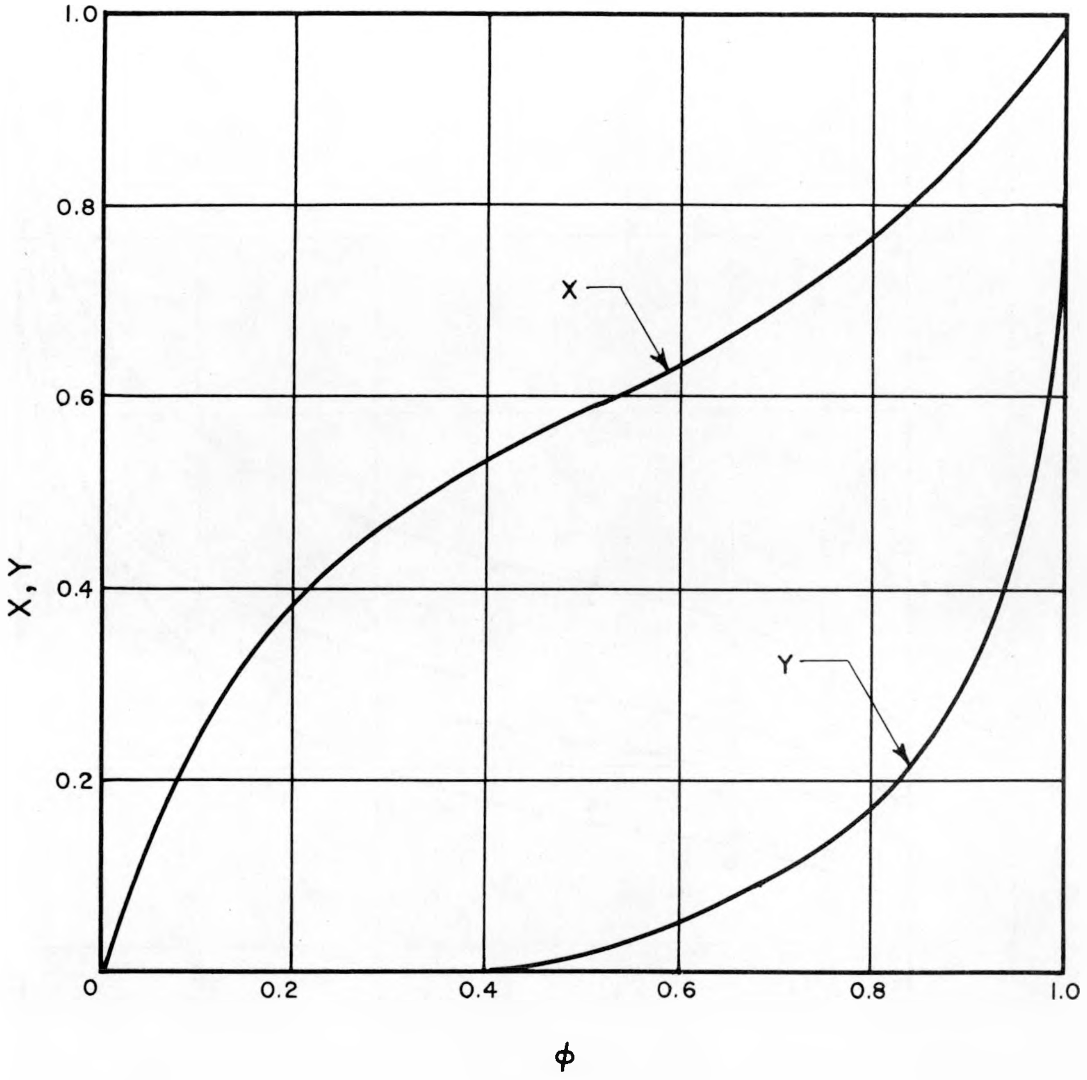

FIG. 8 X = RATIO OF WEIGHT OF GEL-WATER IN CEMENT PASTE AT A GIVEN REL. VAPOR PRESSURE ϕ TO WEIGHT OF GEL-WATER AT SATURATION

Y = RATIO OF WEIGHT OF CAPILLARY WATER IN CEMENT PASTE AT A GIVEN REL. VAPOR PRESSURE TO WEIGHT OF CAPILLARY WATER AT SATURATION

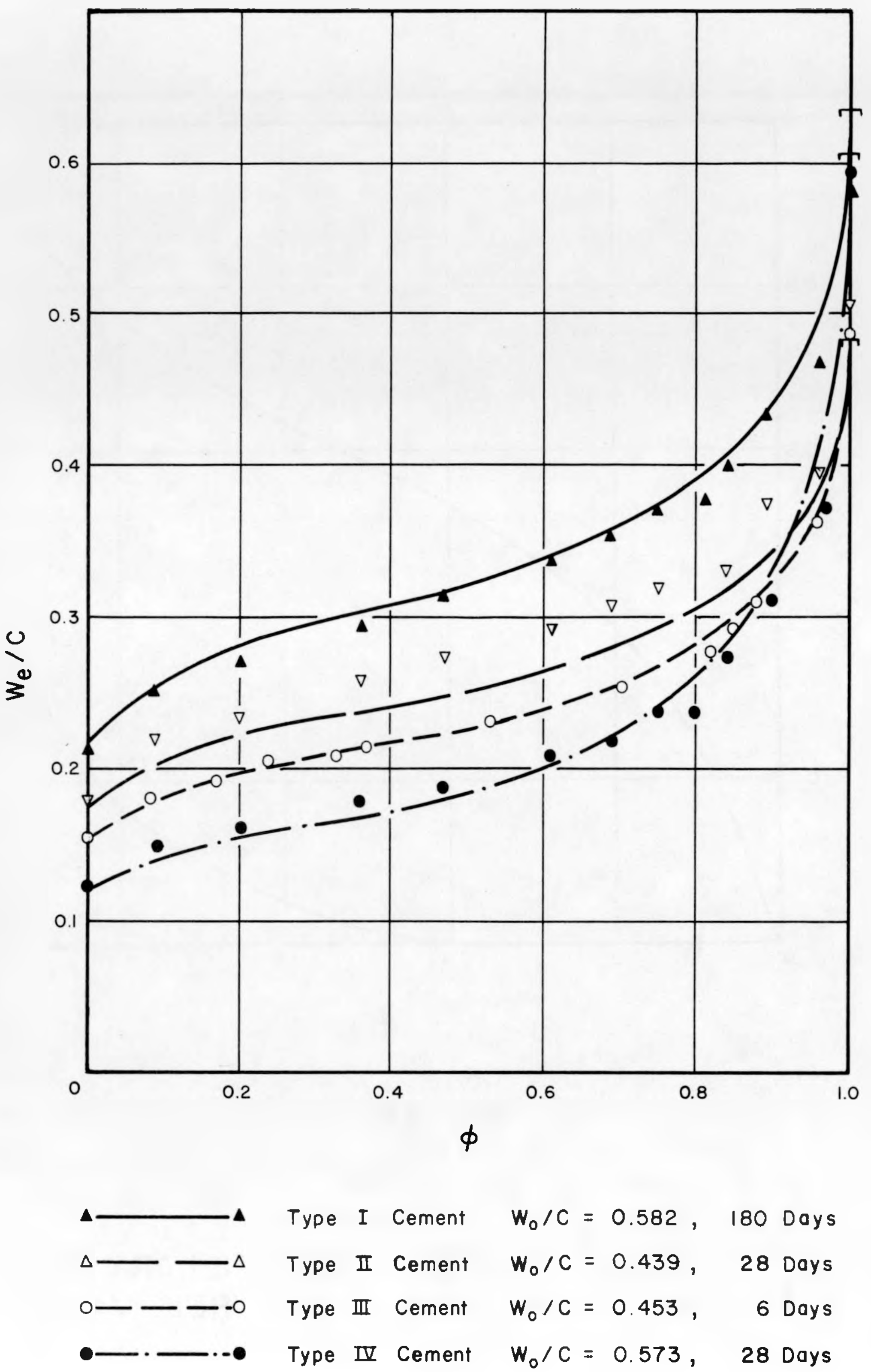

FIG. 9 COMPARISON OF EXPERIMENTAL DATA FROM REF.9 WITH VALUES COMPUTED ACCORDING TO EQ. 11

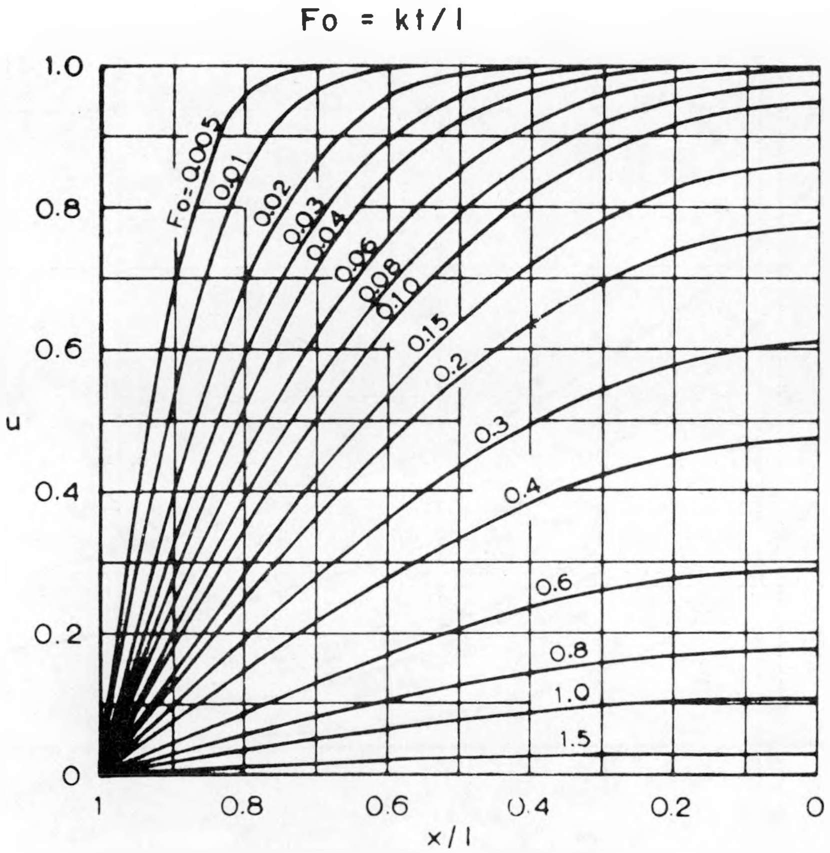

FIG. 10 DISTRIBUTION OF MOISTURE CONCENTRATION ACROSS THE THICKNESS OF A SLAB OF HALFTHICKNESS ℓ ACCORDING TO DIFFUSION THEORY k = CONSTANT (From Ref. 26)

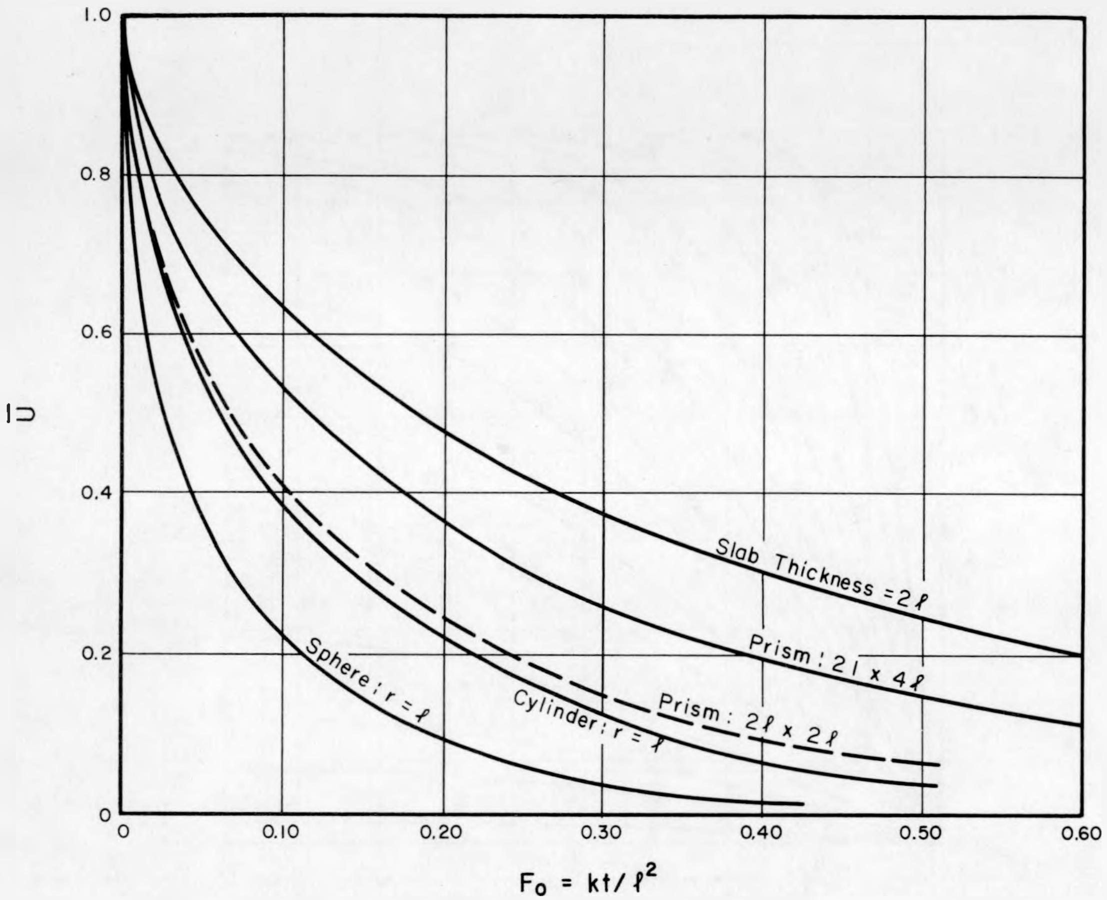

FIG. 11 AVERAGE MOISTURE CONCENTRATION OF INFINITELY LONG SPECIMENS OF VARIOUS CROSS SECTIONS AND OF A SPHERE ACCORDING TO DIFFUSION THEORY FOR K = CONST. (From Ref. 22, 23, and 27)

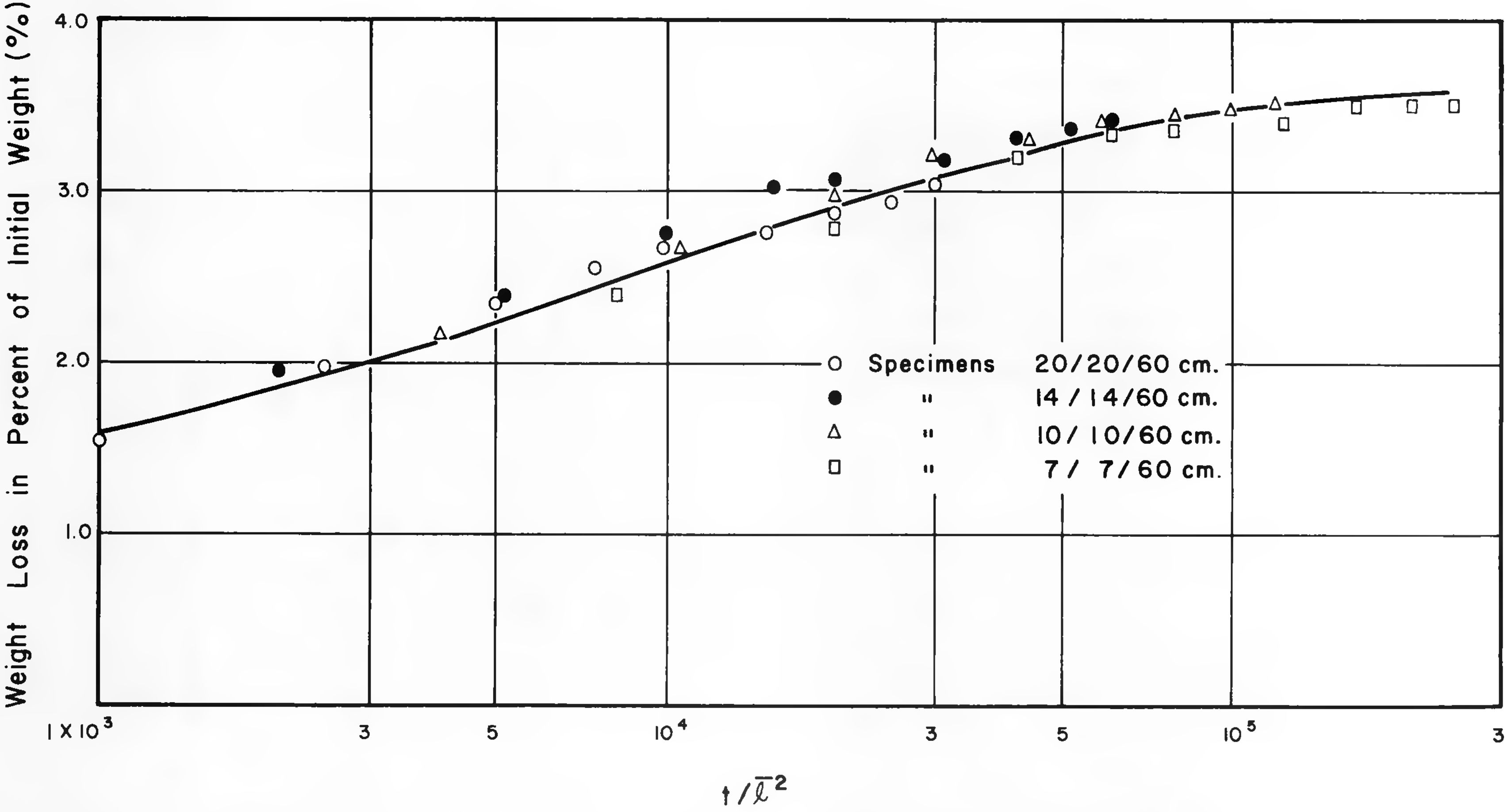

FIG. 12 EFFECT OF SPECIMEN SIZE UPON DRYING OF CONCRETE (From Ref. 33)

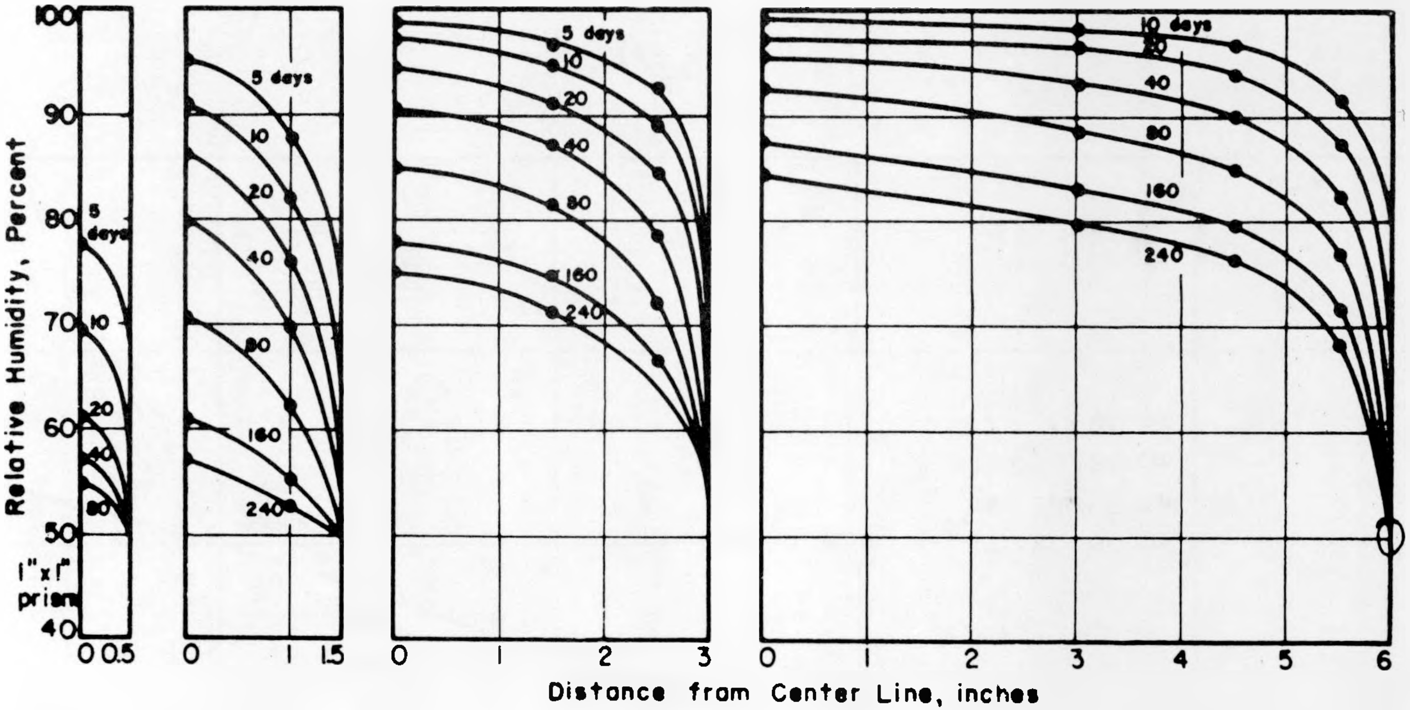

FIG. 13 DISTRIBUTION OF RELATIVE HUMIDITY IN DRYING CONCRETE SPECIMENS OF VARIOUS SIZES (From Ref. 35)

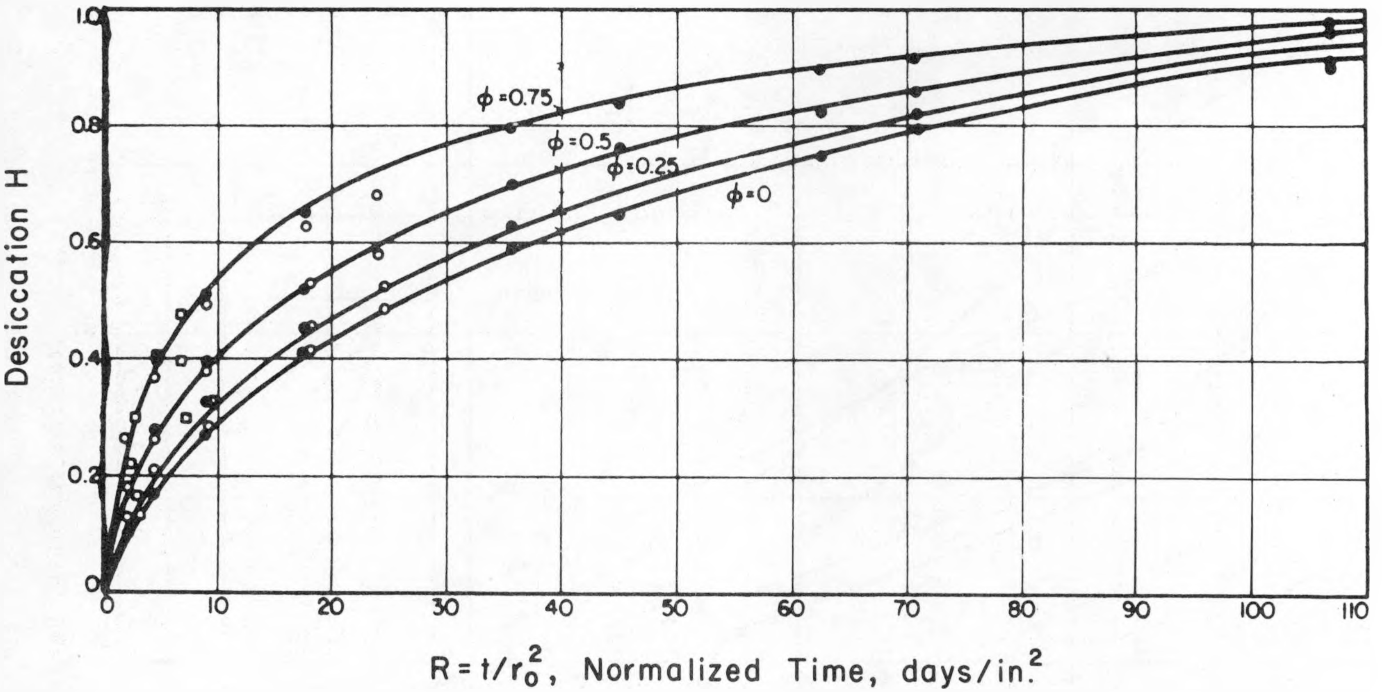

FIG. 14 VARIATION OF DESICCATION OF CONCRETE SPECIMEN DRYING AT 50 PERCENT RELATIVE HUMIDITY (From Ref. 35)

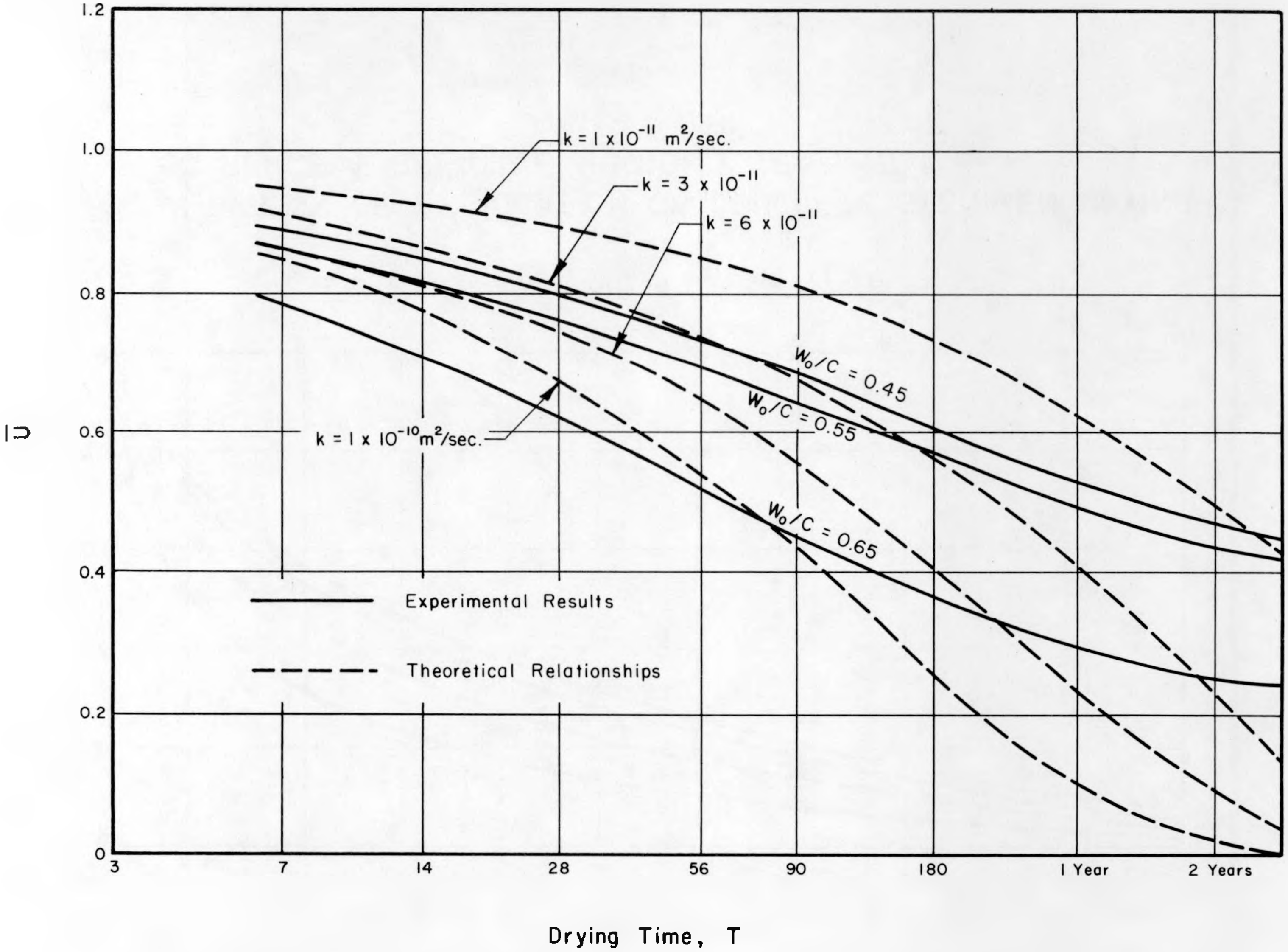

FIG. 15 EFFECT OF W_o/C-RATIO UPON DRYING OF CONCRETE (From Ref. 36)

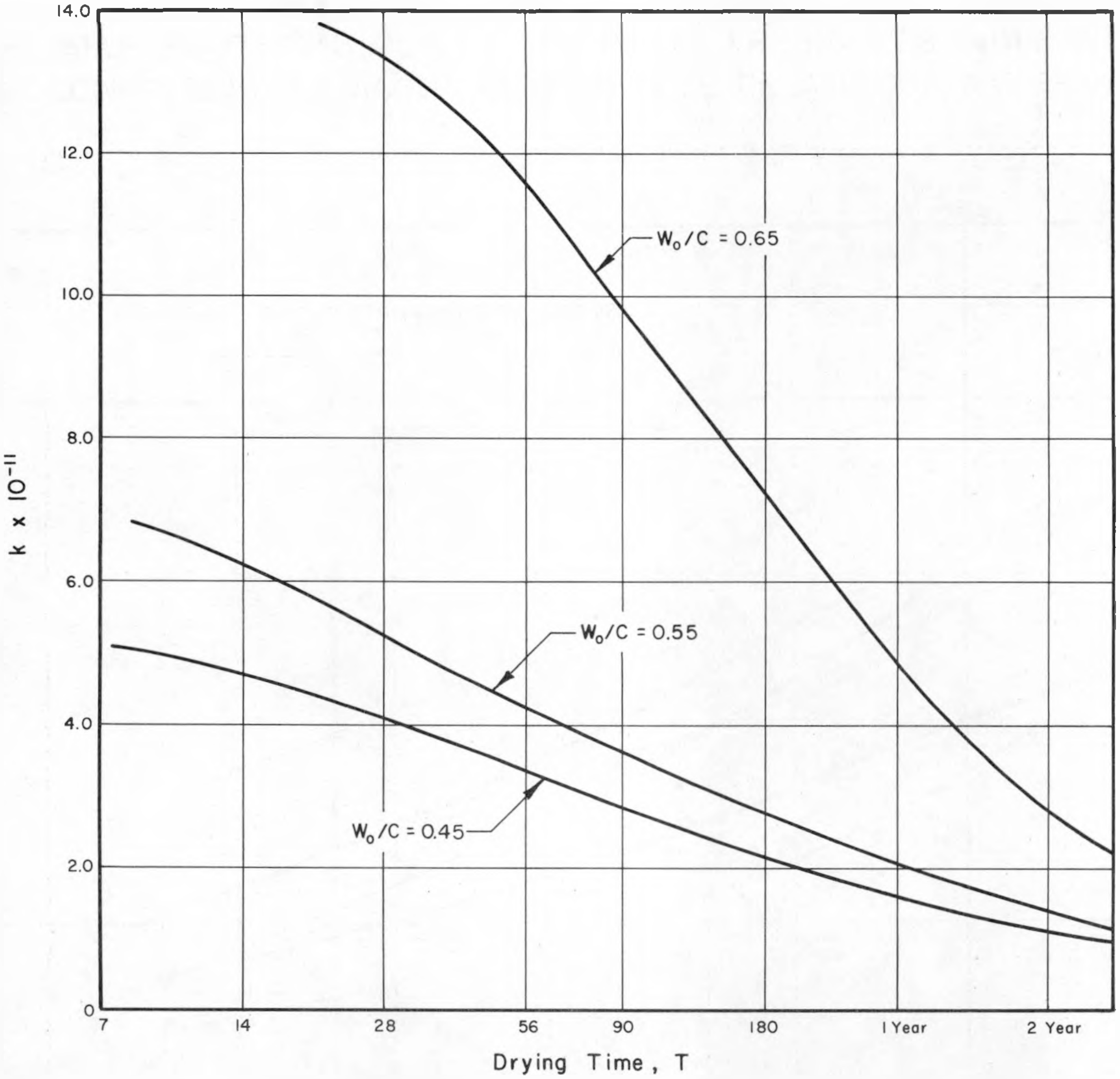

FIG. 16 VARIATION OF MOISTURE CONDUCTIVITY k FOR THE TESTS SHOWN IN FIG. 15

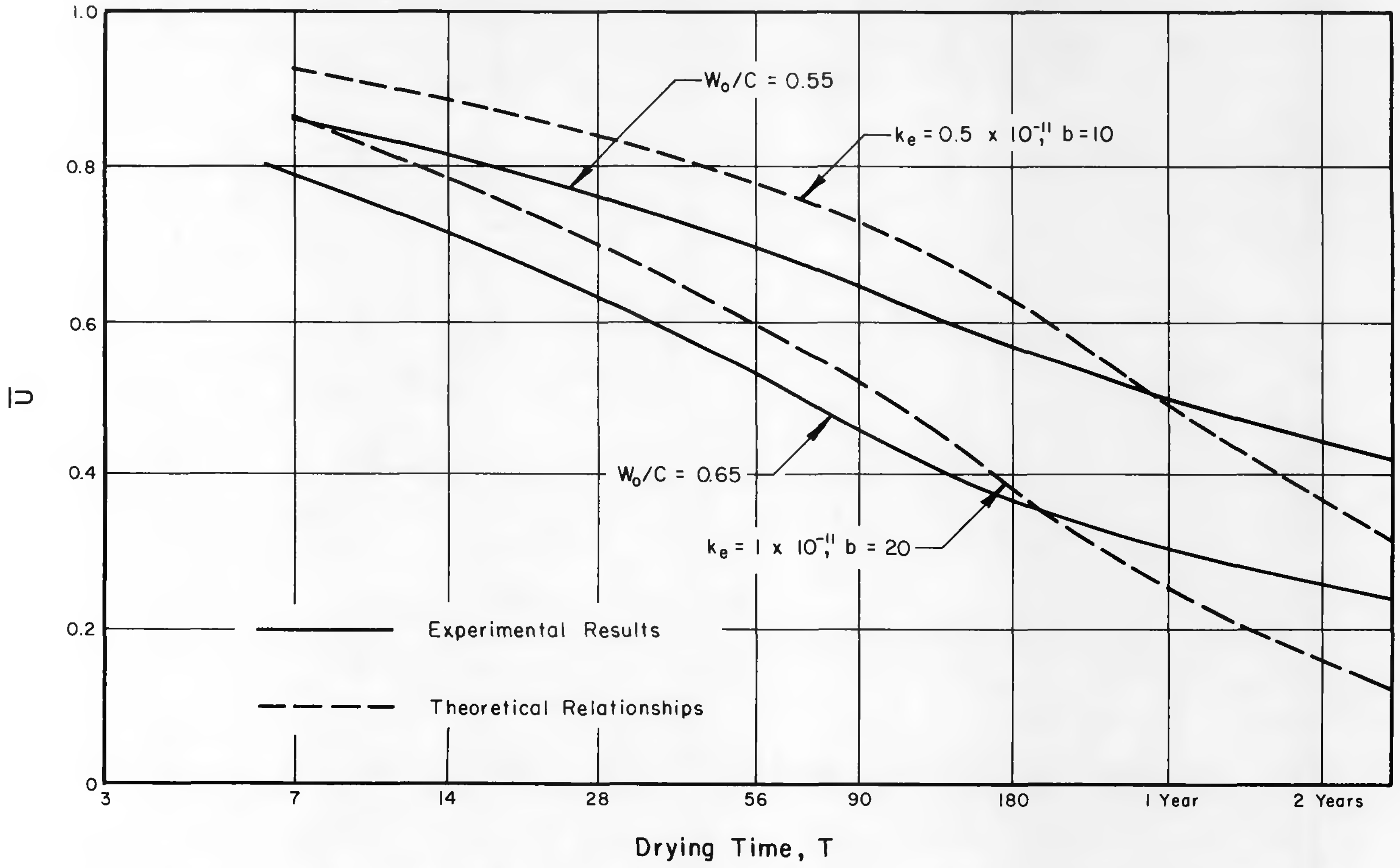

FIG. 17 COMPARISON OF DRYING OF CONCRETE OF VARIOUS WATER–CEMENT RATIOS WITH SOLUTIONS OF THE DIFFUSION THEORY ASSUMING A LINEAR VARIATION OF k

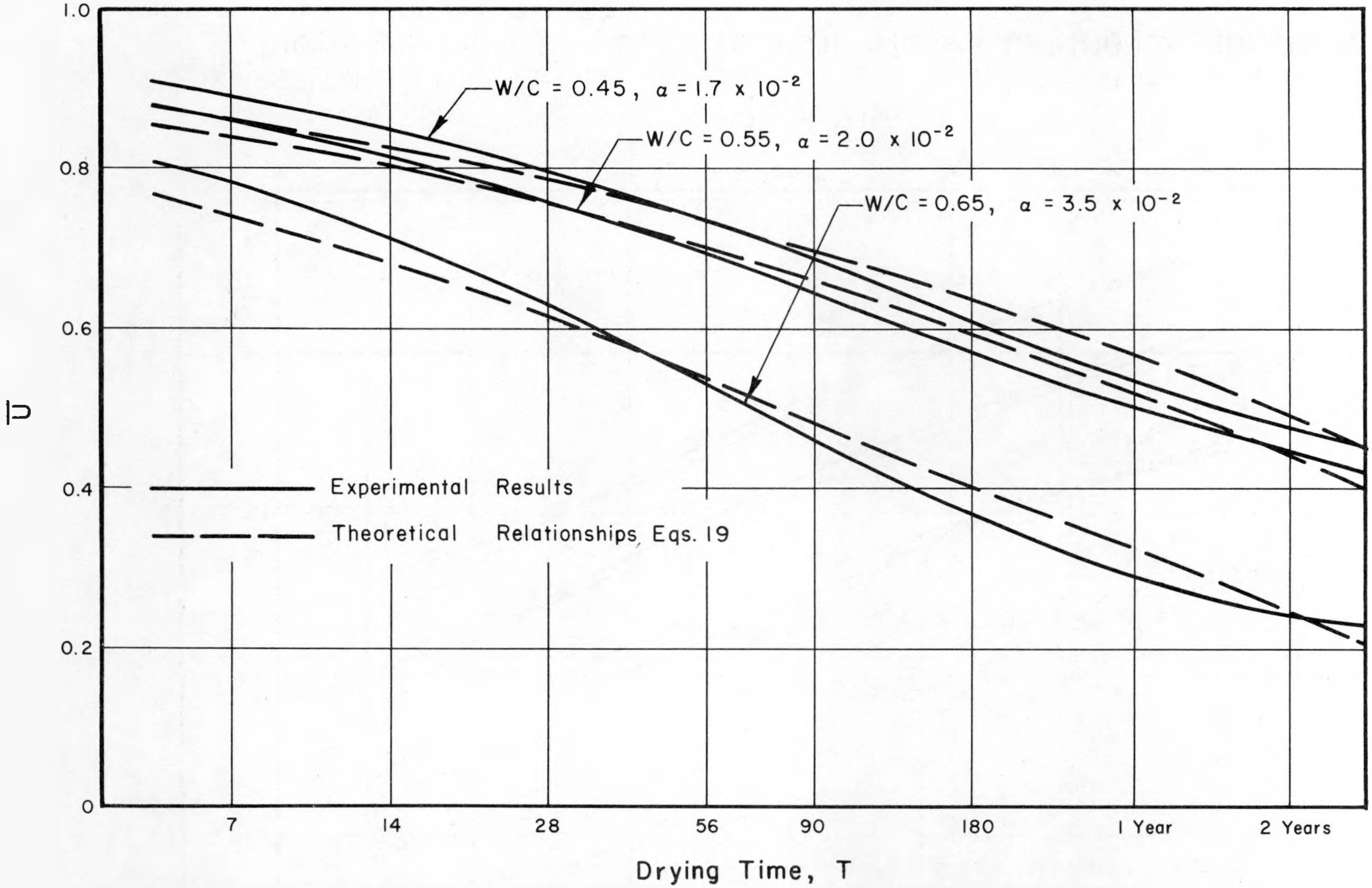

FIG. 18 COMPARISON OF DRYING OF CONCRETE OF VARIOUS WATER CEMENT RATIOS WITH SOLUTIONS FROM APPROXIMATE PROCEDURE, EQ. 19

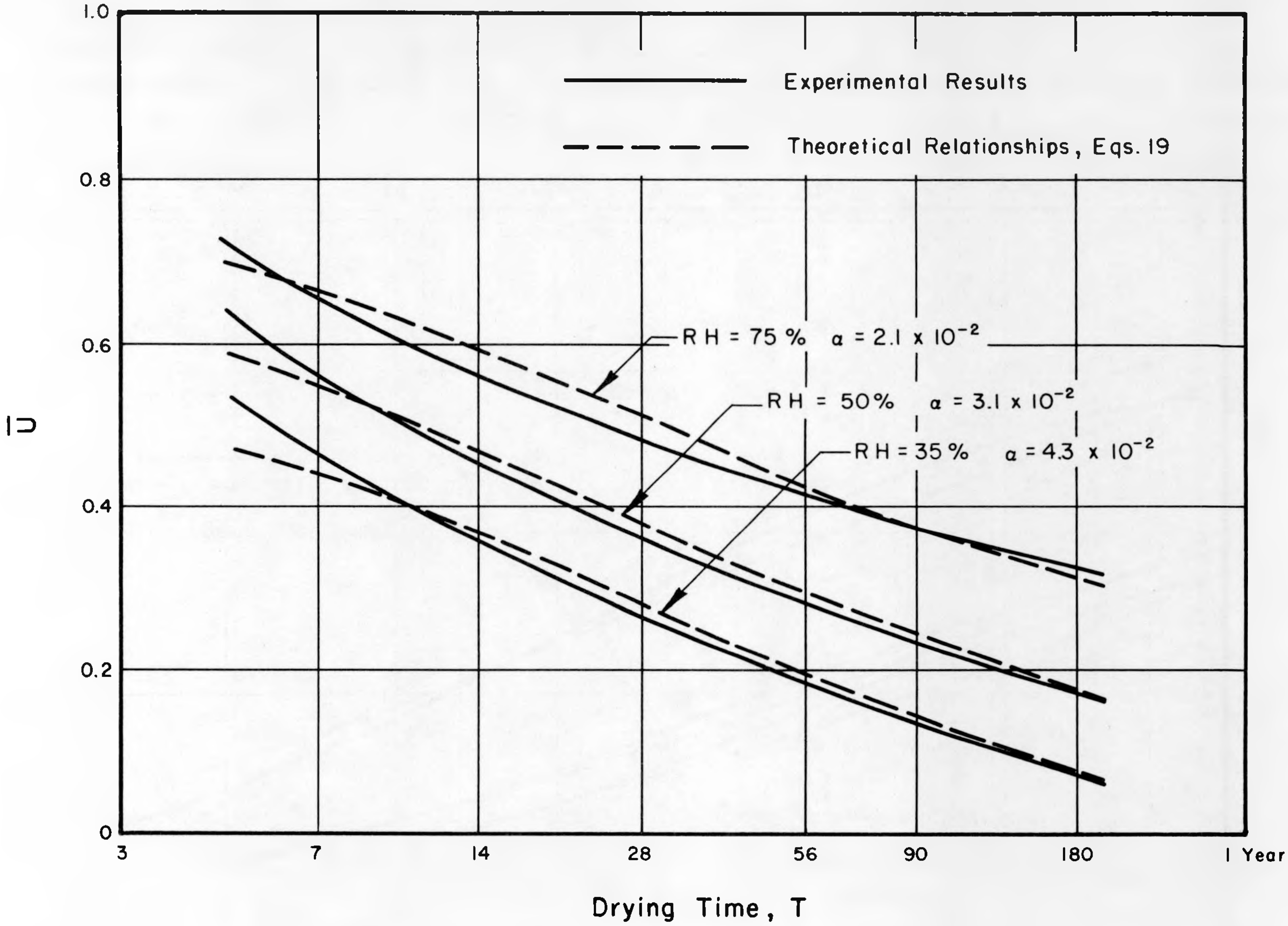

FIG. 19 EFFECT OF RELATIVE HUMIDITY ON DRYING OF CONCRETE (From Ref. 37)

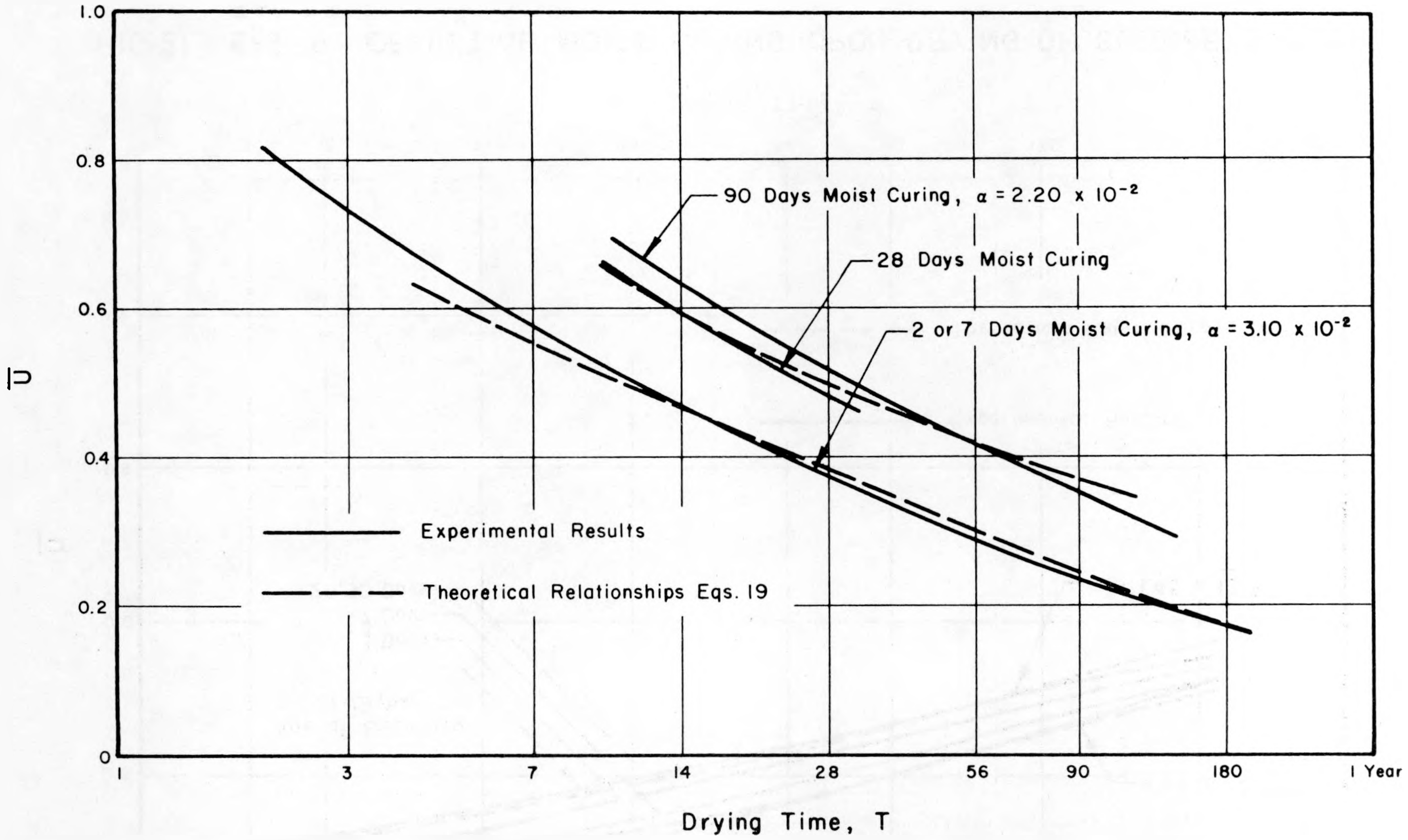

FIG. 20 EFFECT OF INITIAL MOIST CURING UPON DRYING OF CONCRETE (From Ref. 37)

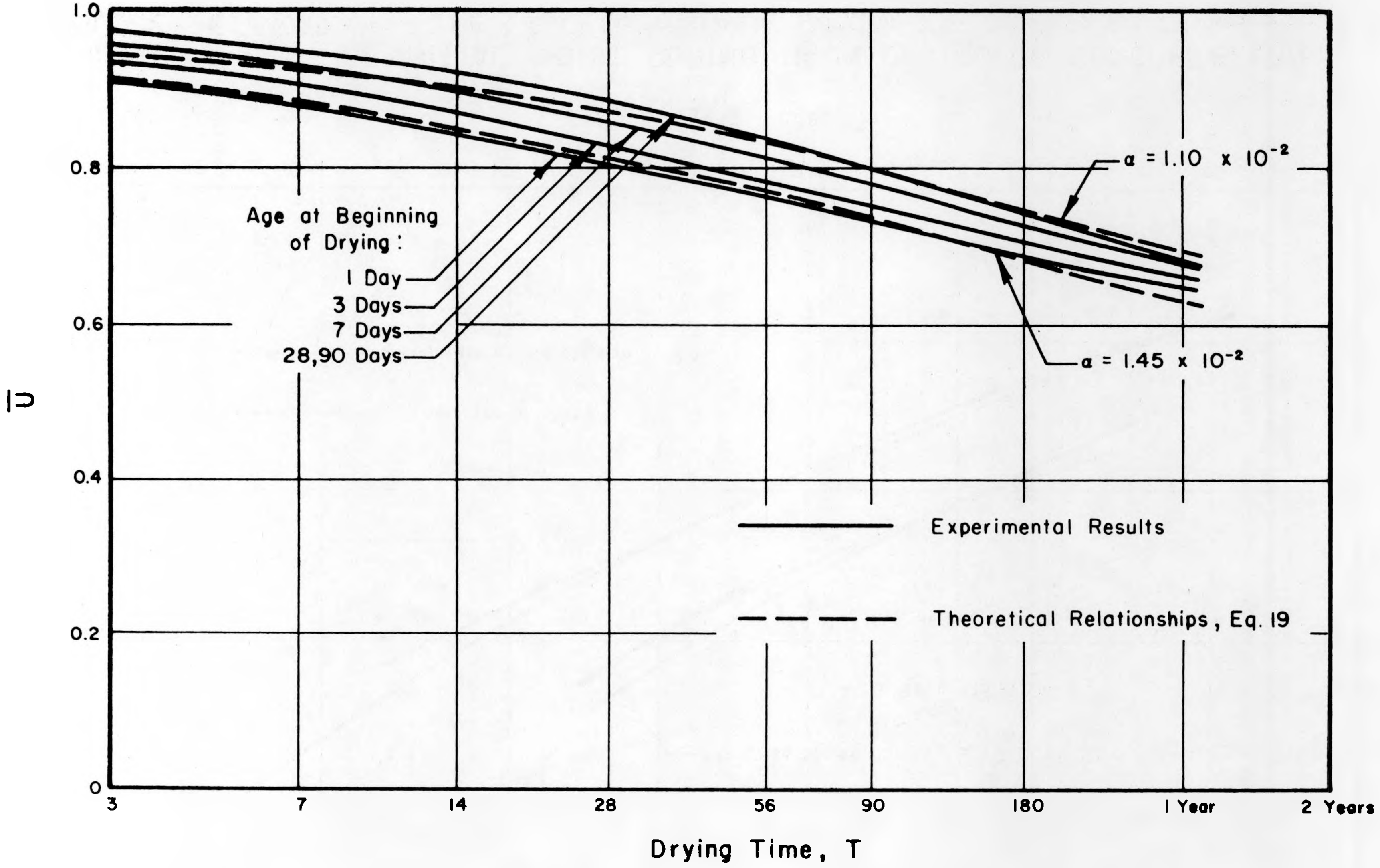

FIG. 21 EFFECT OF INITIAL MOIST CURING UPON DRYING OF CONCRETE (From Ref. 38)

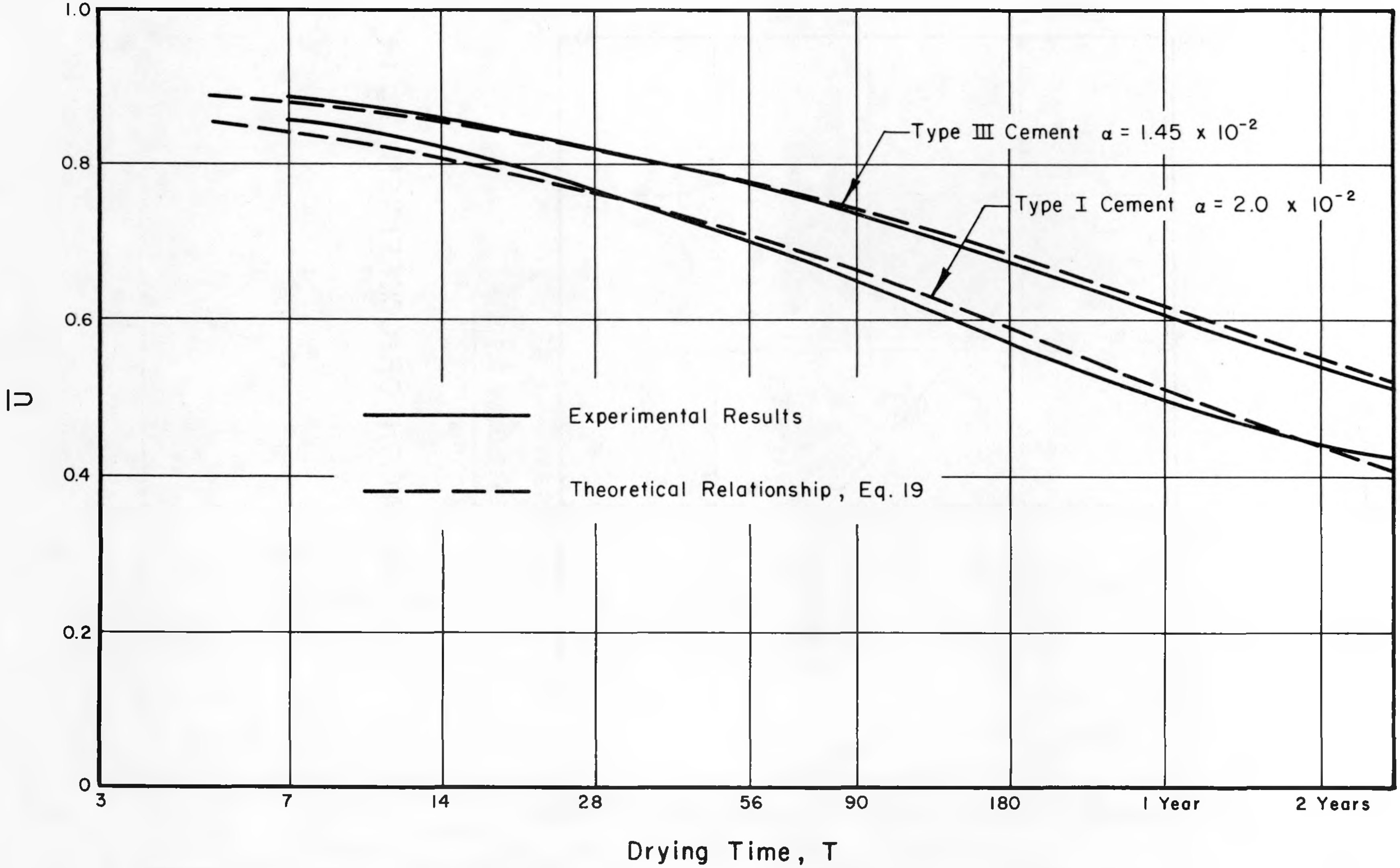

FIG. 22 EFFECT OF TYPE OF CEMENT UPON DRYING OF CONCRETE (From Ref. 36)

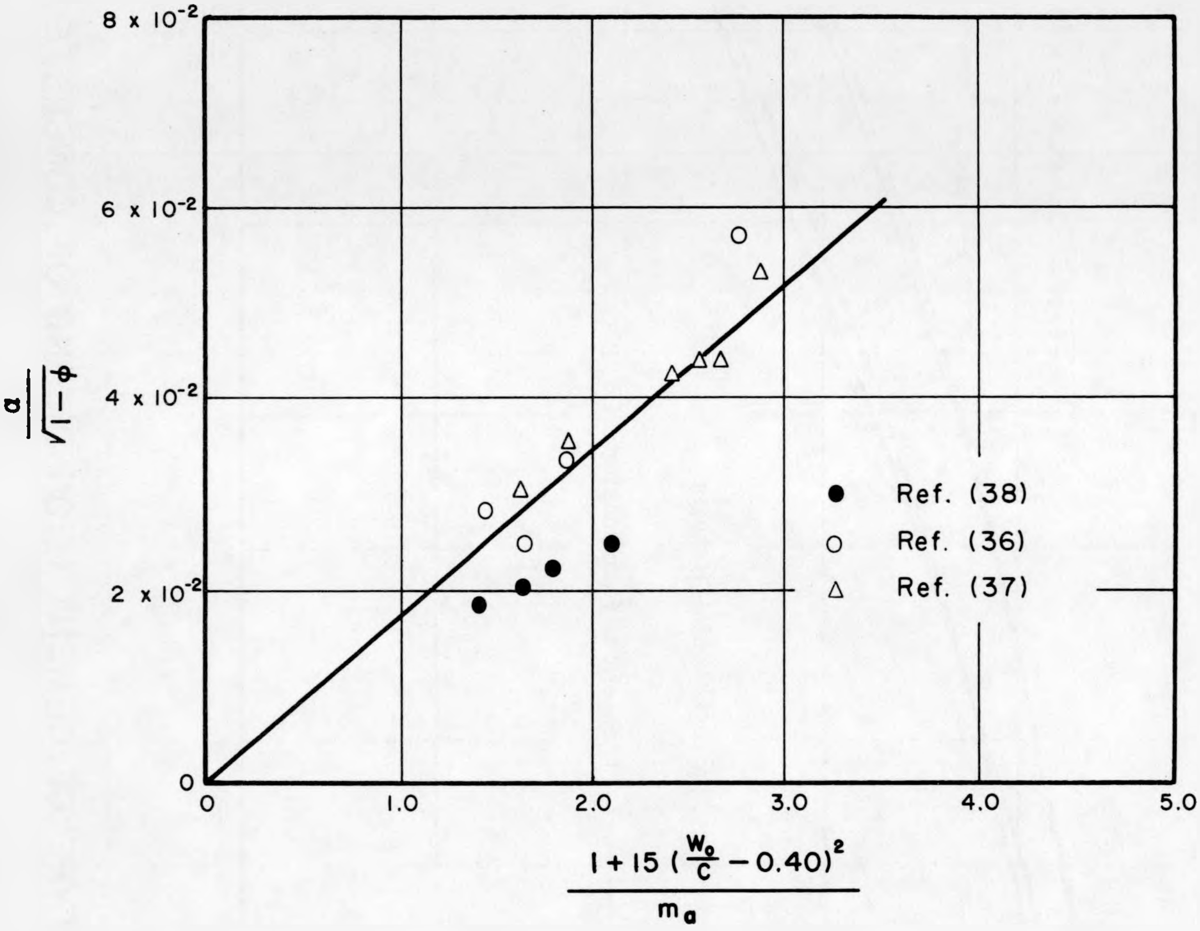

FIG. 23 DETERMINATION OF COEFFICIENT K_3 IN EQ. 25

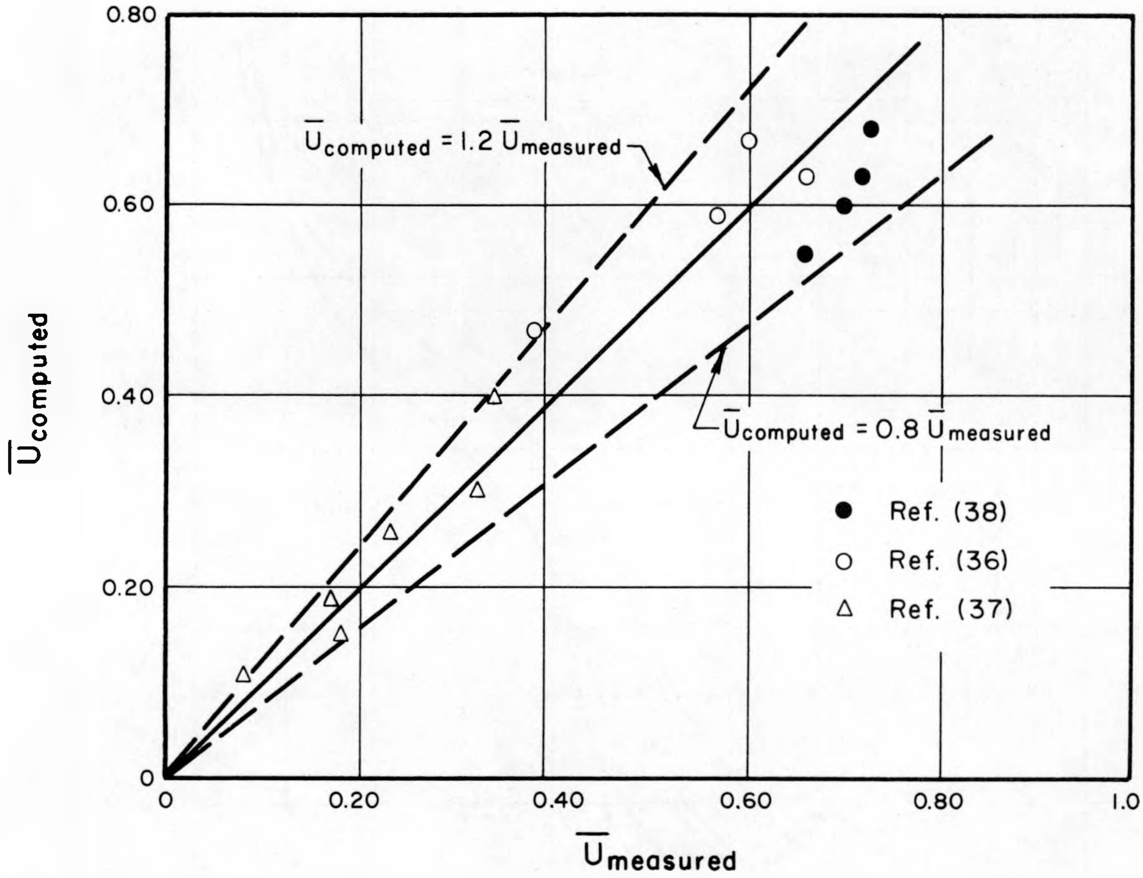

FIG. 24 COMPARISON OF MEASURED LIQUID CONCENTRATION $\overline{U}$ AFTER 200 DAYS OF DRYING WITH COMPUTED VALUES FROM EQS. 19 AND 25

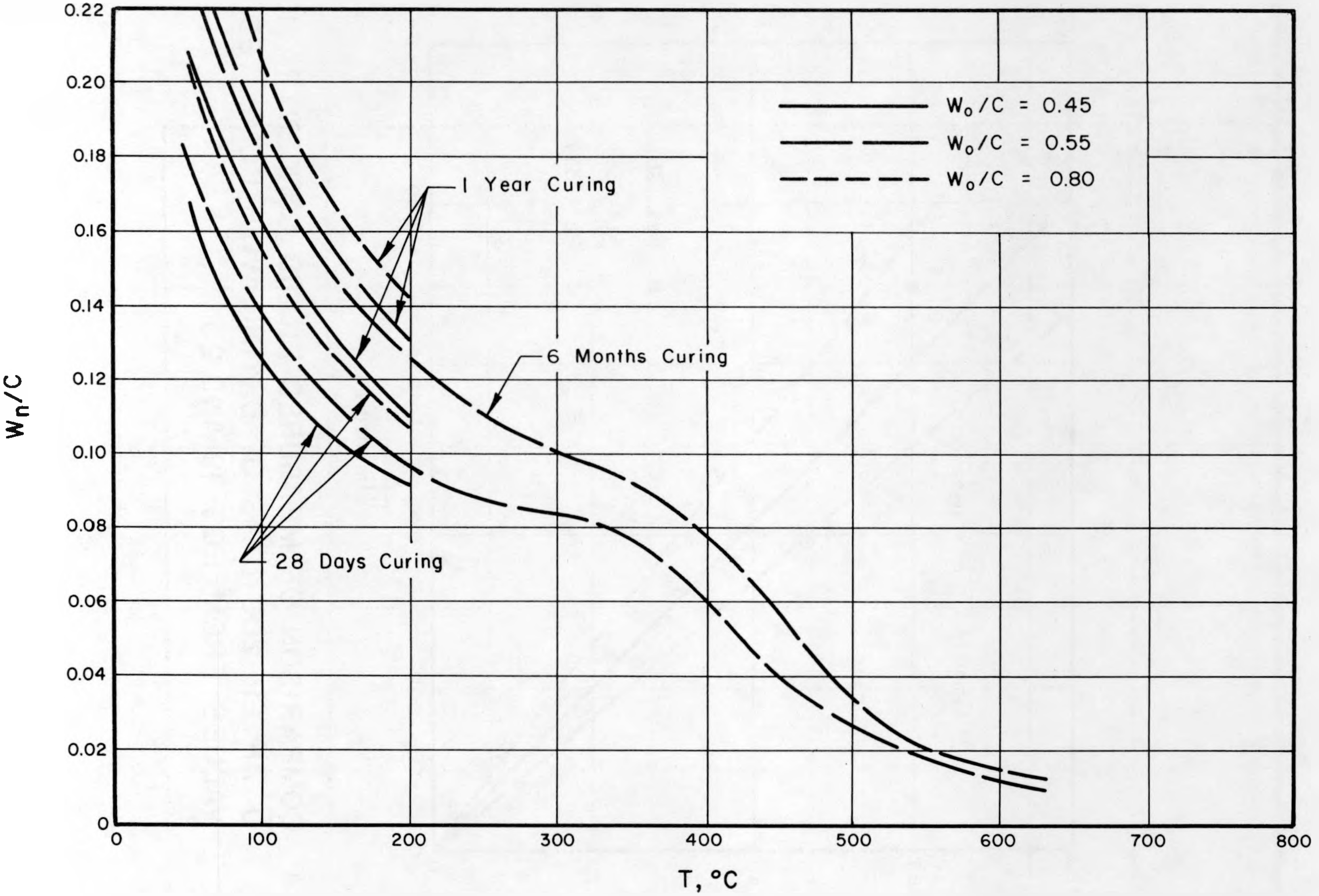

FIG. 25 EFFECT OF TEMPERATURE ON CONTENT OF NON-EVAPORABLE WATER OF HARDENED CEMENT PASTE (From Ref. 41)

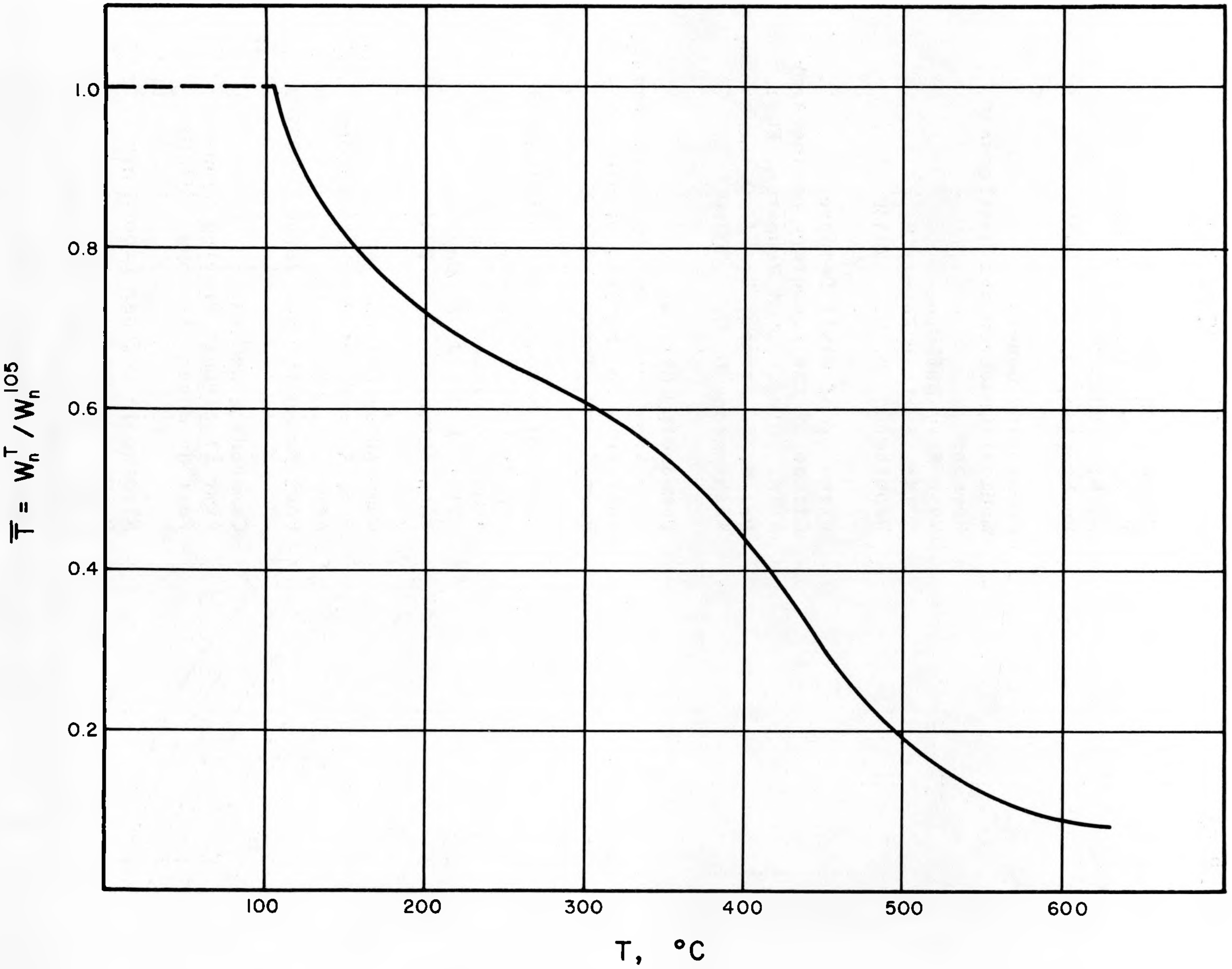

FIG. 26 RATIO $\overline{T} = W_n^T / W_n^{105}$ AS A FUNCTION OF TEMPERATURE, T