

of this idea. True, it would cost some more, but at least for the most important crossings, it is believed that the increased cost would be more than warranted.

JOHN W. McDONALD, *Public Roads Administration*—In evaluating those crossings at which some form of warning device or automatic barrier has already been installed, should not the sight distance to such a device or barrier be considered as well as the sight distance to the approaching train itself? It seems that ample sight distance to a warning signal at a particular crossing would compensate for the fact that an approaching train might be obscured from view and probably this fact was one of the reasons for the original installation.

MR. CRECINK, *Closure*—The factor discussed by Mr. McDonald certainly warrants serious consideration, and there are probably other factors of equal significance that should be considered in a study of this kind. It is believed that a thorough and detailed investigation of the topography at each individual crossing included in the scope of the study will be necessary, if a satisfactory method of evaluating hazards at railroad highway grade crossings is to be attained. Even then the human element will play a great part in the accident toll, and will make the task of developing a mathematical formula by which the relative hazard of crossings can be evaluated a difficult one.

## DEPARTMENT OF MATERIALS AND CONSTRUCTION

C. H. SHOLER, *Chairman*

### REPORT OF COMMITTEE ON WATER IN HARDENED CONCRETE

T. C. POWERS, *Chairman, Manager, Basic Research, Portland Cement Association*

### PHYSICAL CONSTITUTION OF HARDENED PORTLAND CEMENT PASTE (AS REVEALED BY STUDIES OF ITS WATER CONTENT) AND ITS RELATION TO THE PROPERTIES OF HARDENED CONCRETE

#### SYNOPSIS

The discussions presented at an open meeting of the Committee on Water in Hardened Concrete are reported. After a review of the empirical relationships pertaining to the constitution of portland cement paste, including classification of water in hardened paste, and paste porosity, the following topics were discussed: volume changes that accompany changes in moisture content and temperature, freezing of water in hardened paste considered in relation to the durability of concrete. An annotated bibliography pertaining to water in paste or concrete is appended.

The discussion was opened with the following review by Chairman Powers of empirical relationships pertaining to the constitution of hardened portland cement paste, as set forth in the paper by Powers and Brownyard in the Proceedings of the American Concrete Institute.<sup>1</sup>

<sup>1</sup> Ref. B-1-16 to 18, in the bibliography at the end of the report.

Many of the important properties of concrete can be understood in terms of the peculiarities of the hydration products of portland cement. These hydration products form a solid mass called the hardened paste. The hardened paste is not a homogeneous solid; it may be considered to be composed of a large number of primary units bound together to form a porous solid. The chemical con-

stitution of the units of this solid is not yet definitely known, or if it is known the knowledge has not been proved. However, many significant characteristics of concrete appear to depend on the physical state of the solid material composing the paste and on the strong attraction for water that this material exhibits rather than on the chemical constitution of the paste.

The extreme smallness of the structural units of the paste, the corresponding smallness of the interstitial spaces, and the strong attraction of the solid units for water account for the marked influence that changes in moisture content have on the properties of concrete. They account also for the peculiar relationship that exists between the changes in temperature in the subfreezing range and the amount of ice that can exist in hardened paste.

#### CLASSIFICATION OF WATER IN HARDENED PASTE

The water in hardened cement paste may be classified as follows:<sup>2</sup>

1. Nonevaporable water
2. Evaporable water
  - (a) Gel water
  - (b) Capillary water

The nonevaporable water corresponds roughly to that which is commonly regarded as chemically fixed. Strictly speaking, it is that which exhibits a vapor pressure of less than about  $6 \times 10^{-4}$  mm of mercury at 23 deg. C (73.4 deg. F). The amount of nonevaporable water in grams per gram of original cement may vary from zero at the start of hydration to an upper limit of about 0.26 for a typical Type I cement. The limit is lower for Types II, IV, and V.

The evaporable water is the part that does produce a vapor pressure higher than  $6 \times 10^{-4}$  at 23 deg. The amount that may be present depends on the porosity of the hardened paste and the degree of saturation.

As indicated above, the evaporable water may be subdivided into two classes, gel water and capillary water. The basis for this subdivision is brought out further on in this discussion.

#### PASTE POROSITY

*Porosity of Fresh Paste.*<sup>3</sup> Before hydration begins, a cement paste, though apparently

<sup>2</sup> Ref. B-1-16, Bibliography.

<sup>3</sup> Ref. A-1 to 4, Bibliography.

fluid, is technically a weak solid. Such strength as it has is derived from forces of interparticle attraction. The forces apparently act across thin films of water at points of near contact between the particles. The water-filled, interconnected spaces between the particles in the fresh paste constitute a capillary system. Therefore, before hydration starts and before bleeding has begun the capillary water is equal to the total amount of water in the mixture. That is,

$$p_c = w \quad (1)$$

where  $p_c$  = volume of capillary pores, and  
 $w$  = volume of mixing water.

This is illustrated in Figure 1.<sup>4</sup>

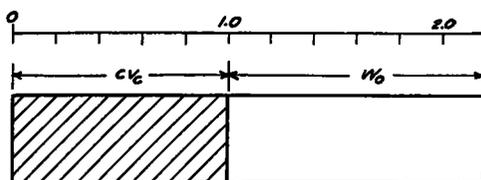


Figure 1. This diagram represents a fresh paste having a water-cement ratio of 1.2 absolute volume units.

Immediately after a mold is filled with paste (or concrete), bleeding begins. At the end of the bleeding period the volume of the capillary pores has been reduced by an amount equal to the decrease in volume of the paste. For neat pastes, this decrease is practically equal to the volume of water lost by bleeding. Thus,

$$p_c = w - \Delta w_B = w_o \quad (2)$$

where  $\Delta w_B$  = the water lost by bleeding, and  
 $w_o$  = the net water content of the fresh paste.

*Porosity of the Hardened Paste.* After the plastic stage when the final reactions of hardening begin, the capillary pores of the fresh paste begin to fill with solids produced by the reaction between water and the cement. At any given stage of hydration the volume of the capillary pores may be expressed as follows:<sup>4</sup>

$$p_c = w_o - \Delta V_B \quad (3)$$

where  $\Delta V_B$  = the increase in the volume of solids in the paste.

<sup>4</sup> Ref. B-1-18 and 19.

The increase in solid volume is proportional to the increase in nonevaporable water, that is,  $\Delta V_B = Nw_n$ , where  $N$  = the increase in volume of solids in the paste, cc. per gram increase in nonevaporable water.

Thus, we may write,

$$p_c = w_o - Nw_n \tag{4}$$

The value of  $N$  was found empirically to be<sup>6</sup>

$$N = 0.75(1 + 4k) \tag{5}$$

where  $k$  is a constant that depends upon cement composition ranging from about 0.24 to 0.28. Since it varies through a comparatively small range, it is permissible to use the figure 0.255 for calculations in which approximate results are acceptable. Hence, under average conditions,<sup>5</sup>

$$p_c = w_o - 1.52w_n. \tag{6}$$

Equation 6 shows that if  $1.52w_n = w_o$ , the paste contains no capillary pores and hence can contain no capillary water. However, it will always be capable of containing some evaporable water. This is due to the fact that the gel formed by cement hydration contains very small pores that are characteristic of the gel. Hence, these pores are called gel pores and the water that they may contain is called gel water.

The relationships just discussed are illustrated in Figure 2. The capillary pores are represented by the open space at the top. The gel pores are in the part represented by double-cross-hatched portion of the diagram.

**Relative Sizes of Gel Pores and Capillary Pores.** Figure 3<sup>6</sup> gives a relation, determined experimentally, between the coefficient of absorptivity and the volume of capillary pores per unit volume of hardened paste. A short extrapolation of the curve through the experi-

mental points indicates that when the capillary porosity is zero the coefficient of absorptivity is very near zero. This is one of the various pieces of evidence indicating that the gel pores are generally much smaller than the capillary pores. Some of the peculiarities that will be pointed out later in connection with the freez-

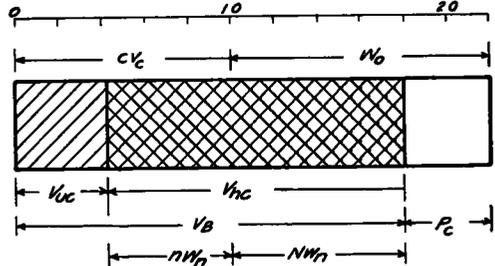


Figure 2. This diagram represents a paste made of cement 15365 having an original water-cement ratio of 1.2 in absolute volume units and at a stage of hydration where  $\frac{wn}{c} = 0.167$ , corresponding to about 64 percent of complete hydration.

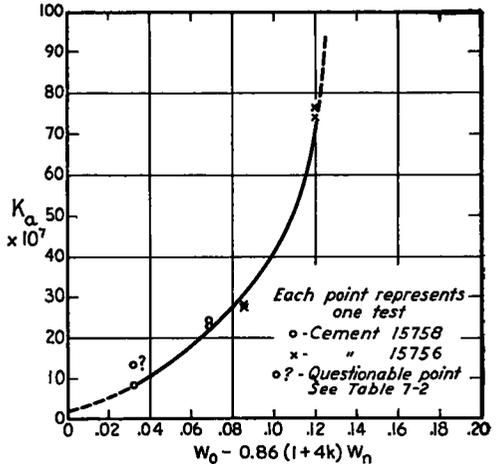


Figure 3. Empirical relationship between coefficient of absorptivity and capillary porosity. (From *Proceedings, American Concrete Institute, Vol. 43, p. 876.*)

<sup>5</sup> At the time of the meeting, and in previous publications (B-1-18) (B-3-17), the numerical constant in Eq. 5 was given as 0.86, and the derived constant in Eq. 6 as 1.74 or a figure near that, depending on the  $k$  for a particular cement. Continued use of 0.86 always led to negative capillary porosity when applied to rich, long-cured pastes. The figure 0.75 is the largest that will avoid this result. The reason why the earlier figure is incorrect has not yet been discovered, but the fact that it was derived from data on pastes that had been dried and resaturated is probably involved.

<sup>6</sup> See Fig. 7-1, page 876, Ref. B-5-14.

ing of water in hardened paste can be explained in terms of the smallness of these pores.

**Size of Units Composing the Gel.** By means of vapor-adsorption techniques that have come into use in recent years, the surface area of the pore walls within the paste has been measured, using water vapor.<sup>7</sup> The results

<sup>7</sup> Ref. B-1-12 and 17.

show that for an average cement this surface area amounts to about

$$\Sigma = 900w_n \quad (7)$$

where  $\Sigma$  is the total surface area in square meters.

For a typical Type I cement the upper limit of  $w_n$  is about 0.26. Thus, in a paste containing 1 gram of cement per cubic centimeter of hardened paste, the total surface area would be  $900 \times 0.26$  or 234 sq. m. This amounts to 2.34 million sq. cm. of surface per gram of original cement. This figure is to be compared with the few thousand square centimeters of surface presented by the original cement.

The high specific surface of the solid material found in hydrated cement is regarded as strong support to those who have contended that the hydrates of portland cement are predominantly colloidal and that the properties and behavior of concrete may be understood in terms of the colloidal characteristics of the cement paste.

After presenting the foregoing material, the chairman said that the ensuing discussion would be centered around two topics: volume changes that accompany changes in moisture content and temperature, and the freezing of water in hardened paste, considered in relation to the durability of concrete.

#### VOLUME CHANGES

*Relationship between Change in Evaporable Water Content and Change in Volume.* In response to a question, Professor Pickett stated that when concrete loses water by evaporation the change in volume is very much less than the volume of the water lost, the ratio being perhaps 1 to 20. This seemed to be due to restraints against the tendency of the gel to shrink, the restraint being offered by elastic bonds within the gel itself and by non-shrinking bodies in the concrete such as aggregate particles, anhydrous cement, and certain hydrates that do not change moisture content under normal drying conditions.

It was pointed out that differences in shrinkage among concretes made with different aggregates might be accounted for in part by differences in the compressibility among the different aggregates. Reference was made to experiments made by Dr. Pickett at the PCA laboratory wherein steel spheres were substituted for calcareous gravel coarse aggregate

with a resultant 25 percent reduction in drying shrinkage. The data referred to are given in Table 1.

With reference to the effects of restraint by the aggregate on shrinkage a visitor asked whether the aggregate would restrain expansion. This question caused various com-

TABLE 1  
EFFECT OF KIND OF AGGREGATE  
ON SHRINKAGE

Cements prepared from Clinker No. 1; Specific surface 1800 sq. cm. per g. Mix by abs vol.: 1-2 86-3.51;  $\frac{1}{4}$ -in. maximum size coarse aggregate  $w/a = 5.5$  gal. per sack, net  
Dimensions of specimens:  $2\frac{1}{4}$  by  $2\frac{1}{4}$  by  $1\frac{1}{4}$  in.

Ref. No.	Fine Aggregate	Coarse Aggregate	Shrinkage <sup>a</sup> %
2	Elgin	Elgin	0.060
16	Cow Bay	Elgin	0.053
13	Elgin	Cow Bay	0.054
8	Elgin	Steel Balls	0.045
9	Elgin	Steel Punchings	0.041

<sup>a</sup> 70 days of drying.

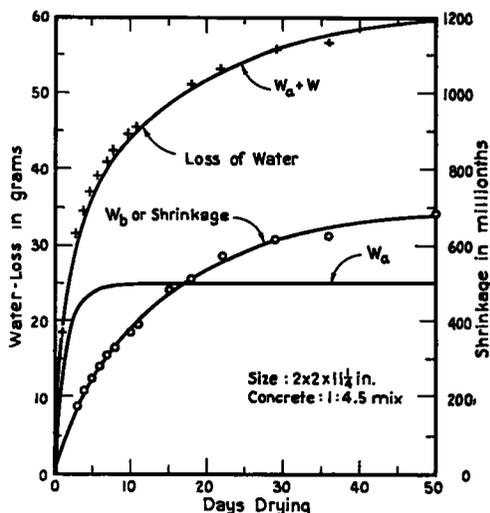


Figure 4. Time relationships for shrinkage and water-loss for a concrete specimen stored in air at 50 percent relative humidity (From *Proceedings*, American Concrete Institute, Vol. 43, p. 588.)

ments, revealing a considerable degree of uncertainty. It was suggested that as long as the paste-to-aggregate bond remained intact, expansion of the paste would be restrained.

Reference was made to Figure 4 showing that the shrinkage of concrete appears to be proportional to a certain fraction of the lost evaporable water. The results shown seem to be compatible with the assumption that the

change in volume is proportional to the change in the water content of the gel and is only incidentally connected with the change in the water content of the capillaries. That is,

$$\Delta V = \text{const. } x(\Delta w_e - \Delta w_c)$$

where  $\Delta V$  = change in volume of the specimen,

$\Delta w_e$  = change in evaporable water content, and

$\Delta w_c$  = change in capillary water content.

To account for differences in specific shrinkage found among pastes made with different types of portland cement Professor Pickett suggested that the differences might be due to the differences in specific surface of the gels produced by the different cements.<sup>8</sup> For example, cements high in tricalcium aluminate and in alkali and relatively deficient in gypsum show relatively high shrinkage and produce gels of high specific surface. Referring to the work of William Lerch,<sup>9</sup> he said that when the rate of reaction of such cements is properly corrected by increasing the gypsum content, the excessive shrinkage is eliminated and there is a concomitant reduction in specific surface of the gel.

As to the influence of the aggregate on the shrinkage of concrete, Professor Pickett referred to an equation introduced by Albert Einstein<sup>9</sup> showing that the apparent viscosity of a fluid is increased when spherical particles are suspended in the fluid, the increase in viscosity being (for small quantities) directly proportional to the volume fraction of the particles with respect to the volume of the whole system. Believing that such a relationship should apply to properties other than viscosity, Professor Pickett developed an equation to account for the reduction in drying shrinkage that is obtained when aggregate is combined with paste. He tested the theoretical relationship by combining a given kind of paste with various amounts and kinds of aggregate and then after a suitable period of curing, measuring the drying-shrinkage. The results were in fairly satisfactory agreement with the theory. Of particular interest was the fact that the effect on shrinkage was substantially independent of the size and grading of the aggregate, as predicted by the theory.

<sup>8</sup> Ref. B-2-23.

<sup>9</sup> Ref. B-2-18, 19, and 20.

These tests showed that at least 90 percent of the tendency of the paste to shrink is prevented by the presence of aggregate, a result in agreement with the earlier published results of R. W. Carlson.<sup>10</sup> It was pointed out that the differences in specific shrinkage found among concretes of various compositions may be expected to be due at least as much to differences in restraining effects of the aggregates as to the differences in the specific shrinkages of pastes made with different cements or at different water-cement ratios.

*Combined Hygric and Thermal Volume Changes.* Mr. S. L. Meyers described his studies of the thermal coefficients of cement paste and concrete.<sup>11</sup> He made specimens suitable for length-change measurements and sealed them in air-tight copper-foil jackets. From time to time he measured the thermal coefficient of the sealed specimens and found that the coefficient varied over a wide range as the specimens aged. The coefficient rose to a maximum and then subsided, the maximum being more than double the estimated coefficient of the original clinker from which the cement was made. Among specimens made with cements of various compositions, and with pure preparations of the compounds found in portland cement, he found considerable variations in the thermal coefficients at given ages. These variations seem to be related to the probable amounts of gel produced in the respective specimens during the period of hydration.

Of particular interest were his experiments in which certain specimens that had been cured in air-tight jackets were thoroughly dried by passing dry air through the jackets. The thermal coefficient of specimens so treated was substantially the same as that of the original clinker. In other experiments he soaked the specimens in water so as to restore the water lost by self-desiccation during the periods of storage in the sealed jackets. He found that the soaked specimens had practically the same thermal coefficient as the dried ones. The point of particular interest is that the thermal coefficient of the soaked and dried specimens is only about one-half that of the partially dried specimen.

Mr. Meyers said that this effect seemed to

<sup>10</sup> Ref. B-2-14.

<sup>11</sup> Ref. B-2-15.

be adequately explained in terms of the factors controlling swelling pressure as given in the Powers-Brownyard paper.<sup>12</sup> The relatively high thermal coefficients found among the specimens that had become partially dried in their air-tight jackets through self-desiccation was due to a hygric swelling or shrinking effect superimposed on the true thermal effect. The point was emphasized that under normal conditions of exposure concrete does not have a constant coefficient of thermal expansion,

solutes in the freezable water. The effect is attributed mainly to the colloidal characteristics of the cement gel. That the solutes have an effect, however, is clearly shown in the right-hand diagram of Figure 5. It will be seen that the final melting point, the temperature at which all ice disappears, is below the normal freezing point. In this particular case, the effect was due to the alkali in the cement, the percentage of which was abnormally high.

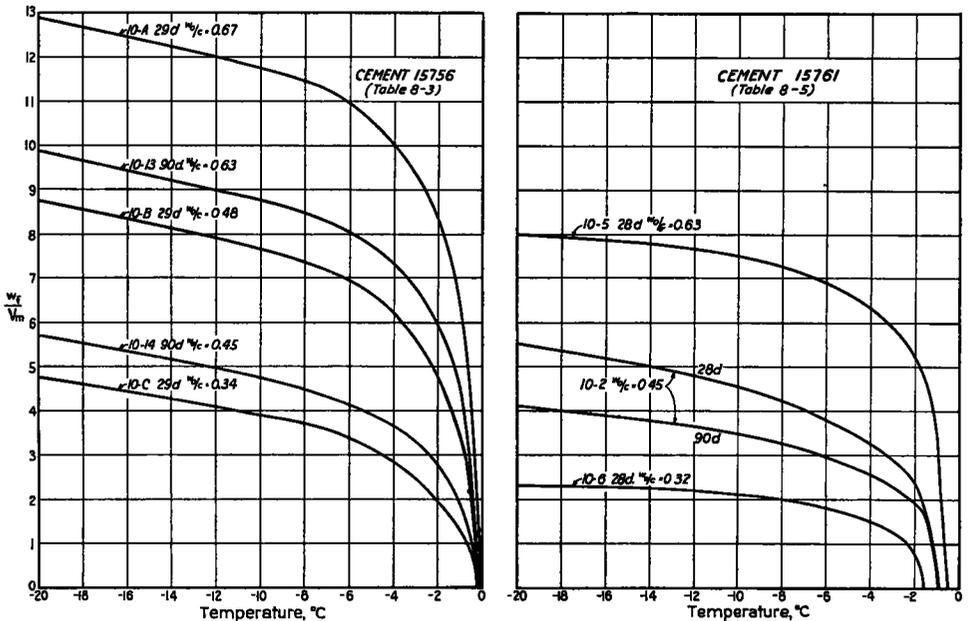


Figure 5. Relationship between ice content and temperature for samples made with cements indicated. (From *Proceedings, American Concrete Institute, Vol. 43, p. 957.*)

contrary to what is generally assumed in engineering calculations.

FREEZABLE WATER AND DURABILITY

The chairman presented data pertaining to factors that determine the amount of ice that can exist in cement paste at subfreezing temperatures.<sup>13</sup> Figure 5 was shown to illustrate the major features of the relationships. The amount of ice in any given specimen varies continuously with the temperature, the melting curves resembling those of a dilute aqueous solution. However, the curve for cement paste cannot be accounted for entirely by the

The curves in Figure 5 indicate that the amount of ice that may exist in a cement paste at a given temperature depends upon the water-cement ratio and age of the specimen. The capacity of a paste for freezable water can be computed from the original water-cement ratio and the nonevaporable water according to the following relationships:<sup>14</sup>

$$(w_f)_{+10^\circ} = w_o - 1.52w_n$$

$$(w_f)_{-4^\circ} = w_o - 1.44w_n$$

$$(w_f)_{-22^\circ} = w_o - 1.32w_n$$

(Temperatures are in F.)

<sup>14</sup> Previously, the numerical constants in these equations have been given as 1.76, 1.68, and 1.55, respectively. The figures now given are consistent with the change discussed in footnote 5.

<sup>12</sup> Ref. B-2-22.

<sup>13</sup> Ref. B-4-5 and 6.

in which  $w_f$  = the amount of water that may be frozen at the temperature indicated by the subscript, and the other symbols have the same significance as before.

There is evidence that ice cannot form in pastes that contain no capillary water. For practical purposes the amount of freezable water may be considered identical with the amount of capillary water. However, when capillary water is present and when the temperature is well below 10 deg., an appreciable amount of the gel water may be withdrawn from the gel and frozen with the capillary water.

Concrete can be so made that after a sufficient period of curing the paste can contain no freezable water. Therefore, in such concrete

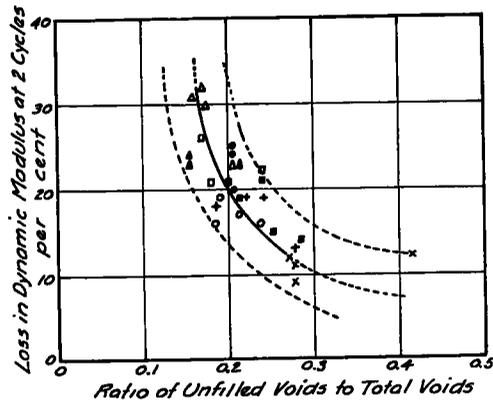


Figure 6. (From Missouri State Highway Department.)

freezing of water in the paste cannot be a cause of disintegration.

With various visitors participating, the discussion then centered around the techniques of laboratory freezing and thawing tests and the theory of frost action on concrete.

Mr. T. F. Willis described how the equations for calculating the amount of freezable water were applied in the Missouri State Highway laboratory to freezing and thawing data obtained several years ago. The results of this work are shown in Figure 6. This indicates a fairly satisfactory relation between performance in the laboratory test and the degree to which the capillary pores were filled with freezable water at the start of the test.

Professor Sweet told of applying similar methods with similar results at the University of Wyoming.

Reference was made to the work of Mr. Verbeck at the PCA laboratories.<sup>15</sup> In those tests a factor representing the degree of saturation with respect to capacity for freezable water (called the durability index) was found to correlate very well with the rate of disintegration in the laboratory tests for various specimens cured in a given way. But for the same kind of specimens cured in a different way the correlation was different from that for an unlike curing condition. This difference was evidence that a factor or factors other than the degree of saturation need to be taken into account if a general correlation is to be obtained.

In this connection reference was made to various laboratory tests, including those of Verbeck, showing that prolonged curing reduces the number of cycles that laboratory specimens can withstand. Professor Wendt told of the Highway Research Board cooperative series made a few years ago in which some specimens that had been moist-cured for several months failed in four or five cycles, whereas companion specimens cured 28 days withstood more than 100 cycles. It was thought that in this case the reduction in resistance might have been due to an increase in the degree of saturation at the start of the test.

However, other data were cited in which the specimens had been dried after the moist-curing period and then soaked for a short period before the beginning of the freezing and thawing test. In some of these tests specimens cured for 6 months were consistently less resistant to the test than were specimens cured for one month, even though measurements showed that the relative degrees of saturation at the start of the test were such as to be favorable to the specimens cured for the longer period.

Mr. F. H. Jackson, Public Roads Administration, as well as Professor Wendt (University of Wisconsin), directed attention to the fact that many tests show that prolonging the curing period increases the resistance to the freezing and thawing test. It was emphasized also that field experience was such as to lead

<sup>15</sup> This work was described by Mr. Gonnerman at a meeting of H.R.B. Project Committee B-1 "Durability of Concrete—Physical Reactions," Professor G. K. Wendt, *Chairman*. The work referred to by Professor Sweet was also presented at that meeting.

to skepticism concerning the reliability of such laboratory-test indications.

The chairman referred to an earlier paper<sup>16</sup> in which a theory of the mechanism of frost action was developed on the hydraulic-pressure premise. It was shown that according to this theory the intensity of hydraulic pressure produced on freezing depends upon the rate of freezing, the amount of freezable water, and the permeability of the material through which must be forced the water displaced by ice-formation. With the rate of freezing fixed and with permeability a constant factor, the intensity of pressure would be greater the greater the amount of freezable water. With the amount of freezable water fixed, the pressure intensity would be greater, the lower the coefficient of permeability. Since prolonging the curing reduces the freezable water and the coefficient of permeability simultaneously, and since these factors affect pressure intensity oppositely, it seemed theoretically possible that an optimum combination of the amount of freezable water and the degree of permeability might be found at some intermediate stage of hydration. It was pointed out also that this same hypothesis accounts for the alleviating effect of entrained air.

A visitor referring to the explanation of the effect of entrained air that was based on the hydraulic-pressure premise, suggested that the effect might better be explained on the basis of stress-strain relationships. It seemed that a paste containing many small empty cells could undergo large strains while developing relatively small stress.

Others present agreed that such an effect might be an important factor in accounting for improved frost resistance due to entrained air.

The chairman suggested that the statement of this possibility should be further developed into a working hypothesis by someone well versed in stress analysis. With such a hypothesis it would be possible to devise laboratory experiments to test it.

Professor Wendt pointed out that the ideas developed from the hydraulic-pressure premise as well as those based on a consideration of stress-strain relationships might all be valid to some degree—that such hypotheses are not mutually exclusive.

In connection with the question of the effect

<sup>16</sup> Ref. B-4-5.

of prolonged curing on the resistance of concrete specimens in laboratory tests, Mr. Rudolph C. Valore, Jr., National Bureau of Standards, described some of his unpublished studies on the volume changes that accompany freezing of saturated and partially saturated specimens. In these studies he measured the degree of saturation of the specimens at various stages of hydration, relative to the water content in the vacuum-saturated state. He found that the degree of saturation did not increase during a prolonged period of immersion in water. The water removed from the pores by self-desiccation during the early stages more than equaled the gain in weight of the specimen. At later stages the gain in weight could no more than equal the water removed by self-desiccation.

Freezing his specimens in mercury-filled dilatometers, Mr. Valore found that under conditions of rapid cooling, the older specimens were more severely damaged than younger specimens at the same degree of saturation. These results seemed to Mr. Valore to be in general agreement with the hypothesis based on the hydraulic-pressure premise. However, Mr. Valore was of the opinion that the pressures developed by water movement were developed by movements of microscopic, rather than macroscopic, magnitude.

#### SELECTED BIBLIOGRAPHY PERTAINING TO WATER IN PASTE OR CONCRETE, ITS PROPERTIES AND RELATIONSHIPS TO THE SOLID MATERIAL

- A. Capillary Phenomena in Fresh Paste
- B. Water in Hardened Paste
  - 1. General
  - 2. Volume Change, Hygric and Thermal
  - 3. Self-Desiccation and Its Effects
  - 4. Freezing, and the Mechanism of Destruction by Frost
  - 5. Miscellaneous Physical Properties: Strength; Plastic Flow or Creep; Absorptivity; Permeability; Moisture Diffusion

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## FREEZE AND THAW DURABILITY OF AIR-ENTRAINED CONCRETE USING INDIANA AGGREGATES

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### SYNOPSIS

This paper reports a study of the freeze and thaw durability of seven Indiana aggregates used in concrete with varying air contents. The purpose of the study was to determine the effect of air-entrainment on the durability characteristics of concrete made with certain aggregates which were chosen for their absorptive and performance characteristics as being fairly representative of those available in Indiana. Two aggregates used by Bugg (8)<sup>1</sup> were used as a means of correlating results of the two studies.

Each of the seven aggregates was divided into two groups. One group was vacuum-saturated and the other was subjected to 24-hr. immersion before mixing. The air content from batch to batch for each aggregate was varied by increments of approximately 1 percent. Seventy-five batches were mixed with air contents ranging from 0.1 to 10.9 percent as determined by the pressure method.

Three 3- by 4- by 16-in. beams from each batch were subjected to freeze and thaw tests. Two of the three beams were cured 28 days in water while the third was cured 14 days in water followed by 14 days dry curing with one 4-in. side in damp sand. The dry-cured beam from each batch lost from 60 to 250 g. weight depending upon the absorption of the coarse aggregate used and the percentage air entrained in the mix. This loss in weight was assumed to be the result of the evaporation of free water. The laboratory durability of the dry-cured beam, made with aggregates with poor performance records, was improved several hundred percent in comparison with the two companion beams cured in water. A saturation coefficient has been devised to evaluate this marked increase in resistance to freeze and thaw testing.

In 1945, a pavement performance survey was reported by Woods, Sweet, and Shelburne (7) in which the performance of 500 projects totaling 3300 mi. or 78 percent of the concrete pavement in Indiana was studied. The report shows a close correlation between the coarse aggregate used in the pavement concrete and the number of blowups which had occurred regardless of other variables such as subgrade soil, cement, or fine aggregate.

<sup>1</sup> Italicized numbers in parentheses indicate references listed in the References at the end of the paper.

In a study of the laboratory durability<sup>2</sup> of concrete, Sweet (1) and other investigators have found that concrete made with poor field-performing aggregates would fail in freeze-thaw testing in a very few cycles while concrete made with good field-performing aggregate would withstand several hundred cycles of freezing and thawing. On the basis of Sweet's study, Bugg (8) investigated the effect of air-entrainment on the freeze-thaw durability of concrete made with four Indiana

<sup>2</sup> “Durability” as used in this paper refers to resistance to freezing and thawing in laboratory tests.