

# EFFECT OF MORTAR SATURATION IN CONCRETE FREEZING AND THAWING TESTS

THOMAS M. WHITESIDE<sup>1</sup> AND HAROLD S. SWEET, *University of Wyoming*

## SYNOPSIS

This paper presents the results of laboratory freezing and thawing tests on concrete in which certain variables were controlled as closely as possible so that variations in durability could be related to variations in the water content and available air space in the mortar or paste component. A total of 130 concrete beams from 31 batches of concrete were tested. Changes in weight and in unit weight were determined at intervals through the course of curing and freezing and thawing. Methods were developed for using these data in calculating the degree of saturation of the mortar phase of the concrete, in connection with a semi-empirical calculation of the change in volume of the cement-plus-combined-water component, and an estimate of freezable water based on relationships with the "nonevaporable water content" of the cement.

It is concluded, on the basis of these tests, that concrete subjected to freezing and thawing when the mortar component (or, more precisely, paste-plus-air component) has a degree of saturation of 0.91 or greater will deteriorate rapidly; in this study all specimens in this range showed rapid deterioration. All specimens with degree of saturation below 0.88 were highly durable although it is recognized that deterioration in this range may be caused by a variety of factors such as expansion of inferior aggregates, differential thermal expansion of concrete components, hydraulic pressure from resistance to flow of water, non-uniform distribution of freezable water, or adverse chemical reactions. It is further concluded that investigations of factors such as different concrete materials or admixtures should be conducted with the degree of saturation on the order of 0.80 so that the results can be considered to reflect the influence of the variable under investigation. A high degree of saturation may obscure entirely other effects. The lower degree of saturation is conveniently obtained by air entrainment. Other conclusions are drawn with regard to water absorption in air-entrained concrete and in partially-dried concrete.

In many investigations of concrete resistance to freezing and thawing, it has been determined that very rapid deterioration occurred when the concrete had a low air content and water was readily available for absorption. This rapid deterioration occurred in spite of other conditions commonly supposed to insure good durability, such as high cement factor, low water-cement ratio, and aggregate of unquestioned quality. It has been indicated in a qualitative manner that the concrete may have been highly saturated with freezable water (17)<sup>2</sup>. On the other hand, freezing and thawing tests made with air-entrained concrete have shown this material to have a generally high resistance to this treatment when good aggregates were also used. In an attempt to study

these effects quantitatively, the tests reported in this paper were conducted with variables controlled as closely as possible so that variations in durability could be related to the degree of saturation of the mortar.

The determination of relationships between the physical characteristics of the paste and the resistance of concrete to freezing and thawing is of importance not only from the standpoint of construction of concrete which will be durable in field exposure, but also in the development of test procedures for evaluating the effect of other variables, such as aggregate, on resistance of the concrete to freezing and thawing.

In the tests described in this paper, a limestone aggregate with good field performance and with low absorption and low void content was used in concrete with different cement factors and different amounts of entrained air. Changes in weight and volume of the concrete beams were measured during cur-

<sup>1</sup> Now Assistant Research Engineer, Portland Cement Association, Chicago, Illinois.

<sup>2</sup> Numbers in parentheses refer to references listed at the end of the paper.

ing and during freezing and thawing. These data were used to calculate the volume of air in the concrete at various stages and the volume of freezable water. The effect of these variables on resistance to freezing and thawing action was analyzed and the results are discussed in relation to some of the late developments in this field.

It has become widespread practice to specify that concrete exposed to ice-removing chemicals or to freezing and thawing shall have from 3 to 6 percent of air entrained (3). Many field and laboratory studies have indicated that this amount of entrained air will markedly improve the resistance of the concrete to such actions. Among the many effects of the entrained air on the properties of concrete it is considered that the "... numerous well dispersed air voids provide reservoirs for the relief of pressure created by differential volume movements in the concrete caused by temperature change and by the expansion accompanying the transition of water to ice. This contribution to durability is reinforced by the reduced w/c and lack of channelization of the matrix due to bleeding." (18)

Papers by Bugg (2) and by Blackburn (1) show that concrete made with durable aggregates can withstand only a few cycles of freezing and thawing when the air content is on the order of one percent, whereas a very small increase in this air content is sufficient to give tremendous increases in durability. In a discussion of Blackburn's paper, Sweet (10) suggested a method for estimating the degree of saturation of the mortar in concrete in which the aggregate moisture content may be considered constant. The degree of saturation, or degree to which the pore space is filled with freezable water, is defined as the ratio of the volume of freezable water to the sum of the volumes of freezable water and air space. This definition, which is based on developments of Powers for estimation of freezable water content and changes in volume of the hydrating paste, was used in evaluating the data in the investigation reported here.

The significance of the degree of saturation in affecting the resistance of materials to freezing is based on the approximately nine percent increase in volume which occurs when water crystallizes to ice. If this expansion is restrained through lack of available air space, pressures as high as 29,000 psi. may be exerted

(when the temperature is as low as  $-8$  deg. F.). Under these conditions, considerable damage might be expected if the pore space is more than 91 percent filled with freezable water. In considering the bulk of a porous material, it should be noted that certain regions might be more than 91 percent saturated while the average degree of saturation was below this value. In order for these regions to escape damage it would be necessary for the unfrozen water, liquid because of pressure, to flow to the available air space. This consideration led Powers to the hydraulic-pressure hypothesis (7) of the mechanism of frost damage to concrete. Recently he has extended this hypothesis to estimate the "Air Requirement of Frost-Resistant Concrete" (8) in which he develops equations for  $A$ , the required air content, and concludes that "... the higher the specific surface of the voids, the smaller the air requirement—provided that  $A$  always exceeds the possible total expansion of the freezable water."

Many other factors besides degree of saturation may influence the durability of concrete. In addition to the important chemical actions, such as alkali-aggregate reaction, temperature changes and freezing may cause damage from differential thermal expansion of the different components, from disruption or expansion of inferior coarse aggregates (11), or from hydraulic pressure, particularly when rate of temperature change is high. Methods for controlling or eliminating these variables are necessary for the proper development of information leading to greater durability.

#### MATERIALS AND METHODS

A total of 130 concrete beams were fabricated for this study. They were made with three cement factors, 4.0, 5.0, and 6.5 sacks per cu. yd., and with air contents ranging from one to thirteen percent. A single lot of cement, and aggregate from one source, were used in all of the concrete.

*Description of Materials*—Type II portland cement from one mill batch was obtained and stored in sealed containers. The chemical analysis of the cement is shown in Table 1. A single air-entraining agent, Darex, was added at the mixer in batches in which higher air contents were desired.

Both coarse and fine aggregate were pro-

duced by crushing limestone from the Casper formation, Pennsylvanian period. This was a high-calcium limestone containing 5 to 16 per cent quartz sand as impurities. It has a good, although limited, field service record. Rock for most of the concrete batches was carefully selected to avoid obtaining weathered or porous particles, and was crushed to the desired

tion); it was expected that the aggregate component would be resistant to freezing and thawing (11).

The aggregate retained on the No. 50 sieve was recombined in the proportions shown in Table 2 and was soaked overnight. The weight of the absorbed water was subtracted from the total water in the aggregate for calculation of the mixing water. The crushed limestone passing the No. 50 sieve was added dry at the mixer. Corrections for entrained air were made by reducing the volume of material passing the No. 50 sieve by one percent of the volume of aggregate for each one percent increase in air content.

*Concrete Mixing, Placing, and Curing*—Each batch of 0.4 cu. ft. was mixed in a 1-cu. ft. rotating drum mixer turning at 23 r.p.m. The following sequence of operations was observed:

1. The mixing drum was wetted and the free water drained.
2. The mixer was started and approximately one-third of the wet aggregate, water, dry fines, and cement was added.
3. Step 2 was repeated at intervals of 30 sec. until the entire batch was in the mixer.
4. The air-entraining agent was added after shaking (15) and the timing of the mixing operation was started.
5. After 5 min. of continuous mixing the concrete was dumped into a damp pan; the mixer drum was scraped to remove the adhering paste which was added to the pan.
6. The concrete was then mixed by hand to obtain an even consistency.
7. A standard slump test and unit weight test were made and the air content was determined by the Washington Method (14). A correction of 0.3 percent was made for air in the aggregate, determined as recommended by Klieger (4) with the exception that the volume of water removed from the container prior to making the test was equivalent to one percent of the volume of the container.

The fresh concrete was placed in four steel molds (lightly oiled) having the inside dimensions 3 by 2½ by 13½ in. A light application of wheelbearing grease was given the joints of the molds to make them watertight. The concrete was placed in three layers, each layer

TABLE 1  
CHEMICAL ANALYSIS AND COMPOUND  
COMPOSITION OF CEMENT

SiO <sub>2</sub>	22.18%
Al <sub>2</sub> O <sub>3</sub>	4.37
Fe <sub>2</sub> O <sub>3</sub>	4.91
CaO	60.80
MgO	0.92
SO <sub>3</sub>	1.69
Loss on Ignition	3.00
Insoluble Residue	0.57
Na <sub>2</sub> O	0.14
K <sub>2</sub> O	0.40
Total Alkalies	0.40
C <sub>2</sub> S	37.6
C <sub>3</sub> S	35.3
C <sub>4</sub> A	3.3
C <sub>1</sub> AF	14.9

TABLE 2  
AGGREGATE PROPERTIES

	Sample 1	Sample 2 <sup>a</sup>
Bulk Specific Gravity (Oven-dry)	2.56	2.48
Bulk Sp. Gr. (Saturated Surface-dry)	2.58	2.53
Apparent Specific Gravity	2.63	2.60
True Specific Gravity <sup>b</sup>	2.73	2.73
Percentage Absorption	0.85	1.80
Calculated total void volume	0.061	0.099

Gradation:	Coarse and Fine	Sample 1 and Sample 2	
		Coarse	Fine
Passing ¾-in. sieve	100.0	100.0	
Passing ½-in. sieve	81.7	60.0	
Passing ¼-in. sieve	72.6	40.0	
Passing No. 4 sieve	54.3	0	100.0
Passing No. 16 sieve	32.6		60.0
Passing No. 50 sieve	13.6		25.0

<sup>a</sup> Used in batches 10A3, 11B0, 12A0, 13A4.

<sup>b</sup> Specific Gravity of powdered material passing No. 50 sieve.

particle sizes. For batches designated 10A3, 11B0, 12A0, and 13A4, run-of-the-quarry stone was used; this material had an average porosity slightly higher than that of the first sample. Specific gravities, absorption, and gradation of the aggregate are shown in Table 2. It should be noted that the total void volume of sample 1 was calculated as 0.061 and of sample 2, 0.099. In view of these low porosities, and since the aggregate was incorporated in the concrete after soaking overnight (attaining less than 50 percent satura-

was rodded 25 times, and after each layer was rodded the mold was struck lightly with a bronze mallet until all observable air spaces were filled. The surface was finished with a dampened wooden float 1 by 3 by 12 in. from which all free water had been wiped. The molded concrete was then placed in a moist box. After 24 hr. the beams were removed

in accordance with the Tentative Method of Test for Fundamental Transverse Frequency of Concrete Specimens, A.S.T.M. Designation C215-47T (19). One beam from each batch was broken in flexure by third-point loading in accordance with the A.S.T.M. Standard Method C78-49.

Two beams from each batch were immediately subjected to a freezing and thawing test in which they were frozen in air at -10 deg. F. and thawed in running water at 57 ± 3 deg. F. The fourth beam was dried in air at room temperature for 7 days and then immersed in water to one-half its depth for 7 days. At the expiration of this 14-day partial drying period, the beam was weighed in air and water, change of length was measured, dynamic E was obtained, and the beam was

TABLE 3  
CONCRETE MIX DATA

Batch No.	Cement Factor	Air Cont.	Water-Cement Ratio by wt.	Slump	Darex	Unit Weight
	<i>sacks per cu. yd.</i>	<i>%</i>		<i>in.</i>	<i>cc.</i>	<i>lb. per cu. ft.</i>
1C0	3.87	1.6	0.98	3.5	0	144.7
2C0	3.88	1.6	0.98	2	0	145.1
3C0	3.89	1.4	0.98	3	0	145.6
1C2	3.88	2.0	0.98	2.5	2	144.5
1C5	3.90	5.1	0.95	4.5	5	137.6
1A8	4.34	9.0	0.81	4.5	8	134.0
1AY	4.15	12.0	0.85	6.5	6	139.1
1AX	4.05	13.0	0.85	6.8	8	127.3
3A0	4.96	1.3	0.71	1	0	147.5
4A0	4.96	1.3	0.71	1.5	0	147.4
5A0	4.95	1.3	0.71	1	0	147.2
6A0	5.03	1.8	0.71	1.8	0	146.9
7A0	5.04	1.7	0.71	2	0	147.2
12A0	4.92	1.35	0.69	1	0	145.3
10A3	4.93	2.2	0.68	2	3	144.4
13A4	5.00	1.9	0.66	1	4	144.3
1A3	4.97	3.0	0.71	2	3	145.3
2A3	4.96	3.0	0.71	2.2	3	145.0
1A4	4.91	3.7	0.71	3.2	4	143.5
1A5	4.85	4.7	0.71	2	5	141.3
1B0	6.41	1.0	0.67	4.5	0	145.9
2B0	6.37	1.0	0.68	5	0	145.2
3B0	6.38	1.0	0.68	5	0	145.6
1B1	6.47	1.6	0.63	2	0	146.7
2B1	6.43	1.8	0.63	3.5	0	145.5
3B1	6.47	1.4	0.63	3.5	0	146.5
11B0	6.36	1.5	0.59	1	0	144.1
1B2	6.35	3.0	0.63	4.5	2	143.9
1B4	6.62	3.0	0.58	1.5	5	144.8
1A6	6.07	6.0	0.85	3.5	7	138.7
1B7	6.28	6.2	0.59	3.5	9	137.6

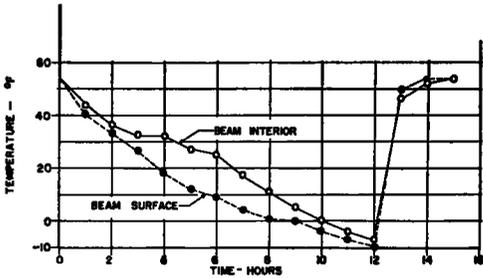


Figure 1. Temperature Variation During a Freeze—Thaw Cycle

subjected to freezing and thawing cycles. The rates of freezing and thawing were determined from thermocouples at the surface and imbedded at the center of a dummy beam. These data, plotted in Figure 1, show that the rate of temperature change from 32 to 28 deg. F. was 2.5 deg. per hr. at the center of the specimen and 7.0 deg. per hr. at the surface.

When the beams had lost 30 percent of the 28-day dynamic E, they were checked for length changes, weighed in air and water and then broken in flexure. Those which did not sustain a 30 per cent loss in dynamic E were subjected to 200 cycles, at the end of which they were placed in frozen storage.

It was necessary to vary the freezing and thawing procedure occasionally in order to maintain constant the load on the freezer. The beams which could not be accommodated were stored in a frozen condition. There was no change in weight or in dynamic E of these

from the molds, and weights in air and water were obtained. All beams were immersed in water at room temperature. The data on the characteristics of the fresh concrete are given in Table 3.

**Concrete Tests**—At 28 days of age the beams were removed from the water bath; weights in air and water were obtained and the lengths were compared to a standard Invar rod. The dynamic modulus of elasticity (hereafter referred to as dynamic E) was determined in

beams during the storage period of up to 10 weeks.

#### RESULTS

The results of the freezing and thawing tests for the specimens tested after water curing are summarized in Tables 4, 5, and 6. Results of the tests on partially dried specimens are given in Table 7. These Tables also show the calculated changes in air volume which occurred during curing, and the degree of saturation determinations. The development of methods for these calculations is discussed below, followed by analysis and discussion of results. The resistance to freezing and thawing was evaluated by the "Durability Factor", defined as (13)

$$DF = \frac{PN}{200}$$

where DF = durability factor;  $P$  = relative dynamic modulus of elasticity in percentage of the dynamic modulus at zero cycles; and  $N$  = number of cycles at which  $P$  reaches 70 percent, or 200 if  $P$  does not reach 70 percent prior to the end of the test.

*Calculation of Degree of Saturation*—The determinations of weight in air and in water showed that the concrete absorbed water during the curing period and that the unit weight increased over the value obtained for the fresh concrete. The absorption of water would tend to decrease the air content and the increase in unit weight, over that to be expected from the increase in weight, would reflect a decrease in the concrete volume at the expense again, presumably, of the air content. Tending to offset these effects would be the decrease in the space occupied by the cement and combined water. By estimating the changes in air space caused by these three factors, a determination of the net air space after curing may be made.

The first of these factors, the space occupied by the water absorbed during curing, may be calculated from the change in weight of the concrete beam, assuming density of this water to be 62.4 lb. per cu. ft. The weight of water absorbed in pounds per cubic foot of fresh concrete,  $\Delta W$ , would be

$$\Delta W = \frac{\delta w \times d_0}{W_b}$$

where  $\delta w$  = change in weight of the concrete beam

$W_b$  = initial weight of the concrete beam

$d_0$  = unit weight of fresh concrete.

The volume  $V\Delta W$  of this absorbed water would be  $\Delta W/62.4$ .

The change in air content due to change in volume may be calculated from the changes in weight and the unit weight. If a cubic foot of the fresh concrete with unit weight  $d_0$  is considered, then  $d_0 = W_0/1$ , where  $W_0$  is the total weight of ingredients in a cubic foot. After curing, the unit weight,  $d_i$ , of this same quantity of concrete would be  $d_i = (W_0 + \Delta W)/V_i$ , where  $V_i$  is the volume after curing of the concrete initially one cubic foot in volume. The difference in volume,  $V_i - 1$ , would represent the change in air volume if all other ingredients had remained the same in volume. Then

$$\Delta V = V_i - 1 = \frac{W_0 + \Delta W}{d_i} - 1$$

Since

$$W_0 = d_0, \quad \Delta V = \frac{d_0 + \Delta W - d_i}{d_i}$$

In this expression  $d_i$  and  $d_0$  are obtained directly by measurement and  $\Delta W$  is calculated from the change in weight.

However, the change in volume  $\Delta V$  can not be taken solely as a change in air content since the volume of cement plus combined water is less than the sum of the volumes of unhydrated cement and mixing water. This shrinkage in volume of these components probably accounts for much of the volume change, hence the net air content is not affected to so great a degree. In evaluating this effect it is convenient, however, to consider these separately and consider the cement-water shrinkage as a contribution tending to restore the air content. Its magnitude was shown by Powers and Brownyard (9), p. 711) to be equivalent to a change in the specific volume of water,  $V_t$ , from 1.0 to

$$V_t = 1 - 0.279 \frac{w_n}{w_t}$$

where  $w_n$  = non-evaporable water content of the cement and  $w_t$  = total weight of water.

Powers and Brownard note that the lower limit for  $V_t$  is 0.86, occurring when the paste contains no capillary water and  $w_n/w_t$  is 0.50. In a later publication (6) Powers notes that the limit 0.86 "... is too high; it consistently gives negative porosity when applied to rich and well cured pastes. The figure 0.75 used above is that required to avoid such a result. ..." Use of the relationship  $V_t = 1 - 0.279w_n/w_t$  in this investigation also gave values of negative porosity; the space provided by this shrinkage in volume of hydrated

weight of water per cu. ft. of fresh concrete, its change in volume,  $\Delta V_w$ , is

$$\Delta V_w = \frac{w_t}{62.4} - \frac{w_t}{62.4} \times V_t = \frac{w_t}{62.4} (1 - V_t)$$

$$\Delta V_w = \frac{w_t}{62.4} \times 0.50 \times \frac{Cw_n}{w_t} = \frac{0.50Cw_n}{62.4}$$

The constant  $w_n$  was determined for the cement used in this investigation following the procedure outlined by Powers (6). Its value for all of the water-cement ratios used

TABLE 4  
DURABILITY AND DEGREE OF SATURATION OF CONCRETE WITH NOMINAL CEMENT FACTOR OF 4 SACKS PER CUBIC YARD—WET CURED

Beam	Orig. Air Cont.	No. of Cyc F & T	Loss in "E"	Durability Factor	Curing Water Absorbed	Volume Change During Curing	Calc. Chg. in Vol. of Cem. plus Comb. Wat.	Net Air at Start of Freezing	Volume Freezable Water	Degree of Saturation $V_{fw}/(V_{fw} + V_A)$		
										28-day	After F & T	Avg.
	%		%			Units: Cubic feet per cubic foot of fresh concrete						
1C0A	1.6	3	42.2	0.7	0.0107	-0.0143	0.0151	0.0061	0.1629	0.96	0.96	0.96
B	1.6	3	37.3	0.8	0.0114	-0.0119	0.0151	0.0078	0.1636	0.95	0.95	0.95
2C0A	1.6	3	33.2	0.9	0.0070	-0.0100	0.0152	0.0142	0.1601	0.92	0.94	0.93
B	1.6	3	39.1	0.8	0.0063	-0.0127	0.0152	0.0122	0.1594	0.93	0.96	0.94
3C0A	1.4	2	40.3	0.5	0.0081	-0.0133	0.0152	0.0078	0.1615	0.95	0.98	0.97
B	1.4	2	29.6	0.7	0.0063	-0.0106	0.0152	0.0123	0.1597	0.93	0.95	0.94
1C2C	2.0	5	56.5	0.9	0.0132	-0.0089	0.0152	0.0131	0.1663	0.93	0.93	0.93
D	2.0	5	57.0	0.9	0.0125	-0.0115	0.0152	0.0112	0.1656	0.94	0.95	0.94
1C5A	5.1	200	1	99.0	0.0138	-0.0193	0.0153	0.0332	0.1609	0.83	0.81	0.82
B	5.1	200	0	100.0	0.0170	-0.0144	0.0153	0.0349	0.1641	0.82	0.83	0.83
1A8A	9.0	184	0.5	99.0	0.0130	-0.0343	0.0170	0.0597	0.1428	0.70	0.74	0.72
C	9.0	207	0	100.0	0.0155	-0.0306	0.0170	0.0609	0.1453	0.70	0.74	0.72
1A4A	12.0	179	0	100.0	0.0155	-0.0329	0.0164	0.0680	0.1490	0.63	0.65	0.64
B	12.0	204	1	99.0	0.0179	-0.0281	0.0164	0.0904	0.1514	0.63	0.65	0.64
1AxB	13.0	200	0	100.0	0.0168	-0.0328	0.0158	0.0982	0.1470	0.60	0.65	0.63
C	13.0	200	0	100.0	0.0177	-0.0365	0.0158	0.0916	0.1479	0.62	0.65	0.63

paste plus the original air content was less than the calculated decrease in air content due to concrete shrinkage and absorption of water. The revised figure for the value of  $V_t = 0.75$  when the paste contains no capillary water can be employed by changing the constant term 0.279 to 0.50 to relate the contraction in volume to the nonevaporable water content and total water content.

To calculate the magnitude of this effect on the cubic foot of fresh concrete: if  $w_n$  is the nonevaporable water content in lb. per lb. of cement, the total nonevaporable water content is  $C \times w_n$ , where  $C$  is the weight of cement per cu. ft. of fresh concrete. If  $w_t$  is the total

was 0.14 g. per g. of cement after curing period in water of 28 days. Substituting this value the relationship above reduces to

$$\Delta V_w = 0.00112C$$

This was used in calculating the values in Tables 4 to 7 for change in volume of cement plus combined water. Some empirical justification for the constant is gained from the result that values of less than 0.001 would indicate net negative air content in mix 13A4, and values less than 0.0008 would give negative air contents for many of the mixes.

The net air content after curing  $V_A$  was calculated as  $V_A = V_{A0} - V_{\Delta w} + \Delta V + \Delta V_w$

where  $V_{A0}$  is the initial air content of the fresh concrete.

The weight of freezable water  $w_f$  was obtained from the relationship given by Powers and Brownyard ((9), p. 965):  $w_f = w_i - 1.96 w_n$  (for a temperature of  $-4$  deg. F.). Its volume  $V_f$  was taken as  $w_f/62.4$ .

was true without exception for 32 specimens from 14 mixes and indicates a high degree of reproducibility for the test in this range. On the other hand no specimen with 3 percent or more air initially had a durability factor of less than 88.0 (12 percent loss in E in 200 cycles). This was reproduced without excep-

TABLE 5  
DURABILITY AND DEGREE OF SATURATION OF CONCRETE WITH NOMINAL CEMENT FACTOR OF 5 SACKS PER CUBIC YARD—WET CURED

Beam	Orig. Air Cont.	No. of Cyc. F & T	Loss in "E"	Durability Factor	Curing Water Absorbed	Volume Change During Curing	Calc. Chg. in Vol. of Cem. plus Comb. Wat.	Net Air At Start of Freezing	Volume Freezable Water	Degree of Saturation		
										Start of Freez.	After F & T	Avg.
	%		%		<i>Units: Cubic feet per cubic foot of fresh concrete</i>							
3A0B	1.3	3	27.0	1.2	0.0100	-0.0186	0.0194	0.0088	0.1309	0.95	0.93	0.94
D	1.3	3	25.3	1.2	0.0128	-0.0085	0.0194	0.0111	0.1337	0.92	0.90	0.91
4A0A	1.3	3	29.1	1.1	0.0100	-0.0169	0.0194	0.0085	0.1309	0.95	0.95	0.95
B	1.3	3	33.1	0.9	0.0107	-0.0119	0.0194	0.0098	0.1316	0.93	0.95	0.94
5A0C	1.3	3	23.5	1.3	0.0113	-0.0145	0.0194	0.0086	0.1321	0.95	0.95	0.95
D	1.3	3	26.7	1.2	0.0121	-0.0116	0.0194	0.0087	0.1329	0.94	0.93	0.93
6A0C	1.8	8	24.4	3.4	0.0115	-0.0096	0.0197	0.0166	0.1342	0.89	0.90	0.89
D	1.8	8	28.1	3.0	0.0120	-0.0105	0.0197	0.0182	0.1347	0.90	0.90	0.90
7A0A	1.7	6	26.9	2.3	0.0133	-0.0086	0.0197	0.0148	0.1362	0.90	0.90	0.90
B	1.7	6	27.6	2.3	0.0113	-0.0152	0.0197	0.0102	0.1342	0.93	0.93	0.93
12A0F	1.35	5	29.0	1.8	0.0123	-0.0050	0.0193	0.0155	0.1261	0.89	0.91	0.90
D	1.35	4	37.7	1.1	0.0127	-0.0062	0.0193	0.0139	0.1265	0.90	0.91	0.90
B	1.35	4	37.9	1.1	0.0107	-0.0104	0.0193	0.0117	0.1245	0.91	0.92	0.92
A	1.35	4	33.2	1.3	0.0060	-0.0150	0.0193	0.0118	0.1198	0.91	0.90	0.91
10A3D	2.2	46	29.1	16.6	0.0085	-0.0154	0.0193	0.0174	0.1196	0.87	0.90	0.89
A	2.2	111	12	77.0	0.0099	-0.0128	0.0193	0.0186	0.1210	0.87	0.90	0.88
13A4E	1.9	24	33.1	7.6	0.0111	-0.0249	0.0196	0.0026	0.1261	0.98	0.96	0.97
D	1.9	11	31.6	3.6	0.0073	-0.0272	0.0196	0.0041	0.1163	0.97	0.94	0.95
A	1.9	11	30.5	3.8	0.0175	-0.0143	0.0196	0.0068	0.1265	0.95	0.98	0.96
1A3C	3.0	291	8	97.0	0.0130	-0.0179	0.0195	0.0186	0.1340	0.88	0.88	0.88
D	3.0	200	9	91.0	0.0136	-0.0188	0.0195	0.0171	0.1346	0.89	0.88	0.89
2A3C	3.0	204	12	88.0	0.0143	-0.0208	0.0194	0.0143	0.1351	0.90	0.90	0.90
D	3.0	204	4	96.0	0.0156	-0.0191	0.0194	0.0147	0.1364	0.90	0.91	0.90
1A4B	3.7	203	5	95.0	0.0094	-0.0187	0.0192	0.0281	0.1288	0.82	0.85	0.84
C	3.7	208	5	95.0	0.0082	-0.0183	0.0192	0.0297	0.1376	0.82	0.82	0.82
1A5A	4.7	200	5	95.0	0.0100	-0.0310	0.0190	0.0250	0.1281	0.84	0.83	0.84
B	4.7	327	0	100.0	0.0125	-0.0289	0.0190	0.0246	0.1305	0.85	0.84	0.85

The degree of saturation was defined as  $S = V_f/(V_f + V_A)$ . Values were calculated for this ratio for each beam at the start of freezing, at the end of the freezing and thawing tests, and the average of these.

#### RESULTS OF FREEZING AND THAWING TESTS

Tables 4 to 6 show that, regardless of cement factor, the wet-cured concrete with less than 1.8 percent air initially suffered a loss of 30 percent in Dynamic E in 6 cycles or less; the maximum durability factor was 2.3. This

was true without exception for 32 specimens from 14 mixes and indicates a high degree of reproducibility for the test in this range. On the other hand no specimen with 3 percent or more air initially had a durability factor of less than 88.0 (12 percent loss in E in 200 cycles). This was reproduced without excep-

tion in 24 specimens from 12 mixes. Between these ranges of excellent reproducibility, there were 11 specimens from 5 mixes with initial air contents from 1.8 to 2.2 percent with durability factors varying from 0.9 to 77. Table 7 shows that the partially-dried concrete with initial air contents of 2 percent or less had durability factors varying from 5.2 to 21.9. No specimens were tested in the range of 2 to 3 percent air content, but all of those with initial air contents of 3 percent or more had durability factors greater than 97.

Comparison of durability factor with the degree of saturation at the start of freezing of water-cured beams may be summarized as follows. The resistance of water-cured beams was high for initial degrees of saturation below 0.87, all of the 20 concrete beams in this range showing less than 0.04 percent loss in E per cycle (durability factor 92 or greater).

to 96 in durability factor. Thirty-five specimens with degree of saturation 0.91 or higher were all below 8 in durability factor.

It appears that the durability may be predicted with slightly more accuracy from the average degree of saturation than from either the initial air content or the initial degree of saturation before the freezing starts. It should

TABLE 6  
DURABILITY AND DEGREE OF SATURATION OF CONCRETE WITH NOMINAL CEMENT FACTOR OF 6.5 SACKS PER CUBIC YARD—WET CURED

Beam	Orig. Air Cont.	No. of Cyc. F & T	Loss in "E"	Durability Factor	Curing Water Absorbed	Volume Change During Curing	Calc. Chg. in Vol. of Cem. plus Comb. Wat.	Net Air at Start of Freezing	Volume Freezable Water	Degree of Saturation		
										Start of Freez.	After F & T	Avg.
<i>Units: Cubic feet per cubic foot of fresh concrete</i>												
1B0A	1.0	2	29.5	0.7	0.0088	-0.0183	0.0251	0.0080	0.1506	0.95	0.96	0.95
B	1.0	2	27.9	0.7	0.0101	-0.0128	0.0251	0.0122	0.1519	0.92	0.93	0.93
2B0A	1.0	4	34.1	1.2	0.0145	-0.0128	0.0248	0.0075	0.1587	0.95	0.96	0.96
D	1.0	4	37.8	1.1	0.0158	-0.0086	0.0248	0.0104	0.1600	0.94	0.96	0.95
3B0A	1.0	4	39.0	1.1	0.0132	-0.0107	0.0250	0.0111	0.1580	0.94	0.94	0.94
D	1.0	4	37.2	1.1	0.0139	-0.0108	0.0250	0.0103	0.1587	0.94	0.94	0.94
1B1A	1.6	5	24.1	2.2	0.0171	-0.0151	0.0253	0.0091	0.1458	0.94	0.94	0.94
B	1.6	5	30.6	1.7	0.0133	-0.0118	0.0253	0.0162	0.1420	0.90	0.90	0.90
2B1A	1.8	6	32.3	1.9	0.0124	-0.0194	0.0252	0.0114	0.1403	0.93	0.92	0.92
B	1.8	6	29.4	2.1	0.0138	-0.0167	0.0252	0.0127	0.1417	0.92	0.94	0.93
3B1C	1.4	4	33.6	1.2	0.0164	-0.0082	0.0253	0.0147	0.1451	0.92	0.93	0.92
D	1.4	4	34.1	1.2	0.0165	-0.0104	0.0253	0.0124	0.1452	0.91	0.93	0.92
11B0F	1.5	4	27.1	1.5	0.0159	-0.0143	0.0248	0.0096	0.129	0.93	0.93	0.93
D	1.5	4	29.8	1.4	0.0201	-0.0051	0.0248	0.0146	0.133	0.90	0.93	0.92
B	1.5	6	27.9	2.3	0.0211	-0.0121	0.0248	0.0066	0.134	0.95	0.96	0.96
A	1.5	6	26.0	2.3	0.0188	-0.0144	0.0248	0.0066	0.132	0.95	0.96	0.96
1B2C	3.0	203	5	97.0	0.0163	-0.0161	0.0248	0.0224	0.1425	0.86	0.84	0.85
D	3.0	204	6	94.0	0.0163	-0.0146	0.0248	0.0239	0.1425	0.86	0.85	0.86
1B4A	3.0	200	7	93.0	0.0144	-0.0104	0.0259	0.0311	0.1274	0.80	0.80	0.80
B	3.0	200	8	92.0	0.0165	-0.0023	0.0259	0.0371	0.1295	0.78	0.77	0.77
1A6A	6.0	186	4	95.0	0.0159	-0.0159	0.0237	0.0519	0.2109	0.80	0.80	0.80
C	6.0	200	0	100.0	0.0162	-0.0222	0.0237	0.0453	0.2112	0.82	0.83	0.82
1B7A	6.2	208	0	100.0	0.0130	-0.0178	0.0246	0.0558	0.1239	0.69	0.70	0.69
B	6.2	202	0	100.0	0.0162	-0.0195	0.0246	0.0509	0.1271	0.72	0.69	0.70

The group of 13 beams with degree of saturation from 0.87 to 0.90 varied in durability factor from 1.1 to 97. The 34 beams with 0.91 degree of saturation or greater all had durability factors less than 8.

If the average of the degrees of saturation calculated before and after freezing is used, a dividing line may be drawn at 0.88. The relationship of degree of saturation to durability factor is shown in Figure 2. All 22 beams having 0.88 or a lower value had a durability factor greater than 76. The 10 beams with values of 0.89 and 0.90 varied from 1.1

be emphasized that the uncertainty in the calculation of degree of saturation is on the order of  $\pm 0.02$  because of the limitations in accuracy of determinations of unit weight and initial air content. With this experimental error, it is not feasible to define from the data the relationship between durability factor and degree of saturation in the range 0.88 to 0.91. The data indicate conclusively that rapid deterioration will occur if the degree of saturation is over 0.92, and that a very high resistance may be obtained if it is below 0.87. However, it should also be emphasized that

poor aggregate durability, excessive spacing of air bubbles, or several other conditions, all of which were carefully avoided in the study reported here, may cause concrete deterioration even though the degree of saturation may be below 0.87.

water during the thawing periods. The low-air-content concrete especially increased markedly in degree of saturation, as shown in Table 7. These relationships indicate that partial drying of low-air-content concrete serves merely to postpone the damage of freezing;

TABLE 7  
DURABILITY AND DEGREE OF SATURATION OF PARTIALLY-DRIED CONCRETE

Beam	Orig. Air Cont.	No. of Cyc. F & T	Loss in "E"	Durability Factor	Curing Water Absorbed	Volume Change During Curing	Calc. Chg. in Vol. of Cem. plus Comb. Wat.	Net Air at Start of Freezing	Volume Freezable Water	Degree of Saturation		
										Start of Freez.	After F & T	Avg.
Nominal Cement Factor 4 Sacks per cubic yard												
	%		%		<i>Units: Cubic feet per cubic foot of fresh concrete</i>							
1C0C	1.6	16	30.0	5.6	-0.0019	-0.0195	0.0151	0.0135	0.1503	0.92	0.95	0.93
2C0C	1.6	17	32.8	5.4	0	-0.0134	0.0152	0.0178	0.1531	0.90	0.96	0.93
3C0C	1.4	16	32.4	5.2	-0.0013	-0.0161	0.0152	0.0144	0.1521	0.91	0.95	0.93
1C2B	2.0	23	21.2	10.4	-0.0032	-0.0199	0.0152	0.0185	0.1499	0.89	0.93	0.91
1C5C	5.1	200	2	98.0	-0.0056	-0.0360	0.0163	0.0359	0.1415	0.80	0.84	0.82
1A8B	9.0	204	0	100.0	-0.0091	-0.0452	0.0170	0.0709	0.1207	0.63	0.72	0.67
1AYD	12.0	205	0	100.0	-0.0006	-0.0391	0.0164	0.0979	0.1329	0.58	0.63	0.60
1AXA	13.0	201	0	100.0	-0.0013	-0.0453	0.0158	0.1018	0.1289	0.56	0.63	0.60
Nominal Cement Factor 5 Sacks per cubic yard												
3A0A	1.3	27	34.8	8.1	-0.0026	-0.0200	0.0194	0.0150	0.1183	0.89	0.94	0.92
4A0C	1.3	32	34.2	9.8	-0.0006	-0.0143	0.0194	0.0187	0.1203	0.87	0.93	0.90
5A0B	1.3	26	36.4	7.5	0.0013	-0.0177	0.0194	0.0134	0.1221	0.90	0.98	0.94
6A0A	1.8	55	32.4	17.8	-0.0056	-0.0181	0.0197	0.0252	0.1171	0.82	0.89	0.86
7A0C	1.7	67	38.2	18.4	-0.0069	-0.0189	0.0197	0.0277	0.1160	0.81	0.89	0.85
1A3B	3.0	204	0	100.0	0.0013	-0.0179	0.0195	0.0303	0.1223	0.80	0.83	0.82
2A3A	3.0	203	0	100.0	-0.0056	-0.0216	0.0194	0.0334	0.1152	0.78	0.86	0.82
1A4A	3.7	201	0	100.0	-0.0032	-0.0218	0.0192	0.0376	0.1162	0.76	0.79	0.77
1A5D	4.7	204	0	100.0	0.0030	-0.0262	0.0190	0.0368	0.1211	0.77	0.79	0.78
Nominal Cement Factor 6.5 Sacks per cubic yard												
1B0C	1.0	34	37.8	9.5	-0.0030	-0.0226	0.0251	0.0155	0.1388	0.90	0.97	0.93
2B0B	1.0	39	31.2	13.1	-0.0093	-0.0261	0.0248	0.0180	0.1349	0.88	0.97	0.93
3B0B	1.0	29	32.8	9.3	-0.0120	-0.0209	0.0250	0.0261	0.1328	0.94	0.95	0.89
1B1D	1.6	51	28.0	19.1	-0.0050	-0.0181	0.0253	0.0282	0.1237	0.81	0.91	0.86
2B1C	1.8	62	29.8	21.9	-0.0043	-0.0247	0.0252	0.0229	0.1236	0.84	0.94	0.89
3B1B	1.4	59	32.5	19.1	-0.0013	-0.0236	0.0253	0.0170	0.1274	0.88	0.96	0.92
1B2B	3.0	200	2.0	98.0	-0.0050	-0.0317	0.0248	0.0281	0.1212	0.81	0.86	0.84
1B4C	3.0	200	0	100.0	-0.0156	-0.0218	0.0259	0.0497	0.0974	0.66	0.76	0.71
1A6B	6.0	204	0	100.0	-0.0112	-0.0261	0.0237	0.0688	0.1838	0.73	0.83	0.78
1B7C	6.2	201	3.0	97.0	-0.0180	-0.0376	0.0246	0.0670	0.0929	0.58	0.77	0.67

Considering the partially-dried specimens, a degree of saturation before freezing of 0.81 separates the specimens having durability factors greater than 19 from those having durability factors less than 18. On the basis of degree of saturation after freezing, all of those with values of 0.89 or greater (15 specimens) had durability factors less than 22, and all of those 0.86 or less (12 specimens) had durability factors greater than 97; there were no specimens between these two ranges. The partially-dried concrete continued to gain

if water is available it will be absorbed and failure will occur when the degree of saturation has increased sufficiently. For air-entrained concrete, water will also be reabsorbed after partial drying, but only up to an amount approximately equivalent to the degree of saturation before drying.

Typical curves showing the change in dynamic modulus with cycles of freezing and thawing are shown in Figure 3. The partially-dried concrete was resistant to freezing and thawing until a certain point, after which its

dynamic modulus dropped rapidly. The initial saturation for this beam was 0.84; after the 62 cycles of freezing and thawing its saturation was 0.94. Although not measured during the intervening cycles, the shape of the curve suggests that the degree of saturation may have increased steadily with little damage occurring until it reached a critical value after which the deterioration increased rapidly.

**Significance of Results**—Since the same air-entraining agent was used in all air-entrained concrete and since the rate of freezing was relatively slow, the test results cannot be interpreted in the light of Powers' hypothesis on required spacing and size of air bubbles; however, they do confirm his calculations of a relatively low air requirement for concrete subjected to a slow rate of temperature change. The rapid deterioration of some of the concrete with a calculated degree of saturation of 0.89 or 0.90 might be caused by non-uniform distribution of air space or excessive distance between air pockets; it might also be that experimental error places the calculated degree of saturation too low.

An important application of the results lies in the field of designing laboratory concrete freezing and thawing tests. It is becoming a widespread practice to evaluate aggregate through concrete freezing and thawing tests. If the variable of paste resistance to freezing and thawing is held constant by keeping its degree of saturation below the critical range, the resistance of the concrete should reflect the durability of the aggregate. This matter is the subject of a discussion by Mather (5), who proposes  $4.5 \pm 0.5$  percent air in the concrete to insure a high degree of resistance in the mortar phase to laboratory freezing-and-thawing. It is also the practice to evaluate new air-entraining agents by freezing and thawing tests. By comparison with other air-entrained concrete of an equivalent degree of saturation, it appears that a valid comparison of the new agent with that used in the reference concrete can be made. If, however, the new agent is rated by comparing air-entrained concrete to non-air-entrained concrete, accidental variations in the degree of saturation of the reference concrete may give misleading results. For example, it may be possible to secure a low degree of saturation in non-air-entrained concrete within the limits of speci-

fied test procedures. The apparent increase in durability for the agent under consideration will then be much lower than if the reference concrete happened to have a high degree of saturation.

**Absorption and Volume Change**—The average absorption of curing water and volume change during the one day of moist storage and 27 days of immersion in water are shown

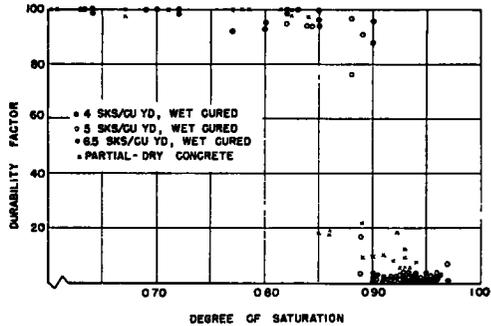


Figure 2. Relationship Between Degree of Saturation and Durability

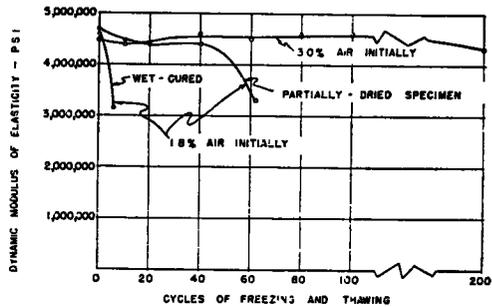


Figure 3. Typical Dynamic Modulus Curves for Concrete with 6.5 Cement Factor

in Table 8. The concrete with less than 3 percent air initially averaged 0.012 cu. ft. of water absorbed per cu. ft. of concrete, and that with 3 percent or more air initially averaged 0.014. Since these figures are so close together, it is indicated that the purposefully-entrained air is essentially inaccessible to the water under the conditions of soaking used.

On the other hand, a greater total volume change was observed in the air-entrained concrete, averaging 0.022 cu. ft. per cu. ft. of fresh concrete, compared with an average of 0.013 for concrete with less than 3 percent air. It should be emphasized that these

changes include those occurring during the first 24 hr. due to initial subsidence and bleeding, as well as all other causes. Direct meas-

average volume change between these ages; hence the volume changes indicated in Table 8 can be considered to be those occurring in the first 24 hr., probably caused primarily by bleeding. (It should be noted that conditions of storage were such that the bleeding water was available for reabsorption by the concrete.)

TABLE 8  
EFFECT OF AIR ENTRAINMENT ON WATER ABSORBED AND VOLUME CHANGE—CONTINUOUSLY MOIST-CURED CONCRETE

Nominal Cement Factor	Concrete with Less than 3% Air		Concrete with 3% Air or More	
	Avg. Curing Water Absorb.	Avg. Volume Change During Curing	Avg. Curing Water Absorb.	Avg. Volume Change During Curing
4.0	0.0094	0.0116	0.0159	0.0286
5.0	0.0111	0.0134	0.0121	0.0217
6.5	0.0151	0.0126	0.0156	0.0149
Weighted Average.....	0.0123	0.0128	0.0145	0.0217

*Cubic feet per cubic foot of fresh concrete*

Since some studies (16) have indicated that the volume of air bubbles in air-entrained concrete remains constant from the fresh to the hardened state, it may be in order to speculate on the components which changed volume to cause the volume change noted. In the low-air-content concrete it is probable that the volume change is primarily subsidence, the water displaced being reabsorbed in the air space initially available or in the space

TABLE 9  
FLEXURAL STRENGTH, DYNAMIC MODULUS, AND CHANGE IN LENGTH

After Curing			After Freezing and Thawing						After Freezing and Thawing							
Beam	Mod. of Rupt. <i>psi.</i>	Dyn. Mod. <i>10<sup>6</sup> psi.</i>	Beam	No. of Cyc.	Modulus of Rupture		Dynamic Modulus		Gain in Lgth. %	Beam	No. of Cyc.	Modulus of Rupture		Dynamic Modulus		Gain in Lgth. %
					<i>psi.</i>	% <i>chg.</i>	<i>10<sup>6</sup> psi.</i>	% <i>chg.</i>				<i>psi.</i>	% <i>chg.</i>	<i>10<sup>6</sup> psi.</i>	% <i>chg.</i>	
1C0D	398	4.05	1C0A	3	134	66.3	2.28	42.2	0.158	1C0C	16	302	24.1	2.85	30.0	0.028
2C0D	398	3.96	B	3	182	54.3	2.42	37.3	0.103							
3C0D	394	3.89	2C0A	3	202	49.2	2.74	33.2	0.059	2C0C	17	269	32.5	2.65	32.8	0.057
1C2A	403	3.64	B	3	211	47.0	2.59	39.1	0.073							
1C5D	326	3.13	3C0A	2	154	60.9	2.45	40.3	0.092	3C0C	16	226	42.7	2.69	32.4	0.045
1A8D	403	3.13	B	2	202	48.7	2.73	29.6	0.059							
1AYC	264	2.64	102C	5	110	72.7	1.56	56.5	0.158	102B	23	259	35.8	2.76	21.2	0.063
1AXD	221	2.54	D	5	125	69.0	1.52	57.0	0.137							
3A0C	523	4.65	3A0B	3	268	48.7	3.52	27.0	0.049	3A0A	27	288	45.0	3.13	34.8	0.091
4A0D	595	4.67	D	3	332	36.6	3.49	25.3	0.047							
5A0A	567	4.59	4A0A	3	307	48.4	3.33	29.1	0.061	4A0C	32	322	95.9	3.14	34.2	0.085
6A0B	576	4.54	B	3	312	47.6	3.11	33.1	0.073							
7A0D	605	4.62	5A0C	3	350	38.4	3.52	23.5	0.032	5A0B	26	351	38.1	2.91	36.4	0.068
12A0C	568	4.91	D	3	283	50.1	3.33	26.7	0.012							
12A0E	686	5.05	6A0C	8	322	44.2	3.35	24.4	0.042	6A0A	55	288	50.1	3.11	32.4	0.020
10A3C	726	4.92	D	8	350	39.4	3.21	28.1	0.046	7A0C	67	317	47.6	2.80	38.2	0.048
10A3E	676	5.17	7A0A	6	370	38.9	3.40	26.9	0.035							
13A4B	750	4.41	B	6	317	47.6	3.46	27.6	0.049	1B0C	34	283	50.1	2.87	37.8	0.087
13A4C	647	4.47	12A0F	5	283	54.9	3.49	29.0	—	2B0B	39	355	46.0	3.10	31.2	0.047
1A3A	595	4.67	D	4	244	61.1	3.09	37.7	—	3B0B	29	310	50.0	2.92	32.8	0.061
2A3B	590	4.41	B	4	170	72.9	3.00	37.9	—	1B1D	51	500	25.6	3.27	28.0	0.058
1A4D	528	4.28	A	4	271	43.2	3.19	33.2	—	2B1C	62	354	48.1	3.27	29.8	0.032
1A6C	514	4.06	10A3D	6	403	42.6	3.48	29.1	—	3B1B	59	365	54.1	3.31	32.5	0.043
			B	84	361	48.5	3.49	28.7	—							
1B0D	566	4.55							0.050	1B1A	5	408	38.5	3.62	24.1	0.034
2B0C	658	4.38	13A4E	24	343	51.0	3.24	33.1	—	B	5	336	49.3	3.13	30.6	0.051
3B0C	620	4.35	D	11	388	44.5	3.25	31.6	—	2B1A	6	360	48.7	3.11	32.2	0.072
1B1C	662	4.81	A	11	330	52.8	3.11	30.5	—	B	6	322	52.9	3.18	29.4	0.065
2B1D	682	4.53							—							
3B1A	795	4.92	1B0A	2	254	55.2	3.39	29.5	0.050	3B1C	4	264	66.8	3.08	33.6	0.092
11B0C	712	4.78	B	2	370	34.8	3.40	27.9	0.045	D	4	307	61.4	3.14	34.1	0.082
11B0E	811	4.58	2B0A	4	254	61.4	2.91	34.1	0.053	11B0F	4	369	51.5	3.50	27.1	—
1B2A	595	4.73	D	4	254	61.4	2.68	37.8	0.060	11B0D	4	433	43.2	3.22	29.8	—
1B4D	662	4.54	3B0A	4	283	54.3	2.65	39.0	0.084	11B0B	6	421	44.6	3.37	27.9	—
1A6D	470	3.62	D	4	283	54.3	2.71	37.2	0.084	11B0A	6	322	57.7	3.28	28.0	—
1B7D	534	3.99														

urements of the volume of each specimen were made by weighing in air and in water at one day and at 28 days. These volume determinations, with only small variations, showed zero

created by shrinkage of cement plus combined water. In the air-entrained concrete with a high cement factor the volume change was low and close enough to that of the corre-

sponding non-air-entrained concrete that the same hypothesis may serve, leaving the volume of air bubbles unchanged. In the leaner air-entrained mixes, the shrinkage was much greater, indicating a probability that the air voids had decreased in volume on the order of 0.01 cu. ft. per cu. ft. of concrete. An alternative exists that approximately this amount of displaced water entered the air bubbles during the water-regain period following bleeding. However, it was indicated that the air bubbles were essentially impervious to water during the later soaking period. It is planned to measure by microscopic methods the void sizes in this concrete after some additional freezing and thawing tests have been made.

*Flexural Strength, Dynamic Modulus, and Change in Length*—The effects of freezing and thawing on strength, dynamic modulus, and length of the concrete are indicated in Table 9. These data show that the flexural strength decreased 45 to 50 percent when the dynamic modulus decreased 30 percent; this result confirms many other investigations. The concrete gained in length on the order of 0.05 percent when the dynamic modulus was reduced 30 percent, confirming the figure reported by Sweet (11).

#### SUMMARY AND CONCLUSIONS

Relationships have been developed for calculating changes in air content of concrete during curing based on measurements of weight, unit weight, and on a semi-empirical estimate of the change in volume of cement and combined water. Relating the final air content, thus determined, to the freezable water content through the factor of degree of saturation, the following relationships were obtained with results of freezing and thawing tests:

1. For continuously moist cured concrete, all of the 22 specimens which had a degree of saturation of 0.88 or lower had durability factors of 76.0 or greater. Thirty-five specimens, all with degree of saturation of 0.91 or higher, had durability factors of 7.6 or below. The 10 specimens with values of 0.89 and 0.90 varied in durability factor from 1.1 to 96.

2. For partially-dried concrete, based on degree of saturation after freezing, all of those with degree of saturation of 0.89 or greater (15 specimens from 15 mixes) had durability factors less than 22, and all of those 0.86 or

less (12 specimens from 12 mixes) had durability factors greater than 97; there were no specimens between these two ranges.

The following conclusions may be drawn, subject to qualification by further research with other types of materials, concrete mixes, or methods of testing:

1. Concrete subjected to freezing and thawing when the paste-plus-air component has a degree of saturation of 0.91 or greater will deteriorate rapidly. All specimens in this study with degree of saturation below 0.88 were highly durable, although it is recognized that deterioration in this range may be caused by a variety of factors such as expansion of inferior aggregate, differential thermal expansion of components, hydraulic pressure from resistance to flow of water, non-uniform distribution of freezable water, or adverse chemical reactions.

2. In investigations of the effects of variables such as type of concrete materials, admixtures, or mix design, the effect of high degrees of saturation may obscure entirely the effect of the variable which was intended to be primary. If tests are run with the degree of saturation on the order of 0.80, the results can be expected to reflect the influence of the variable being considered. This degree of saturation is conveniently obtained by air-entrainment.

3. Partial drying of low-air-content concrete serves merely to postpone the damage of freezing; if water is available it will be absorbed and failure will occur when the degree of saturation has increased sufficiently. Water will also be reabsorbed in air-entrained concrete after partial drying, but only up to an amount approximately equivalent to the degree of saturation before drying.

4. The absorption of water while submerged for 27 days of curing, and during the thawing periods, was essentially the same for both non-air-entrained and high-air-content concrete. Since much more space was available for filling with water in the higher-air-content concrete, it is indicated that the purposefully-entrained air is essentially inaccessible to the water under normal conditions of soaking.

5. In conducting freezing and thawing tests, the test procedure should include the determination of changes in weight and unit weight throughout the curing and testing periods. Analysis of these data, together with estima-

tion of the change in volume of the paste and of the freezable water content, should indicate the probable influence of degree of saturation on the test results.

#### ACKNOWLEDGMENTS

The Research Council of the University of Wyoming made possible this study through a Grant-in-Aid for the purchase of equipment, and this assistance is gratefully acknowledged. The authors also wish to express their appreciation to Professor A. J. McGaw, Head of the Department of Civil and Architectural Engineering, for his cooperation and assistance; to Dr. H. G. Fisk, Director of the Wyoming Natural Resources Research Institute, for extending the Institute's facilities; and to Mr. B. W. Brown, Chemist, Wyoming Natural Resources Research Institute, for helping with some of the technical phases of the investigation. Mr. T. C. Powers, Manager of Basic Research, Portland Cement Association, was most helpful in clarifying certain points.

#### REFERENCES

- Blackburn, "Freeze and Thaw Durability of Air-Entrained Concrete Using Indiana Aggregates," *Proceedings*, Highway Research Board, Vol. 28 (1948).
- Bugg, "Effect of Air Entrainment on Durability Characteristics of Concrete Aggregates," *Proceedings*, Highway Research Board, Vol. 27 (1947).
- "Use of Air-Entrained Concrete in Pavements and Bridges," Highway Research Board, *Current Road Problems* No. 13R, May, 1950.
- Klieger, Discussion of a paper by Tremper and Gooding, "Washington Method of Determining Air in Fresh Concrete," *Proceedings*, Highway Research Board, Vol. 28 (1948).
- Mather, "The Testing of Aggregates in Air-Entrained Concrete," in Bulletin 30, "Air-Entrainment in Concrete Design," Waterways Experiment Station, Corps of Engineers, United States Army, November, 1947.
- Powers, "The Non-Evaporable Water Content of Hardened Portland Cement Paste—Its Significance for Concrete Research and Its Method of Determination," *A.S.T.M. Bulletin*, No. 158 (May 1949).
- Powers, "A Working Hypothesis for Further Studies of Frost Resistant Concrete," *Proceedings*, American Concrete Institute, Vol. 41 (1945).
- Powers, "The Air Requirement of Frost-Resistant Concrete," Research Laboratories of the Portland Cement Association, September, 1949.
- Powers and Brownard, "Studies of Physical Properties of Hardened Portland Cement Paste," *Proceedings*, American Concrete Institute, Vol. 43 (1947).
- Sweet, Discussion of a paper by Blackburn, "Freeze and Thaw Durability of Air-Entrained Concrete Using Indiana Aggregates," *Proceedings*, Highway Research Board, Vol. 28 (1948).
- Sweet, "Research on Concrete Durability as Affected by Coarse Aggregates," *Proceedings*, American Society for Testing Materials, Vol. 48 (1948).
- "Tentative Method of Test for Fundamental Transverse Frequency of Concrete Specimens for Calculating Modulus of Elasticity (Sonic Method)," A.S.T.M. Designation C 215-47 T, 1947 Supplement to the Book of A.S.T.M. Standards.
- "Tentative Method of Testing Air-Entraining Admixtures for Concrete," A.S.T.M. Designation C 233-49 T, 1949 Book of A.S.T.M. Standards, p. 825.
- Tremper and Gooding, "Washington Method of Determining Air in Fresh Concrete," *Proceedings*, Highway Research Board, Vol. 28 (1948).
- Tuthill, "Information and Instructions for Use of Air-Entraining Admixtures in Concrete," Technical Concrete Control Section Report No. C-307, Bureau of Reclamation, Branch of Design and Construction, Denver, Colorado.
- Verbeck, "The Camera Lucida Method for Measuring Air Voids in Hardened Concrete," *Journal*, American Concrete Institute, May, 1947.
- Withey, "Progress Report, Committee on Durability of Concrete," *Proceedings*, Highway Research Board, Vol. 24 (1944).
- Wuerpel, "Laboratory Studies of Concrete Containing Air-Entraining Admixtures," *Journal*, American Concrete Institute, February, 1946, p. 352.