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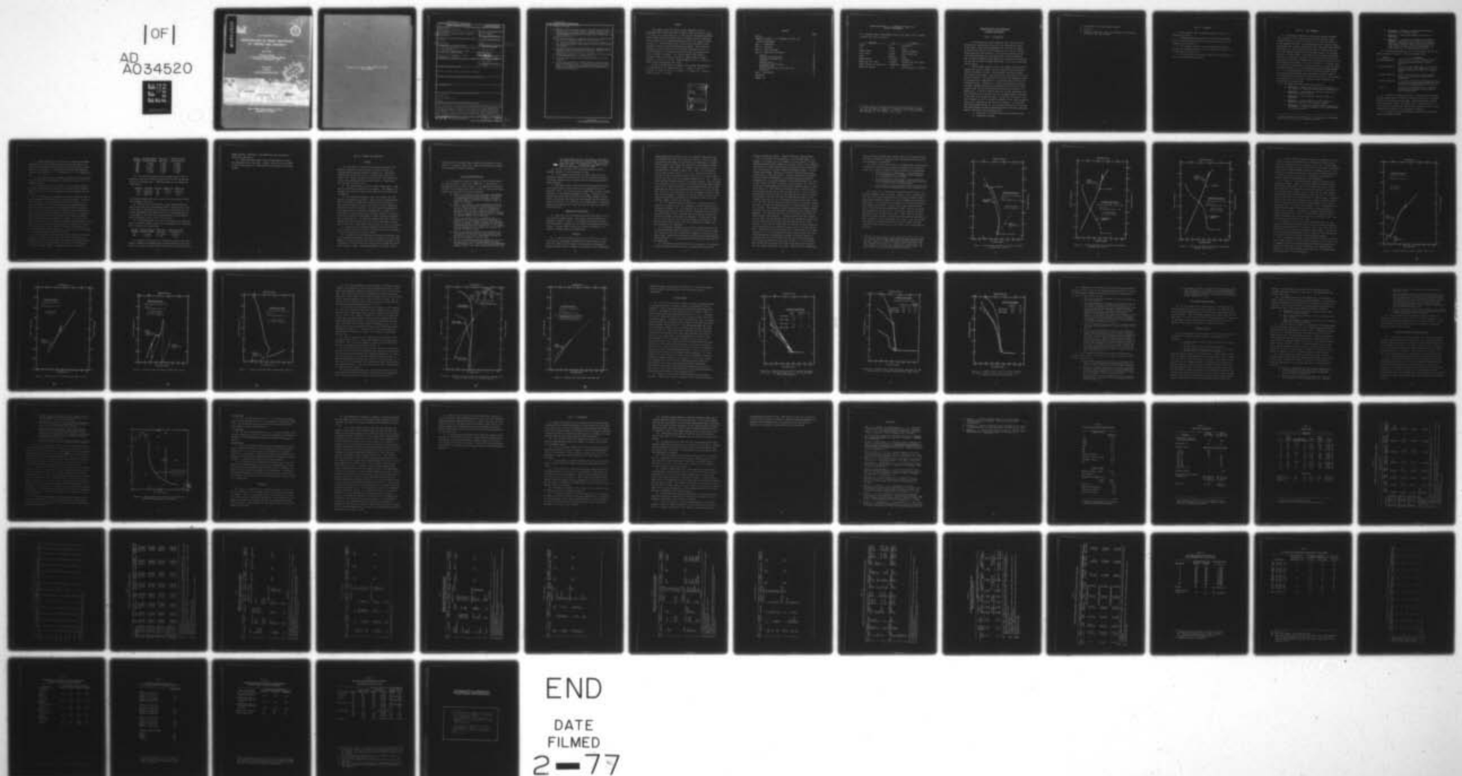

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TECHNICAL REPORT C-76-4

# INVESTIGATION OF FROST RESISTANCE OF MORTAR AND CONCRETE

by

Alan D. Buck

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October 1976

Final Report

Approved For Public Release; Distribution Unlimited



Prepared for Office, Chief of Engineers, U. S. Army
Washington, D. C. 20314

INVESTIGATION OF FROST RESISTANCE OF MORTAR AND CONCRETE    OCT. 1976

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## REPORT DOCUMENTATION PAGE

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| | |
|---|---|
| 1. REPORT NUMBER: Technical Report C-76-4 | 2. GOVT ACCESSION NO. |
| | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle): INVESTIGATION OF FROST RESISTANCE OF MORTAR AND CONCRETE | 5. TYPE OF REPORT & PERIOD COVERED: Final report |
| | 6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s): Alan D. Buck | 8. CONTRACT OR GRANT NUMBER(s) |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS: U. S. Army Engineer Waterways Experiment Station, Concrete Laboratory, P. O. Box 631, Vicksburg, Miss. 39180 | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: Work Unit 31131 |
| 11. CONTROLLING OFFICE NAME AND ADDRESS: Office, Chief of Engineers, U. S. Army, Washington, D. C. 20314 | 12. REPORT DATE: October 1976 |
| | 13. NUMBER OF PAGES: 65 |
| 14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) | 15. SECURITY CLASS. (of this report): Unclassified |
| | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE |

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Concrete tests
Eisenhower Lock
Frost resistant concrete
Mortars

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Specimens from 12 mortar mixtures and one concrete mixture were tested for frost resistance by accelerated freezing-and-thawing tests and by dilation, for compressive strength, for freezable water (FW), and for weight changes after each of eight different treatments. One variable of treatment was age of continuous moist curing; the other was age together with cyclic fluctuation of water pressure to simulate the conditions that would affect concrete at a low level in the Eisenhower Lock of the St. Lawrence Seaway. The results of these tests indicated: (Continued)

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20. ABSTRACT (Continued)

a. The cyclic pressure treatment did not cause critical saturation to develop in most of the test specimens, including those most like the concrete in the Eisenhower Lock. Therefore, changing water levels presumably would not have developed critical saturation of the concrete in the lock.

b. The concrete mixture which simulated the concrete in Eisenhower Lock with the large aggregate removed was frost resistant.

c. The usual relationships between frost resistance and variables of age, compressive strength, water cement (w/c) ratio, and air content were apparent.

d. The amount of air needed to obtain maximum frost resistance of the mortars increased with increasing w/c ratio to a maximum of about 9 percent air for a w/c ratio of 0.8 by weight.

e. The data indicated that FW is not a useful index of frost resistance for air-entrained mortar or concrete mixtures.

f. Frost resistance increases with increasing age as the w/c ratio increases.

g. Dilation testing provides a sensitive measure of the frost resistance of mortar and concrete. Dilation testing could be a useful adjunct to accelerated freezing-and-thawing tests of concrete to provide more information on the relation of environmental influences and frost resistance.

## PREFACE

This report covers the results of work authorized by first indorsement dated 29 May 1969 from the Office, Chief of Engineers (OCE), U. S. Army, to a letter from the U. S. Army Engineer Waterways Experiment Station (WES) dated 12 May 1969, subject: "Project Plans for Investigation of Concrete in the Eisenhower and Snell Locks, St. Lawrence Seaway" (ES 601.17). The work formed a part of item ES 601, "Research in Mass Concrete," of the Civil Works Investigations Program. This report was prepared as a part of Work Unit 31131, "Highly Saturated Concrete in Severe Environment." The technical monitor for this investigation was Mr. J. A. Rhodes, DAEN-CWE-C. All work was done at the Concrete Laboratory under the supervision of Messrs. Bryant Mather, Leonard Pepper, R. V. Tye, Jr., and Mrs. Katharine Mather. Mr. A. D. Buck was project leader and prepared this report.

Directors of WES during the conduct of this study and preparation and publication of this report were COL L. A. Brown, CE, BG E. D. Peixotto, CE, COL G. H. Hilt, CE, and COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

## CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

| Multiply | By | To Obtain |
|---|---|---|
| inches | 25.4 | millimetres |
| feet | 0.3048 | metres |
| square inches | 6.4516 | square centimetres |
| cubic inches | 16.38706 | cubic centimetres |
| ounces | 28.34952 | grams |
| pounds (mass) | 0.4535924 | kilograms |
| pounds per cubic yard | 0.5932764 | kilograms per cubic metre |
| pounds (force) per square inch | 0.0068947657 | megapascals |
| Fahrenheit degrees | 5/9 | Celsius degrees or Kelvins* |

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: C = (5/9)(F - 32). To obtain Kelvin (K) readings, use: K = (5/9)(F - 32) + 273.15.

# INVESTIGATION OF FROST RESISTANCE OF MORTAR AND CONCRETE

## PART I: INTRODUCTION

1. The investigation of the parameters that affect the frost resistance of concrete described herein was undertaken as a part of the study of the factors responsible for the frost resistance of some of the concrete in the Eisenhower Lock on the St. Lawrence Seaway being less than expected.[1] This work was intended to simulate and bracket some of the Eisenhower Lock concrete parameters and to develop information that would explain the factors responsible for the lack of frost resistance manifested, so that such occurrences can be avoided.

2. Twelve mortar mixtures of four air contents and three water-cement (w/c) ratios to bracket and one concrete mixture were made to simulate Eisenhower concrete. Specimens made from these mixtures were exposed to freezing at four ages and with and without prior cyclic pressure treatment. The concrete in the filling and emptying culverts in Eisenhower Lock ranged from 19 to 28 months in age after the first navigation season. Therefore, its average age was about 24 months. The normal navigation season for Eisenhower and Snell Locks is about 8 months long, but the first navigation season was only about 5-1/2 months long. It was the intention that the pressure saturation treatment following each of the four test ages be approximately equivalent to the short first navigation season. In addition, the effect of the last treatment was also to include the effects of the second navigation season after allowing time for the winter shutdown. It was planned that weight changes during the cyclic pressure treatments be recorded and that different specimens representing each of the eight conditions would be subjected to the following tests:

   a. Resistance to accelerated freezing-and-thawing tests.

   b. Compressive strength.

c. Air content by the high-pressure method.

d. Dilation.

e. Freezable water (FW). This was determined as dilation was measured on the same specimen.

## PART II: MATERIALS

4. One low-alkali Type II portland cement was used; it was identified as RC-602.

5. Beekmantown dolomite similar to that used in Eisenhower Lock was used as coarse aggregate in the concrete mixture; it was identified as CRD-G-34(3).

6. The standard laboratory limestone-manufactured sand was used in the concrete mixture and in all of the mortar mixtures. It is identified as CRD-MS-17(9).

7. The laboratory stock supply of neutralized vinsol resin was used as an air-entraining admixture.

## PART III: TEST PROCEDURE

8. The elevation change for a ship passing through Eisenhower Lock is about 40 ft;* it was calculated that the pressure change involved is about 17 psi (14 to 31 psi or vice versa) for concrete at the bottom of the lock. Data furnished by the St. Lawrence Seaway Development Corp. (SLSDC) indicated that there were about 4000 lockages during the first short navigation season that the lock was open and about 5800 lockages during the next navigation season. Each lockage involves a pressure change as the water level is changed and requires about 7 min. Therefore, an automatic cyclic pressure storage system was designed which would alternate the desired pressures in about 7 min. This change was programmed to occur once each hour. It required about 5-1/2 months for this system to accumulate 4000 cyclic pressure changes and about 8 months for it to accumulate 5800 cyclic pressure changes.

9. The storage capacity of the cyclic pressure system and the test times involved dictated that three mortar mixtures be made in one day followed by one round of concrete 6 weeks later. This sequence was repeated until all 12 mortar mixtures and three rounds of one concrete mixture had been made.

10. The eight conditions of test were as follows:

- a. Condition 1. Fourteen days of curing in limewater or in a fog room at about 100 percent relative humidity (RH).
- b. Condition 2. Fourteen-day age (curing as above) plus 4000 cyclic pressure changes.
- c. Condition 3. Twenty-eight-day age with curing as in Condition 1.
- d. Condition 4. Twenty-eight-day age with curing as in Condition 3 plus 4000 cyclic pressure changes.
- e. Condition 5. Eighteen and one-half months of curing as in Condition 1. This was changed to 20-1/2 months before this testing started.

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

f. Condition 6. Curing as in the modified Condition 5 plus 4000 cyclic pressure changes.

g. Condition 7. Twenty-eight months of curing as in Condition 1.

h. Condition 8. A sequence to simulate two navigation seasons; it consisted of 18-1/2 months of curing like Condition 1 followed by 4000 cyclic pressure changes, then another 4 months of moist curing followed by a longer period of ~5800 cyclic pressure changes. The total specimen age at this time was about 3 yr.

11. Fifty-seven specimens were cast from each mortar mixture and from each round of concrete. They are described below:

| Number | Description |
| --- | --- |
| 24 (3 per condition) | 3-1/2- by 4-1/2- by 16-in. beam for accelerated freezing-and-thawing testing by CRD-C 20.[2] |
| 16 (2 per condition) | 2- by 2- by 2-in. mortar cubes or 6- by 12-in. concrete cylinders for compressive strength testing by CRD-C 227[2] or CRD-C 14,[2] respectively. |
| 8 (1 per condition) | 3-1/2- by 4-1/2- by 16-in. beam with metal inserts for simultaneous dilation and FW measurements. |
| 8 (1 per condition) | 6- by 12-in. cylinder for determination of air content by the high-pressure method (CRD-C 83)[2] without the prescribed drying at 290 ± 10°F. |
| 1 (only) | 6- by 12-in. cylinder for use as a control to determine weight changes during storage at about 100 percent RH. |

12. The control cylinders were kept in the fog room (~100 percent RH) and weighed whenever companion specimens were put into or removed from the cyclic pressure system tanks. Knowing the amount of weight gain during moist storage, the weight gain of specimens during the cyclic pressure treatment was separated into gain due to moist storage and gain due to exposure to water-pressure treatment.

13. The groups of seven specimens per condition were cured and tested as already described.

14. Mortar specimens were identified by a number-letter-number sequence with the first number indicating the mixture number, the letter "M" designating a mortar mixture, and the final number identifying the test condition. If there were more than eight specimens, then they were grouped as 1, 2, 3 (Condition 1), 4, 5, 6 (Condition 2), etc.

15. The identification of concrete specimens was similar except that the first number identified the round and the letter was "C" to indicate concrete.

16. Determination of air content by the high-pressure method was found to be impractical because of the excessive times required. Hence the use of this test was abandoned after 13 specimens had been tested.

17. The simultaneous measurement of dilation and FW was done in general agreement with the method of Verbeck and Klieger.[3] The original intent had been to make this combined test for one cycle, but it was increased to 10 cycles when this was recommended informally during discussions relating to the development of ASTM Designation: C 671.[4] This increase necessitated a change from data accumulation on paper tape to accumulation on magnetic tape for input to a computer. The original plans for this work called for 10 cycles of testing or until dilation equaled or exceeded 75 millionths. The bulk of this testing was cut back to one cycle when it became apparent that 10 cycles were not enough to indicate a change in frost resistance for most of the specimens being tested. ASTM C 671[4] provides that testing is to continue until the critical dilation is exceeded or until the specimens have been exposed for the period of interest.

18. Some dilation and FW beams were either immediately returned to storage in limewater in the moist room after their testing was completed or were so returned after an intermediate period of drying in room air. Six of these specimens were tested for an additional cycle after extended storage. Identifying data are listed below:

| Mortar Specimen | Age when Regular Testing Started | Extra Storage Time | Total Age at Time of Extra Cycle |
|---|---|---|---|
| 3M8 | 3 years | 2 years | 5 years |
| 9M6 | 2+ years | 2 years | 4+ years |
| 9M8 | 3 years | 1 year | 4+ years |
| 12M1 | 14 days | 4 years | 4+ years |
| 12M6 | 2+ years | 2 years | 4+ years |
| 12M8 | 3 years | 1 year | 4 years |

19. The test for dilation and FW was made several times on portions of two NX-size concrete cores from a filling and emptying culvert in Eisenhower Lock. Identifying data for the samples are shown below:

| Monolith | Position | Core No. | Length, in. | Depth, in. |
|---|---|---|---|---|
| N-54 | River wall | 181 | 10-1/2 | 42-52-1/2 |
| N-55 | Land wall | 189 | 10-1/2 | 39-49-1/2 |
| N-55 | Land wall | 189 | 16 | 9-25 |

The different lengths were used to see if this factor had an effect on the degree of dilation.

20. There are several differences in the dilation method as used in this work and as prescribed by ASTM.[4] The major one is that in this work the specimens were cooled from an unspecified but convenient temperature in the range 35° to 55°F at an uncontrolled rate to a minimum of -10°F over a 24-hr period, whereas the ASTM method calls for cooling from 35° to 15°F at 5°F per hr.

21. Two concrete beams (1C6, 3C5) were tested for an additional cycle for dilation without testing, also simultaneously for freezable water. Age data are listed below:

| Concrete Specimen | Age when Regular Testing Started | Extra Storage Time | Total Age at Time of Extra Cycle |
|---|---|---|---|
| 1C6 | 2+ years | 2-1/2 years | 4+ years |
| 3C5 | 2+ years | 2+ years | 4+ years |

22. Questions were raised as to whether the effect of the cyclic pressure treatment was different than sustained pressure at the low (14 psi) or the high (31 psi) values would be and as to when the water

uptake occurred. Therefore, a few additional tests were made to answer these questions.

23. There were three rounds of the concrete mixture so there was replication of the test data. However, there was only one round of each mortar mixture so no replications were involved in the mortar testing.

## PART IV: RESULTS AND DISCUSSION

### General

24. The results of this work are presented in Tables 1-19. Materials properties and mixture data are given in Tables 1-3. Freezing-and-thawing data are given in Tables 4-5. Compressive strength data are given in Table 6. Dilation data are given in Tables 7-10. FW data are given in Tables 11-13. Air content data by the high-pressure method are given in Table 14. Weight-gain data are given in Tables 15-19.

25. The mixture data in Table 3 include casting dates. Slump and air content were measured for each mixture. The comparison of intended and actual air contents shows that the latter values were satisfactory.

26. This program included w/c ratio, air content, age, and degree of saturation as variables. While the cyclic pressure treatment did increase the degree of saturation of test specimens as indicated by increases in weight, this proved to have a negligible effect on most of the test data. The fact that this treatment did not produce critical saturation of specimens over a range of w/c ratios and air contents shows that the wetted concrete in locks with lifts up to 40 ft will not necessarily become critically saturated due to water pressure. The long-term weight-change data in Table 19 suggest that this relation may be true for any time span, but these data do not cover a sufficiently long-time span to be fully conclusive.

27. Since the cyclic pressure treatment proved to have little or no significant effect, the test results were generally predictable in terms of w/c ratio, age, and air content.

28. Although it was not possible to continue the dilation tests on all specimens long enough to determine the duration of their frost immunity, the test proved to be a sensitive measure of whether or not a specimen is frost resistant when tested, which confirms the conclusion of Powers in 1955: "length measurements can be used to tell

whether or not at any given time a specimen is vulnerable to frost action."[5] As noted in ASTM C 671, "Highly frost-resistant concrete may never exhibit critical dilation."

## Freezing-and-Thawing Data

29. The durability factors ($DFE_{300}$) for all 360 beams tested are shown in Table 5. When it was judged that a result was not representative of its group of three, it was underlined and was not included in the average values shown in Table 4. The data in Table 4 indicate the following for the mortar mixtures:

a. There is a decrease in frost resistance with increase in w/c ratio for similar air contents. For the nine air-entrained mortar mixtures the effect of higher w/c ratio tends to override the beneficial effect of higher air contents.

b. There is an increase in frost resistance with age for the 7.0 and 8.6 percent air content mixtures (2, 9) at 0.8 w/c ratio but not with the 10.7 percent air mixture at this w/c ratio. There is no age effect with the 0.6-w/c ratio air-entrained mixtures; at this w/c ratio it appears that an age of 14 days is adequate for maximum durability to be achieved.

c. There is an increase in frost resistance with air content for the eight mortar mixtures containing 0.6 and 0.8 w/c ratios. However, the lack of a consistent increase of durability with air content for the three air-entrained 0.8-w/c ratio mixtures (9, 2, 11) suggests that the intermediate air content of 8.6 percent is adequate for this w/c ratio.

d. There is no significant effect of air content or age on durability of the three air-entrained mortar mixtures with 0.4 w/c ratio. Seven percent air and 14-day age are adequate at this w/c ratio.

e. The two nonair-entrained mortar mixtures (12, 3) with 0.6 and 0.8 w/c ratios have poor durability values that range from 1 to 4. The values for nonair-entrained mixture 7 with 0.4 w/c ratio are much better (8-39) and show improvement with age. While $DFE_{300}$ values below 50 or 60 are not usually considered good, the dilation data shown later also indicate that a $DFE_{300}$ value of about 9 is substantially different than one of 4 and indicates much greater frost resistance.

30. The data in Table 4 for the concrete mixture show the expected increase in frost resistance with age.

31. It is apparent from the data in Table 4 that the cyclic pressure treatments did not result in critical saturation of mortar or concrete specimens nor do the data show any real decrease due to these treatments.

32. The data in Table 4 for the nine air-entrained mortar mixtures indicate that a 14-day curing age was adequate for all but mixtures 2 and 9. In these two cases, an additional 14 days of curing resulted in a substantial improvement in $DFE_{300}$. Although it was pointed out earlier that 8.6 percent air was about adequate for the 0.8-w/c ratio group, the $DFE_{300}$ data also suggest that the higher air content of mixture 11 (10.7 percent air) was beneficial in providing better frost protection at 14 days than did the lower air contents of mixtures 2 and 9.

## Compressive Strength Data

33. There were 192 2-in. mortar cubes and forty-eight 6- by 12-in. concrete cylinders broken. The average value for each pair of specimens is shown in Table 6. The strengths predictably decrease with increasing air contents and w/c ratios and increase with increasing age. The only effect of the cyclic pressure treatments is to result in strength gain with increasing age.

## Dilation

34. A total of 120 beams, each 3-1/2 by 4-1/2 by 16 in., were tested for the simultaneous measurement of dilation and FW content. CRD-C 40[2] (ASTM C 671-74T) requires that dilation be determined by measuring distance from a straight-line projection of the prefreezing,

length-versus-time contraction curve (at constant cooling rate) and the maximum deviation of the strain trace from it. The test is made by monitoring the length of a specimen as its temperature is lowered. Dilation curves were obtained for each test of each specimen as part of the computer output data. The amount of total dilation was read from them and is recorded in Tables 7-10. Table 7 is for the four 0.4-w/c ratio mortar mixtures (7, 4, 1, 6). Table 8 shows data for the four 0.6-w/c ratio mortar mixtures (12, 5, 10, 8). Table 9 shows data for the four 0.8-w/c ratio mortar mixtures (3, 9, 2, 11). Table 10 shows data for the three rounds of the concrete mixture. Data are shown by cycles where up to 10 cycles were run until testing was later reduced to one cycle. This was done when it became apparent that most of these beams were not going to be significantly affected by 10 cycles of testing. Each cycle was separated by two weeks of storage in water at about 35°F for each specimen. The data are shown as total microinches (μin.) and may be expressed as millionths by dividing the values by 15 (the effective length in inches of each beam).

35. It is apparent from the tables that a variation of several hundred μin. between cycles for a specimen is neither significant nor indicative of damage. It is also apparent, as it was from the freezing-and-thawing data, that the cyclic pressure treatments did not produce critical saturation of the specimens with one exception (mixture 12). Therefore, the data for specimens of Condition 1 (14-day age), Condition 2 (14-day age plus cyclic pressure change), and Condition 3 (28-day age) are of most interest since they represent the youngest and most susceptible test specimens.

36. In general, specimens of the concrete mixture and all of the air-entrained mortar mixtures, except No. 9, were of sufficiently high-frost resistance not to be significantly damaged by 10 cycles of dilation testing. However, mortar mixture 9 and the three nonair-entrained mortar mixtures (7, 12, 3) exhibited interesting results which will be described later.

37. The intent of the dilation test is to determine if a specimen is frost resistant and whether or not it becomes frost susceptible

during the period of interest. Powers[5] originally suggested that "...If it (a specimen) shrinks normally in the freezing range, it is immune; if it dilates, it is not immune" (to frost action). In 1953, Higginson and Kretsinger[6] showed a curve (their Figure 7) that suggested that dilation of about 200 millionths represented the zone wherein the frost resistance of a concrete specimen was greatly reduced. In 1961, Tremper and Spellman[7] reported a criterion of dilation greater than 50 millionths as denoting failure. In 1969, Ainsworth and Alexander[8] followed Tremper and Spellman[7] in specifying dilation exceeding 50 millionths as being possibly damaging to the specimen under test. Also in 1969, Larson and Cady[9] stated that critical dilation (Dc) in micro-inches may be approximated by multiplying the specimen length in inches by the factor 70. They found by calculation and by testing of 6-in.-long specimens that Dc was a total of about 420 μin. It is interesting to note that use of this value in their equation says that Dc is about 70 millionths. This was the basis for adopting the value of 75 millionths as the value for Dc in the original plans for this work. ASTM C 671-74T (CRD-C 40-76) defines critical dilation as the dilation during the last cycle before the dilation began to increase sharply by a factor of 2 or more. Thus, damaging dilation was described by absolute amount for about 20 yr and is now described by amount of change between cycles. Regardless, the intent has been and is to use dilation as a method of detecting frost susceptibility. It further states that when dilations are less than 0.005 percent they should not be interpreted as indicating critical dilation even if numerically the criterion for Dc is met. However, in this work the three values for dilation at three consecutive cycles required to use the ASTM criterion were not in all cases available. The dilation criterion used was that a specimen that is not frost resistant (i.e., is frost susceptible), once dilation begins, will show increasing dilation as temperature continues to decrease (Figure 1). A specimen that is frost resistant will not show increasing dilation with continuously decreasing temperature (Figures 2, 3); it will show some limited initial dilation as all moist specimens do, but dilation will not continue throughout the cooling. While there are intermediate types of behavior between these extremes that will be discussed later, the basic criterion for separating frost susceptible from frost resistant specimens is as described.

38. After a review of the data it is apparent that a quantitative criterion for critical dilation would be desirable for use with the results of a single test, and the following appears to be appropriate:

a. If the dilation is 0.005 percent (= 50 millionths) or less, the specimen may be regarded as frost resistant, i.e., the dilation is not critical.

b. If the dilation is 0.020 percent (= 200 millionths) or more, the specimen may be regarded as not frost resistant, i.e., critical dilation has been exceeded.

c. If the dilation is in the range between 0.005 percent and 0.020 percent, an additional cycle or more should be run.

39. Figures 1,* 2, and 3 show both dilation and FW curves. The following comments refer to dilation. Figure 1 shows a typical dilation curve for a nonair-entrained frost-susceptible specimen (12M1). Once dilation started at about 22°F it was continuous with decreasing temperature. The total dilation was 5860 μin. (Table 8) when the test was stopped just below 0°F. Figures 2 and 3 show typical dilation curves of frost-resistant specimens (3C1, 10M1). There is an initial total dilation of 510 and 65 μin., respectively, and then continuous shrinkage for the remainder of the test. Tables 8 and 10 show that none of the mortar mixture 10 specimens nor the concrete specimens were frost susceptible at any time during this testing. Some initial dilation appears to be normal behavior for all of the frost-resistant specimens tested even though it was not always clearly perceptible by the curves.

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* The plots of length-change versus temperature given in this report use a variety of scales, and temperature is plotted, decreasing to the left. Figure 1 of ASTM C 671 shows length-change versus time where temperature decreases at a constant rate to the right. The graphs shown in this report were mechanically produced, and it was not believed the cost of redoing them was justified.

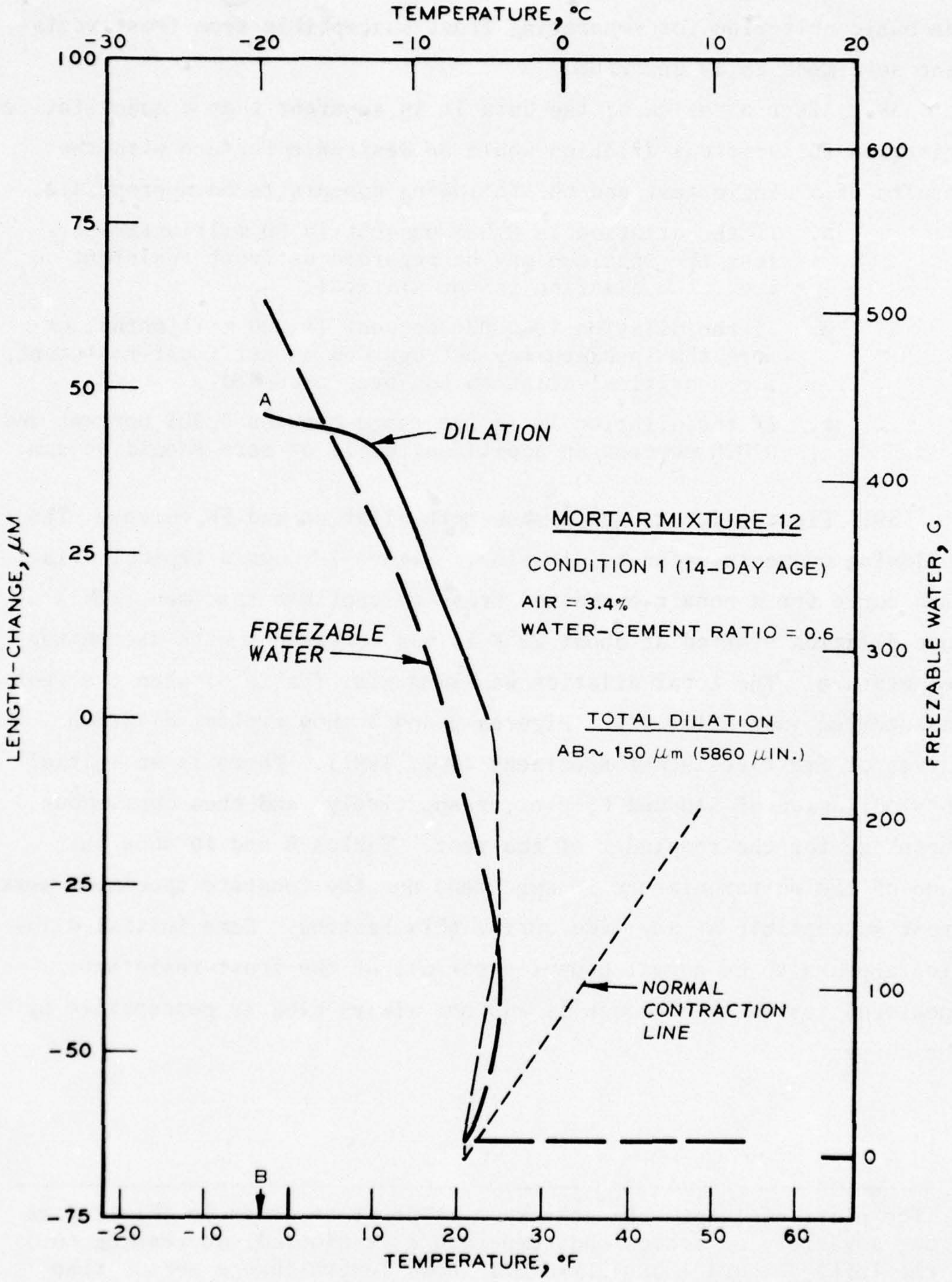


Figure 1. Dilation and freezable water data for mortar specimen 12M1, cycle 9

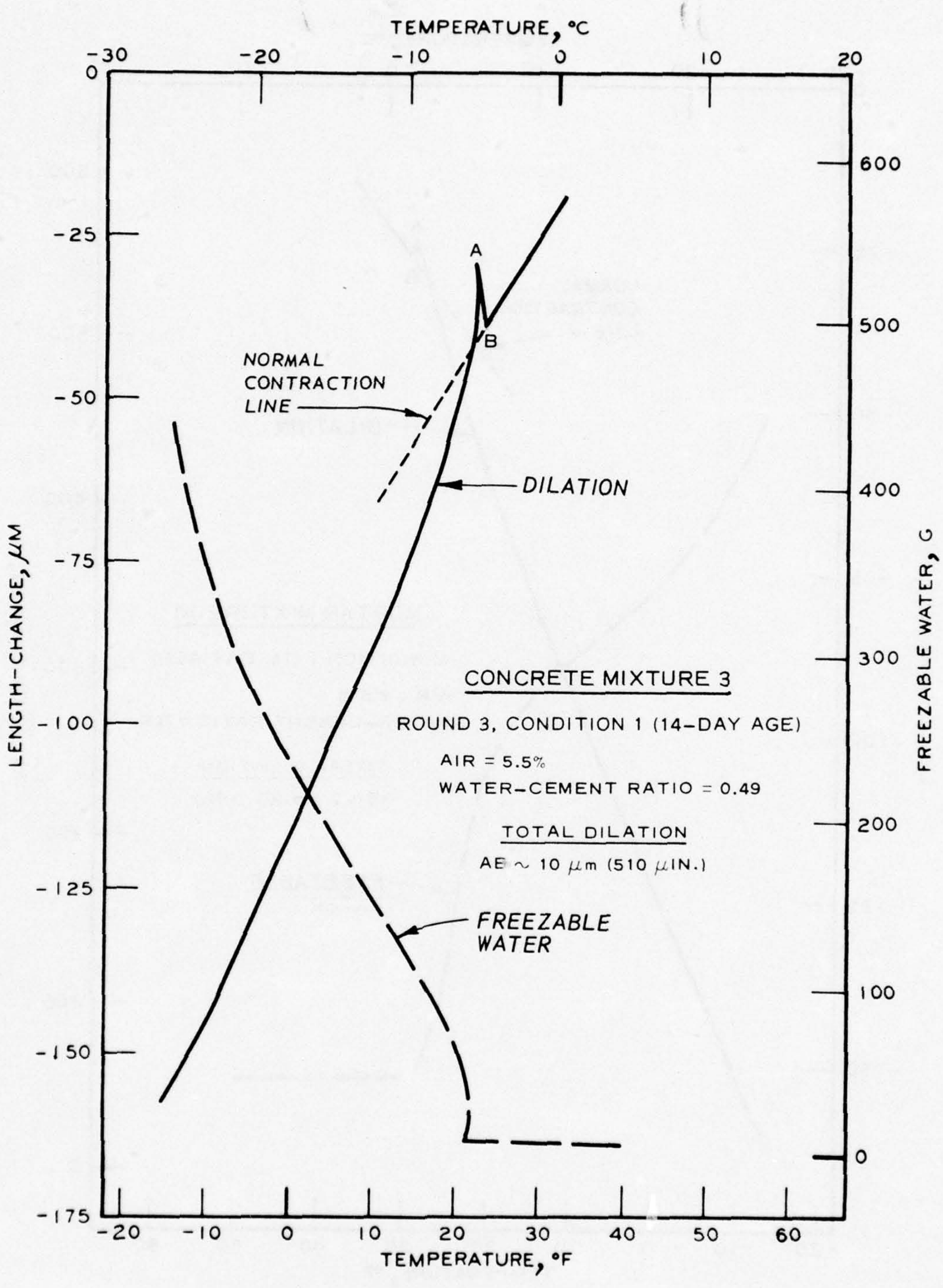


Figure 2. Dilation and freezable water data for concrete specimen 3C1, cycle 4

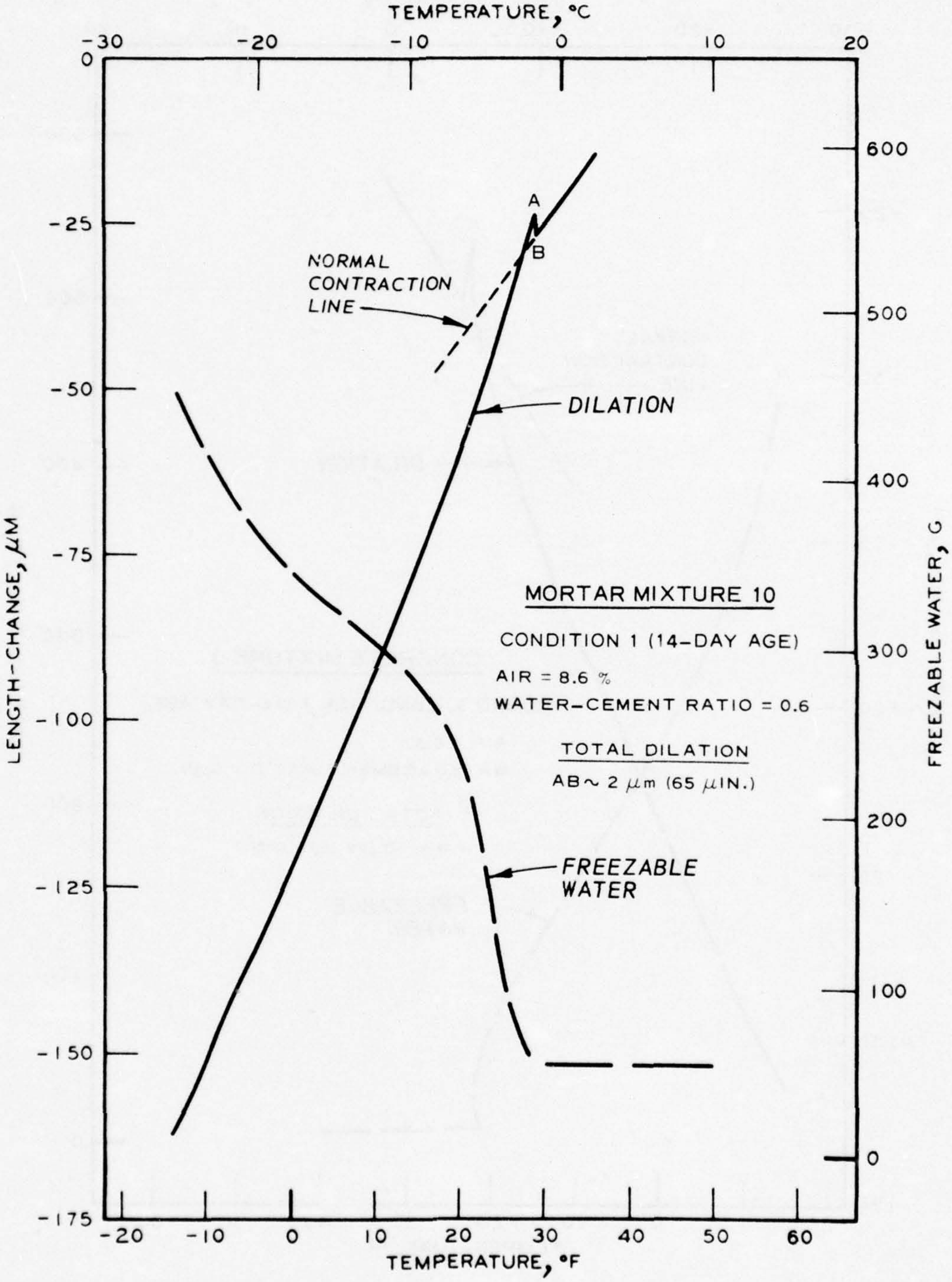


Figure 3. Dilation and freezable water data for mortar specimen 10M1, cycle 10

40. Figure 4 shows the length-change versus temperature curve for a mortar specimen which showed 180-μin. increase in length at about 22°F; and a further increase in length at about -6°F. The definition of dilation in ASTM C 671 does not provide for constructing a new normal contraction line and measuring dilation as a departure from it. This specimen is regarded as being frost resistant if not cooled below -6°F. If cooled below -6°F, it may be frost susceptible since there is an apparent large dilation beginning at that temperature.

41. Figures 5-7 illustrate another example of the problem of measuring dilation. Figure 5 shows that mortar specimen 9M1 (14-day age) is frost resistant at the time of its 8th test cycle. Figure 7 shows that mortar specimen 9M2 is not frost resistant at the time of its 10th test cycle; however, Figure 6 shows that this same specimen manifested multiple dilations during its 5th test cycle. It dilated a total of about 1600 μin. and then started to contract again. Comparison of this curve with those in Figures 5 and 7 suggests that the curve in Figure 6 indicates that the specimen is beginning to lose its frost resistance, but it is still frost resistant. This is suggested by its contraction from about 15°F on down and by its similar behavior in cycles 2 and 4 (Table 9). Therefore, a procedure similar to that of Larson, Boettcher, Cady, Franzen, and Reed[10] of recording multiple dilations separately was used in the present work (Tables 7-10). This method seemed preferable for these data.

42. Figures 5-7 for specimens 9M1 and 9M2 show that this test method can differentiate between frost-resistant and frost-susceptible specimens and may indicate a transitional stage. These curves and the data in Table 9 also show that adequate air entrainment (7 percent air) will not prevent the development of frost damage for some combinations of w/c ratio (0.8) and saturation (cyclic pressure change).

43. The behavior of nonair-entrained beam 7M1 as shown in Figure 4 and by data in Table 7 for this mixture shows that a low w/c ratio (0.4) is adequate of itself to provide protection from frost damage down to below 0°F for at least 10 cycles of freezing; this assumes durable aggregates. Below that temperature the lack of air entrainment means that the material is frost susceptible.

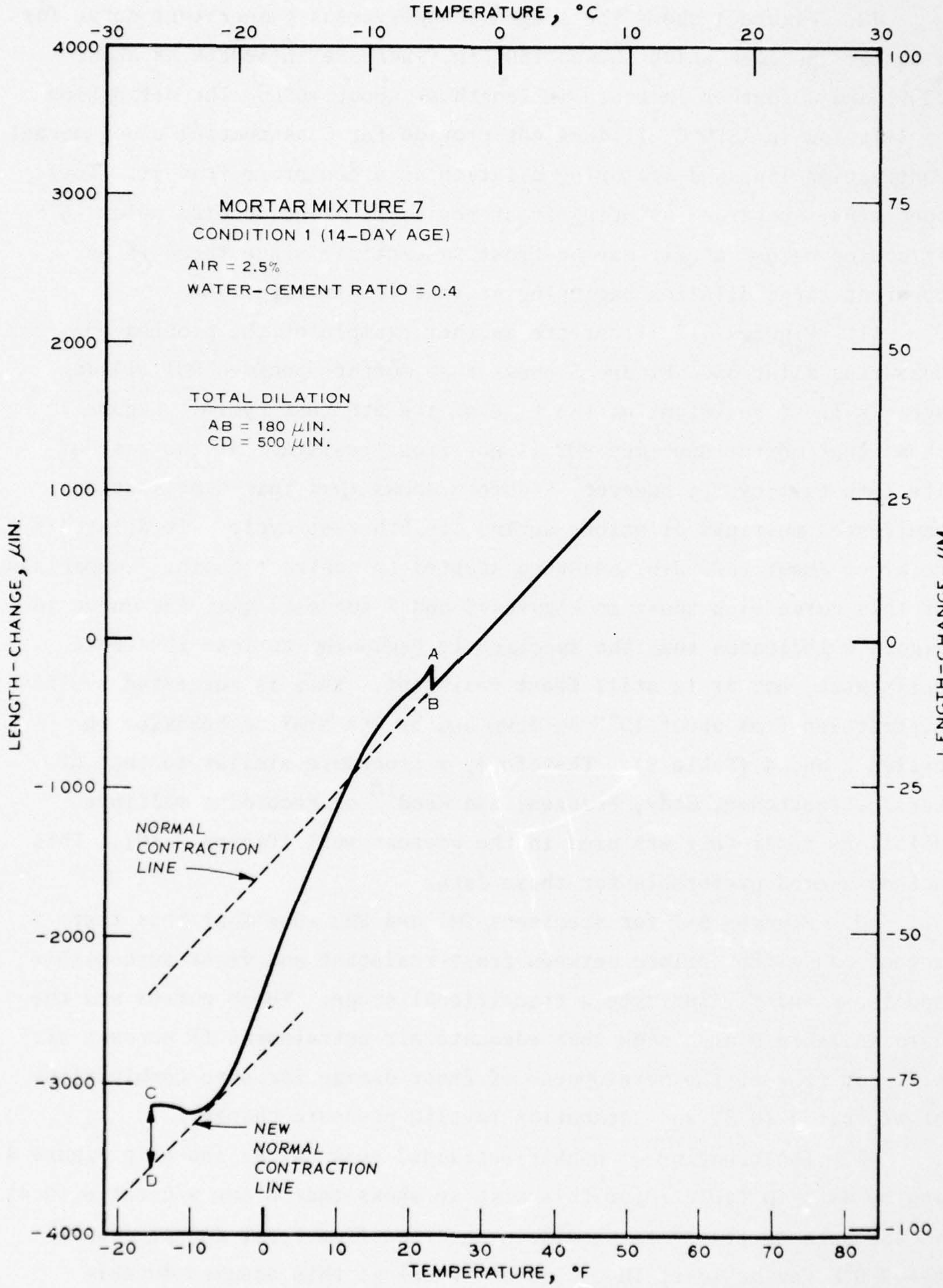


Figure 4. Dilation curve for mortar specimen 7M1, cycle 7

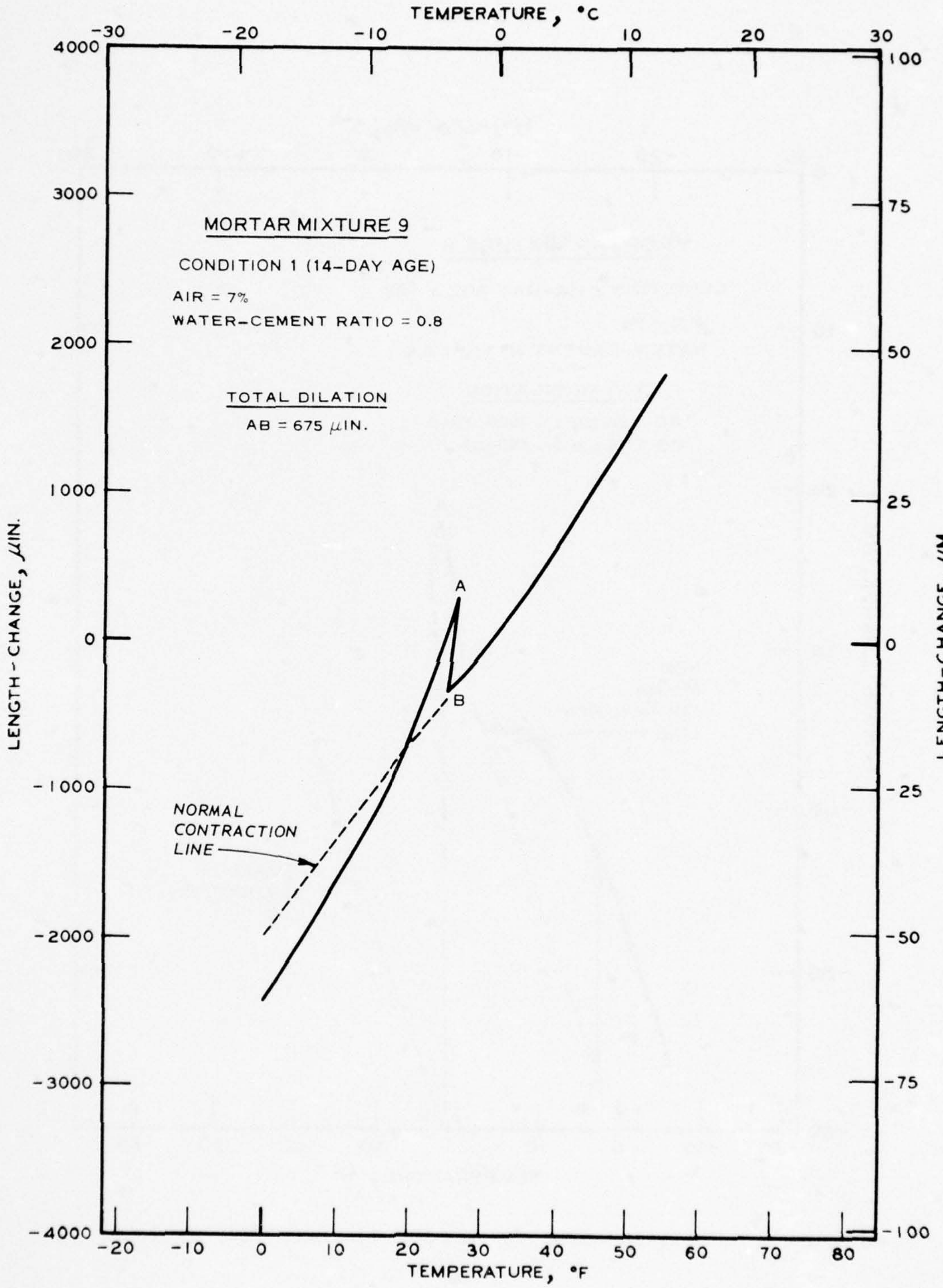


Figure 5. Dilation curve for mortar specimen 9M1, cycle 8

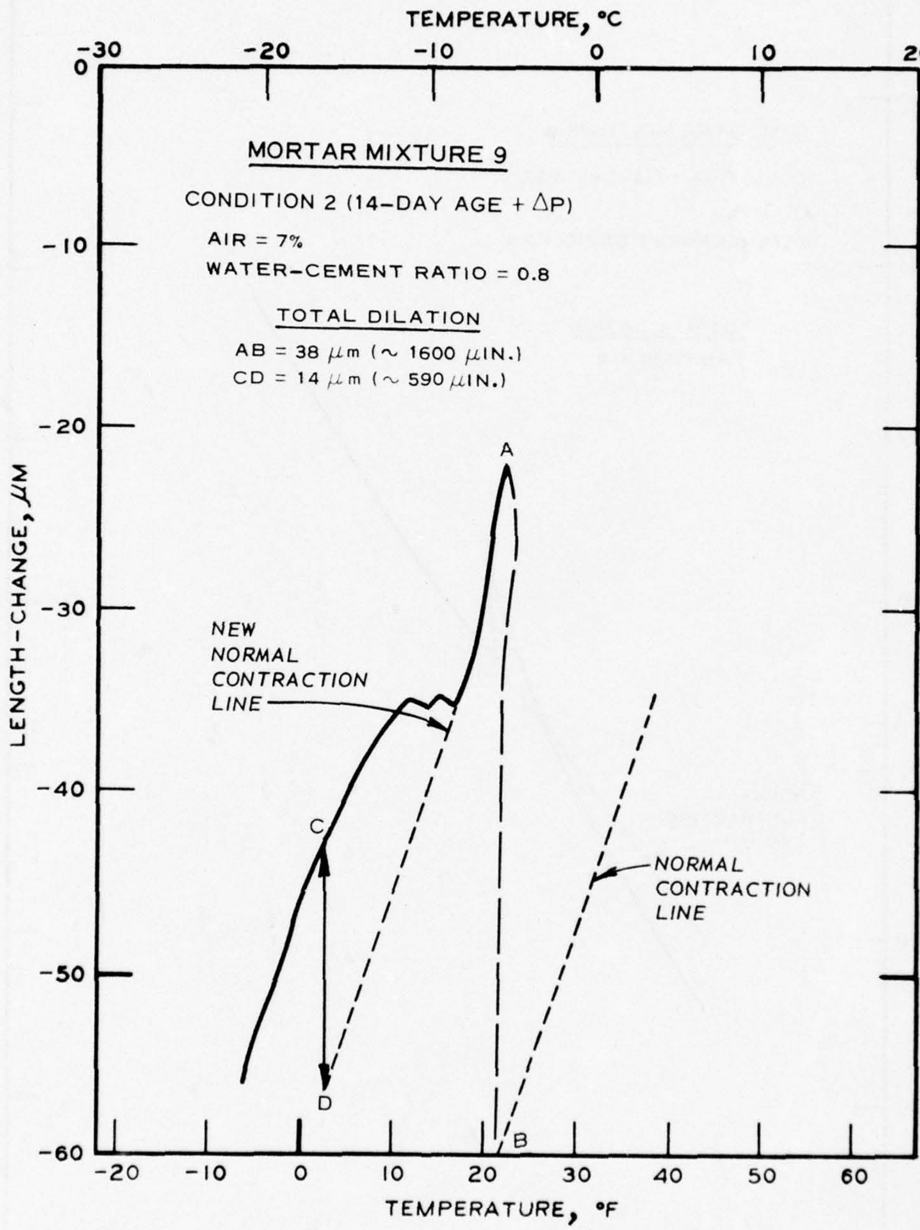


Figure 6. Dilation curve for mortar specimen 9M2, cycle 5

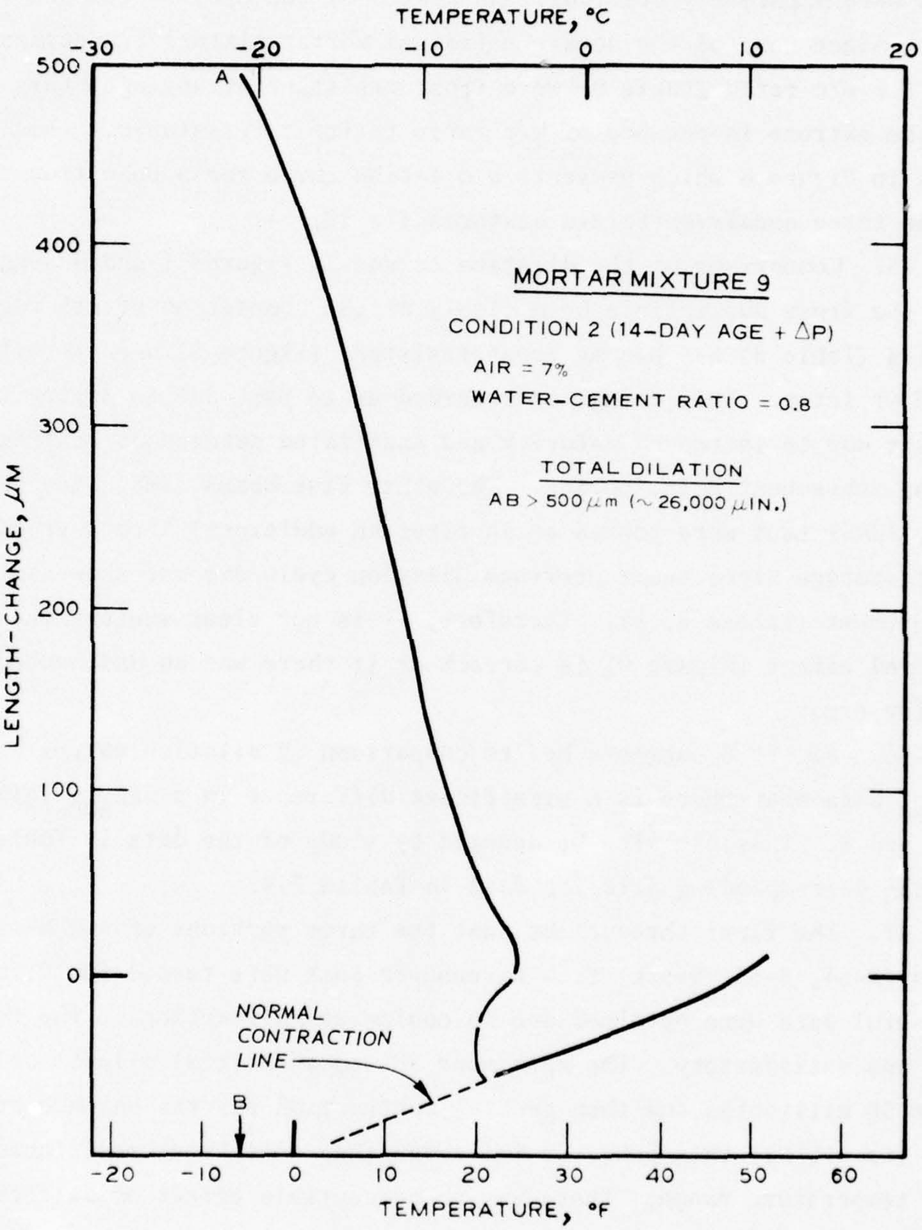


Figure 7. Dilation curve for mortar specimen 9M2, cycle 10

44. The dilation behavior of mortar mixture 12 specimens (Table 8) indicates that specimens of this nonair-entrained mixture with 0.6 w/c ratio were apparently critically saturated by the cyclic pressure treatment. Since none of the nonair-entrained mortar mixture 3 specimens with 0.8 w/c ratio (Table 9) were frost resistant at any age, this points out the extreme importance of w/c ratio to frost resistance. This is shown in Figure 8 which presents a dilation curve for a beam from each of the three nonair-entrained mixtures (7, 12, 3).

45. Comparison of the dilation curves in Figures 1 and 9 suggests that the frost susceptible beam (12M1) at the completion of its regular testing (Table 8) had become frost resistant (Figure 9) when retested 3-1/2 yr later. This change is regarded as in part due to drying and in part due to increased maturity and associated autogenous healing during subsequent moist curing. The other five beams (3M8, 9M6, 9M8, 12M6, 12M8) that were tested again after an additional 1 to 2 yr of moist storage since their previous dilation cycle did not show similar improvement (Tables 8, 9). Therefore, it is not clear whether the observed effect (Figure 9) is correct or if there was an undetected testing error.

46. Figure 8 suggests by its comparison of dilation curves and $DFE_{300}$ data that there is a significant difference in a $DFE_{300}$ value of 1 and 8. This can also be deduced by study of the data in Table 4 and the corresponding dilation data in Tables 7-9.

47. The first three times that the three portions of two NX-size cores (N-54, N-55, N-55L) from Eisenhower Lock were tested for dilation no useful data were obtained due to equipment malfunctions. The fourth test was satisfactory. The specimens showed an initial dilation of about 50 millionths and then general contraction for the balance of the test (to -15°F); this behavior indicated they were frost resistant over this temperature range. There was no perceptible effect of differences in specimen length or shape.

48. The two concrete beams (1C6, 3C5) that were tested for dilation without simultaneous measurement of freezable water showed total initial dilations of 500 μin. and were frost resistant over the

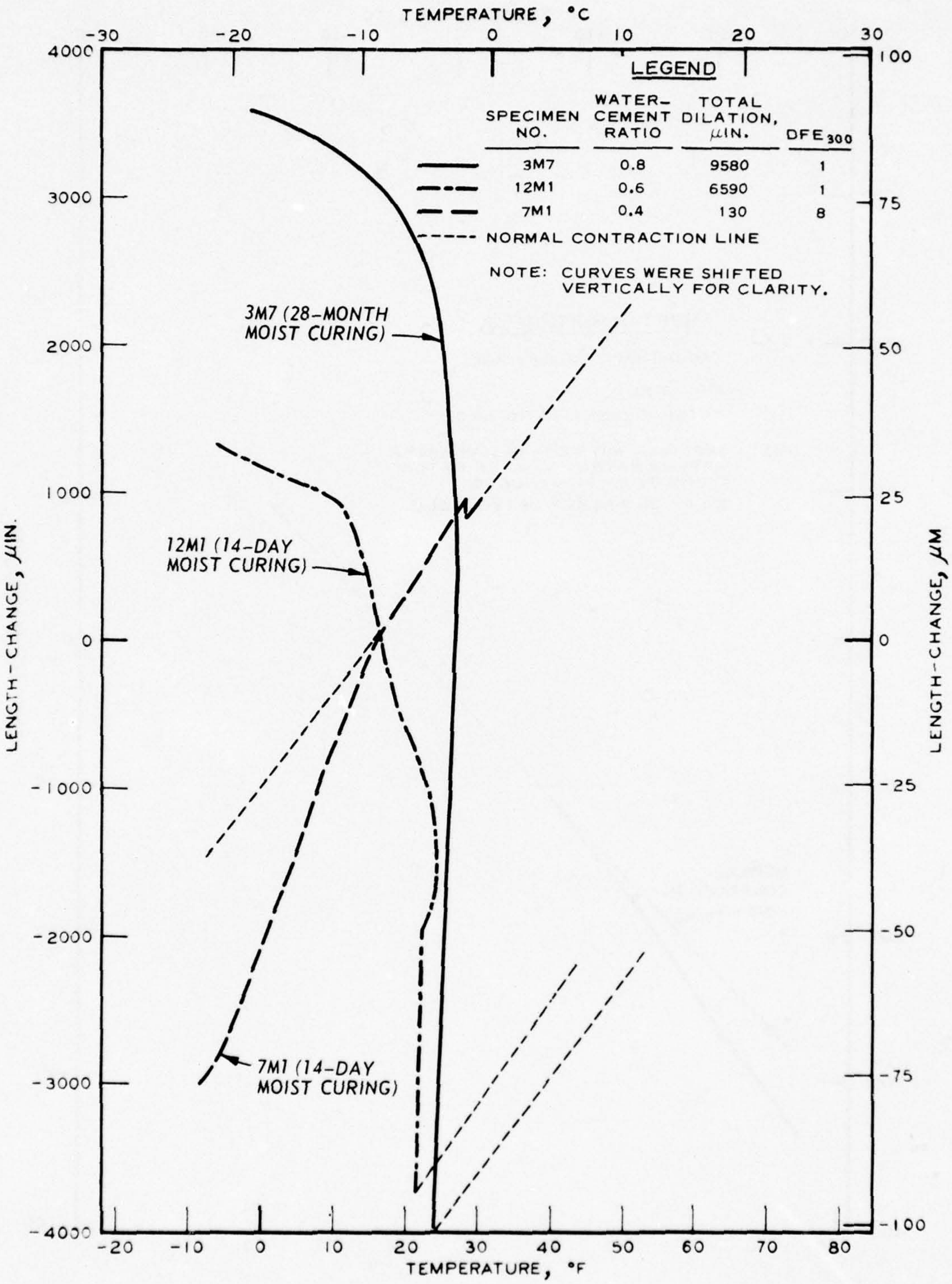


Figure 8. Dilation curves of nonair-entrained mortar specimens 7M1 (cycle 8), 12M1 (cycle 10), and 3M7 (cycle 1)

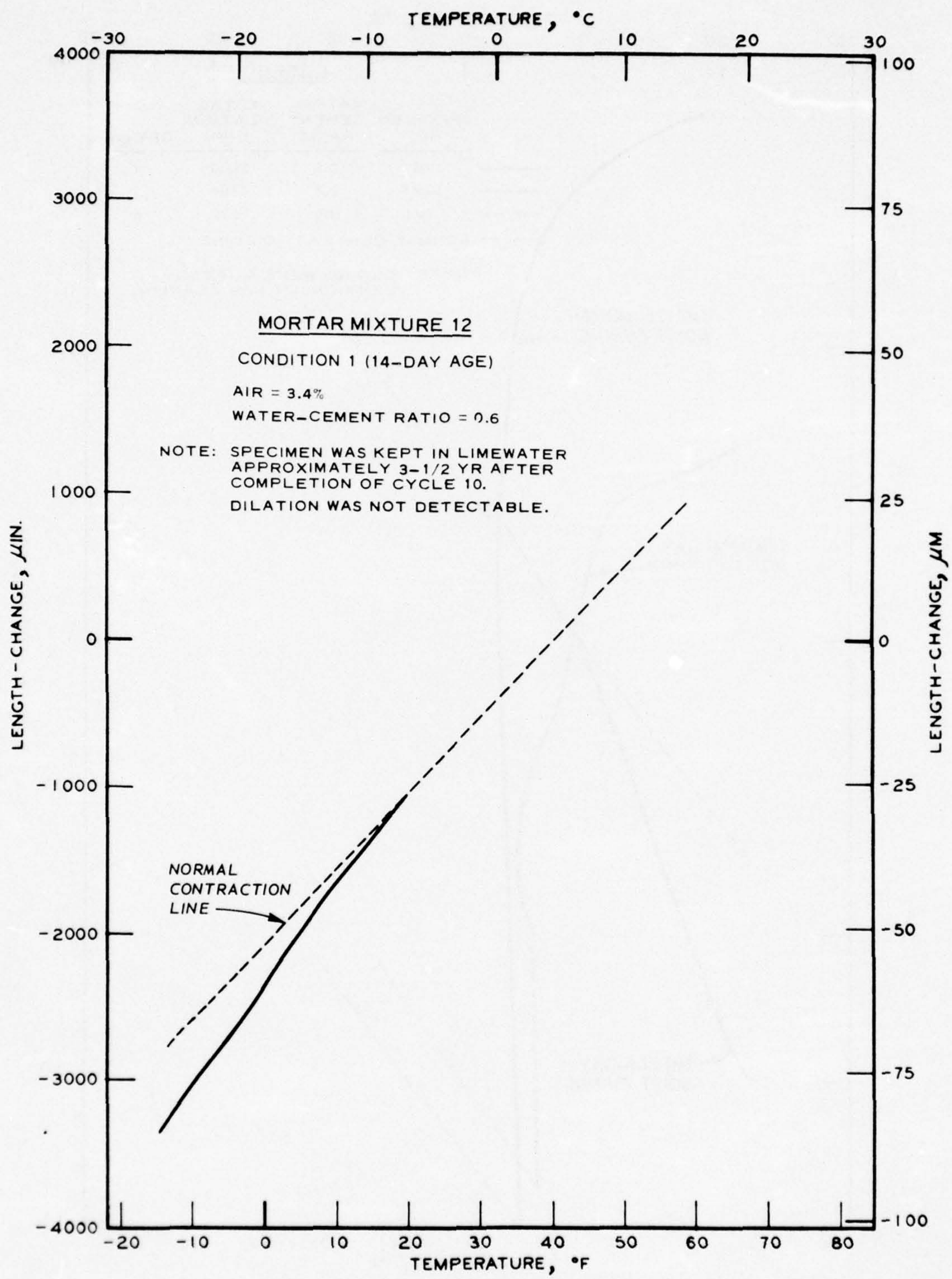


Figure 9. Dilation curve for mortar specimen 12M1

temperature range covered (plus 70° to minus 9°F). The data agreement for this condition and that used in the rest of the work was satisfactory.

## Freezable Water

49. Data on FW in concretes, mortars, or both have been published by Verbeck and Klieger;[3] by Wong, Anderson, and Hilsdorf;[11] and by Vuorinen.[12] Most of the data given were for nonair-entrained concrete mixtures. The amount of FW at 20°F and at 10°F is shown in Table 11 for the three nonair-entrained mortar mixtures (3, 7, 12). The amount of FW at 0°F during the first test cycle is shown in Table 12 for the 12 mortar mixtures. The amount of FW and dilation by cycle, as averages, and the standard deviations are shown in Table 13 for nonair-entrained mortar specimen 3M5 at 20 and 10°F. This tabulation shows that there is no progressive increase in FW as the dilation increases from about 4200 to 16,000 μin. This same lack of correlation was also shown for specimen 9M2 and specimens 12M1, 12M2, 12M3, and 12M4, which were the other five cases where there was enough progressive dilation to make an evaluation. This last finding is unexpected since Verbeck and Klieger[3] reported a large increase of FW in a specimen made from nonair-entrained, 0.72-w/c ratio concrete combined with excessive expansion during testing. Their first and tenth cycles were done in conventional laboratory rapid freezing-and-thawing equipment. All test cycles for specimen 9M2 were done in the calorimeter-strain apparatus. It seems probable that both findings are correct with the differences being due to degree of damage sustained by the specimens. The dilation testing here suggested that the end of frost immunity had been reached for specimen 9M2, but it had not actually developed any appreciable deterioration; whereas the rapid freezing-and-thawing test used for test cycles 2-9 by Verbeck and Klieger[3] had actually developed physical damage which was indicated by both expansion and FW.

50. Figures 1-3 show typical FW and dilation curves for three specimens. Figures 10-12 show the response of FW to selected variables.

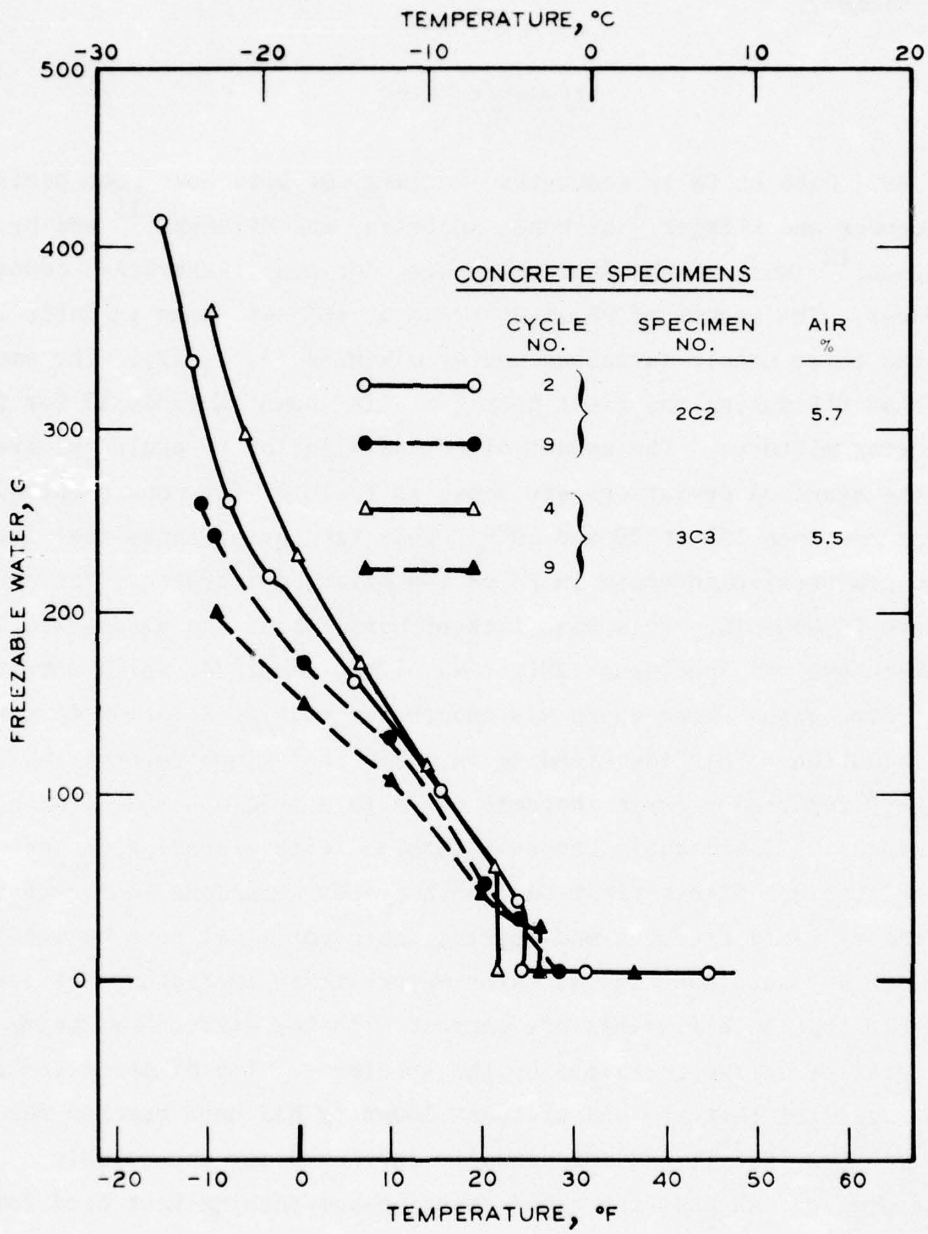


Figure 10. Freezable water curves for concrete specimens, 2C2 and 3C3, with water-cement ratio = 0.49 and different cycles and conditions

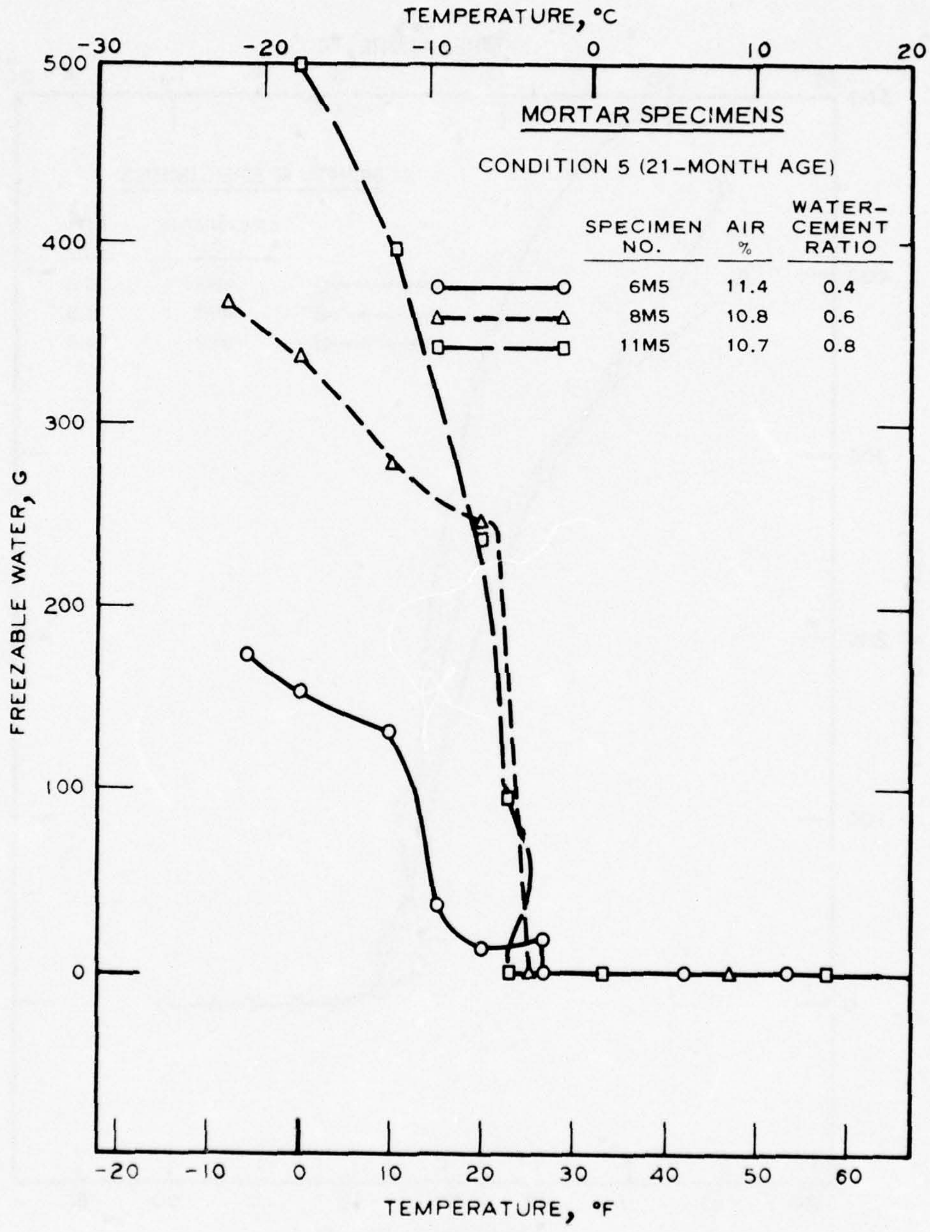


Figure 11. Freezable water curves for mortar specimens 6M5, 8M5, and 11M5, cycle 1, at three different water-cement ratios

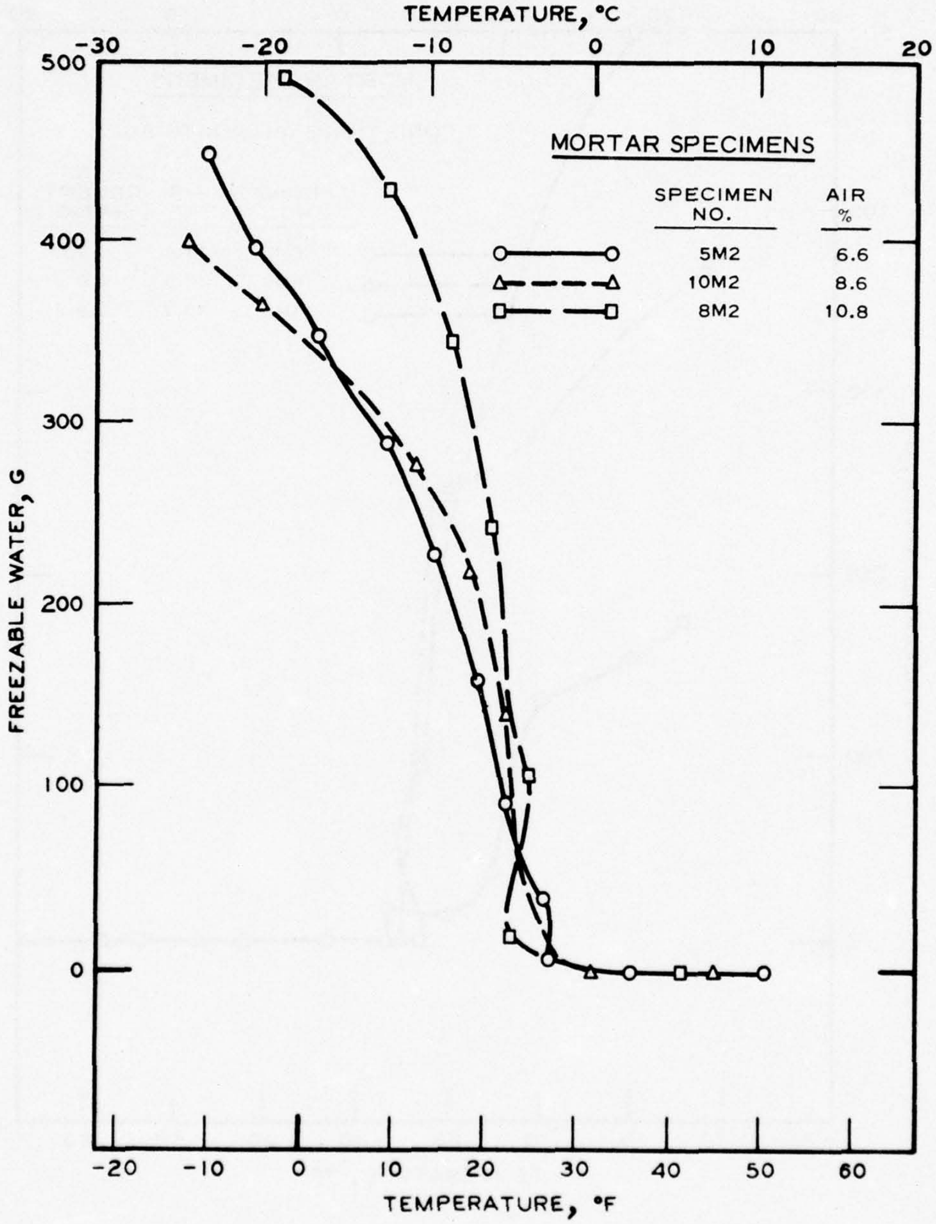


Figure 12. Freezable water curves for mortar specimens 5M2, 10M2, and 8M2, cycle 5, with water-cement ratio = 0.6 and three different air contents

51. Examination of the FW data for three nonair-entrained mortar mixtures in Table 11 and of the companion dilation-FW curves in Figures 1-3 shows general agreement with applicable portions of References 3, 11, and 12. These results include:

a. There is an increase in amount of FW with an increase in w/c ratio (Table 11).

b. The reported decrease in amount of FW with increasing age is not well shown by the present data (Tables 11, 12). The effects of different w/c ratios and air contents and of missing data probably hamper the detection of this expected correlation. There does seem to be a general tendency for short-time decrease, as reported by others,[3, 11] but there also seems to be a tendency for the amount of FW to increase between 28 days and 21 months; this suggests that the reduction in FW due to hydration is overcome by an increase in FW due to increased saturation during continued moist curing.

c. There is a general increase in FW with increasing dilation for nonair-entrained mixtures as shown for mixture 12 in Figure 1.

d. The reverse relationship holds true for air-entrained mixtures where FW increases as the specimens continue to contract with decreasing temperature; this is typified by the curves for the concrete mixture and mortar mixture 10 in Figures 2 and 3. The fact that there is no direct relationship between amount of FW and amount of dilation for air-entrained mixtures indicates that examination of data for FW at maximum dilation is not the desirable way to examine such FW data. For this reason, the data for FW at one temperature (0°F or minus 17.8°C in this case) were obtained (Table 12), and selected FW curves are compared in Figures 10-12.

52. The following observations may be made by consideration of the data shown in Tables 11-13, Figures 1-3 and 10-12, and other dilation data shown earlier:

a. The saturation caused by the cyclic water-pressure treatments of selected specimens at different ages did not result in critical saturation of air-entrained specimens.

b. None of the concrete specimens have undergone significant dilation. The FW content of the concrete specimens did not show definite response to age or saturation of specimens or to number of test cycles (Figure 10).

c. The FW content of air-entrained mortar mixtures tends to increase with w/c ratio as it does with nonair-entrained mixtures (Figure 11).

d. The amount of FW does not appear to correlate with overall age, saturation, or air content of air-entrained mortar mixtures (Table 12, Figure 12). The lack of correlation between amount of FW and air content agrees with previous results (References 3, 12).

## Air Content (High Pressure)

54. The air contents of 13 cylinders and a calculated value for relative saturation of each are shown in Table 14. As stated earlier, this testing was stopped because of the excessive times needed to establish equilibrium. The air contents measured when mixtures were made are also shown. It is not believed that the calculated values for saturation are more than relative, but the overall indication that none of the specimens were critically saturated is thought to be correct.

## Weight-Gain Data

55. The weight gains of specimens due only to the cyclic pressure treatment(s) are shown in Tables 15 and 16. These data show the following:

a. The gain tends to increase with air content at a constant w/c ratio.

b. The gain tends to decrease with increasing age.

c. The gain tends to increase with w/c ratio (i.e., permeability) when the air content is a constant.

While the mass of a beam is less than that of a cylinder, their surface areas are similar; consequently, surface area per unit of mass or volume (s/v) is 1.14 for a beam and 0.84 for a cylinder. Thus, beams should gain more mass on soaking expressed as fraction of the original mass. However, the data in Tables 15 and 16 indicate the reverse; they show, for the comparisons that are possible, that the cylinders gained more mass than beams in about 65 percent of the comparisons. Review of the original data showed that the increase in mass of the control specimens (stored in the fog room) was expressed as unit change in mass and subtracted from the gross values for unit change in mass for each test specimen. Thus no cognizance was taken of the difference between cylinders and beams in surface to mass ratio. The reversals may well be due to this fact.

56. The increase in mass of the controls over a 3-yr period is shown in Table 17 for the concrete and mortar mixtures. The increase in mass due to uptake of water increases with increasing air content of the concrete. The increase in mass due to water uptake did not vary with water-cement ratio. The control specimens showed the following:

- a. Approximately half of the total increase in mass takes place in the first 6 months.
- b. Most of the remaining increase in mass occurs during the next 12 months.
- c. There is essentially no additional increase after 18 months under moist storage conditions.

57. Table 18 shows the results of a comparison to determine whether the cyclic pressure (changes of 14-31 psi) treatment produced different results than a constant pressure of 14 or 31 psi. Specimens from mortar mixtures (7, 8, 9) representing the full range of w/c ratios and air contents were used. The data show that there is a distinct difference in the amount of saturation achieved between a constant pressure of 14 psi and cyclic changes between 14 and 31 psi. The constant pressure results in less increase in mass. A constant pressure of 31 psi and cyclic changes between 14 and 31 psi seem to produce similar results except for the low w/c ratio mixture 7 cylinder. In that case, cyclic changes do appear to cause more saturation than constant pressure.

58. Table 19 shows the effects of extended periods of cyclic pressure change testing and moist storage on one or more cylinders from every mixture. A change of 1 ounce (~26 g) for a 30-lb cylinder is about the experimental error in determining mass. The data show the following:

- a. There is a progressive increase in water uptake with increased w/c ratio and with increasing air content for 14- and 28-day-old cylinders during the initial 4000 cycles of fluctuating pressure.
- b. There was little effect from the additional cyclic pressure treatment for periods approaching 2 yr. However,

what effect there was occurred in the specimens with lower w/c ratio.

c. The more permeable eight mixtures of the 0.6- and 0.8-w/c ratio groups tended to take up all of the water they were going to during the first 4000 cycles of fluctuating pressure, whereas the 0.4 group, except for mixture 7, tended to continue picking up a little water with additional cyclic pressure treatment. The cylinders of mixture 7 were so impermeable that they were essentially unaffected by about 9000 additional cycles.

d. There is little loss of mass after extended cyclic pressure changes for specimens kept damp at atmospheric pressure for periods approaching 6 months in length.

59. Some specimens that had been moist cured for about 20-1/2 months were placed in the cyclic pressure system and weighed after each 1000 cycles to determine when weight gains occurred. However, the data were inadequate for this purpose because there were not enough mass changes with these older specimens.

## Freezing-and-Thawing and Dilation Data

60. To this point, the data from each kind of test (freezing-and-thawing, compressive strength, dilation, FW, air content by the high-pressure method, and increase in mass) have been evaluated against the test variables of w/c ratio, air content, and age; it was pointed out earlier that exposure to pressure changes turned out to have a rather negligible effect as a variable. Correlations for one kind of test data against another were also considered and will be described next.

61. In 1953, Higginson and Kretsinger[6] published some data that indicated a correlation of laboratory freezing-and-thawing data with length-change (dilation) data. In 1970, Vuorinen[13] presented similar data that indicated general correlation of data from the two test methods. He also pointed out that there appeared to be a zone of poor correlation. Since this correlation is of considerable interest, a great deal of effort was expended in the present work trying to correlate freezing-and-thawing and dilation data. The following comparisons were plotted:

a. Average $DFE_{300}$ values against dilation values for all 12 mortar mixtures by each of the 8 test conditions (i.e., age or age plus cyclic pressure changes).

b. Average $DFE_{300}$ values for the three nonair-entrained mixtures (7, 12, 3) against corresponding final dilation values by each of the eight test conditions.

c. The relative E value after 10 cycles of freezing-and-thawing testing against corresponding final dilation values by each of the eight test conditions. It was hoped that this comparison after a generally equal number of freezing-and-thawing cycles might provide a better correlation, but it did not.

d. Similar comparisons were made using fewer data so that any effects of w/c ratios or air contents would be apparent.

62. All of the comparisons tend to suggest a correlation similar to those found by Higginson and Kretsinger[6] and by Vuorinen.[13] In general, it can be said that there is a separation into a group representing air-entrained specimens which have high $DFE_{300}$ (>60) and low-dilation values and a nonair-entrained group which has low $DFE_{300}$ (<40) and high-dilation values. However, there are always data that do not fit into these groupings because they exhibit a range of dilation values at a $DFE_{300}$ value or a range of $DFE_{300}$ values at a dilation value.

63. Figure 13 shows this plot for the three nonair-entrained mortar mixtures (7, 12, 3). A freehand curve was sketched in to indicate the general correlation pattern. This plot was included for two reasons. The vertical line at a total dilation of 1600 μin. was drawn in to denote a general separation between "safe and unsafe" dilations; there was a general indication in all of the study of $DFE_{300}$ and dilation data that dilation of about 100 millionths indicated frost susceptibility or the beginning of it. This value is in general agreement with those mentioned in References 4-9. Figure 13 also provides an indication of a difference between $DFE_{300}$ values below 5 and those above 10 as indicated by the horizontal line.

64. Plots of mortar compressive strengths versus $DFE_{300}$ for each w/c ratio were made for each of the eight test conditions (not shown). In each case, these served mainly to separate the air-entrained from the nonair-entrained mixtures.

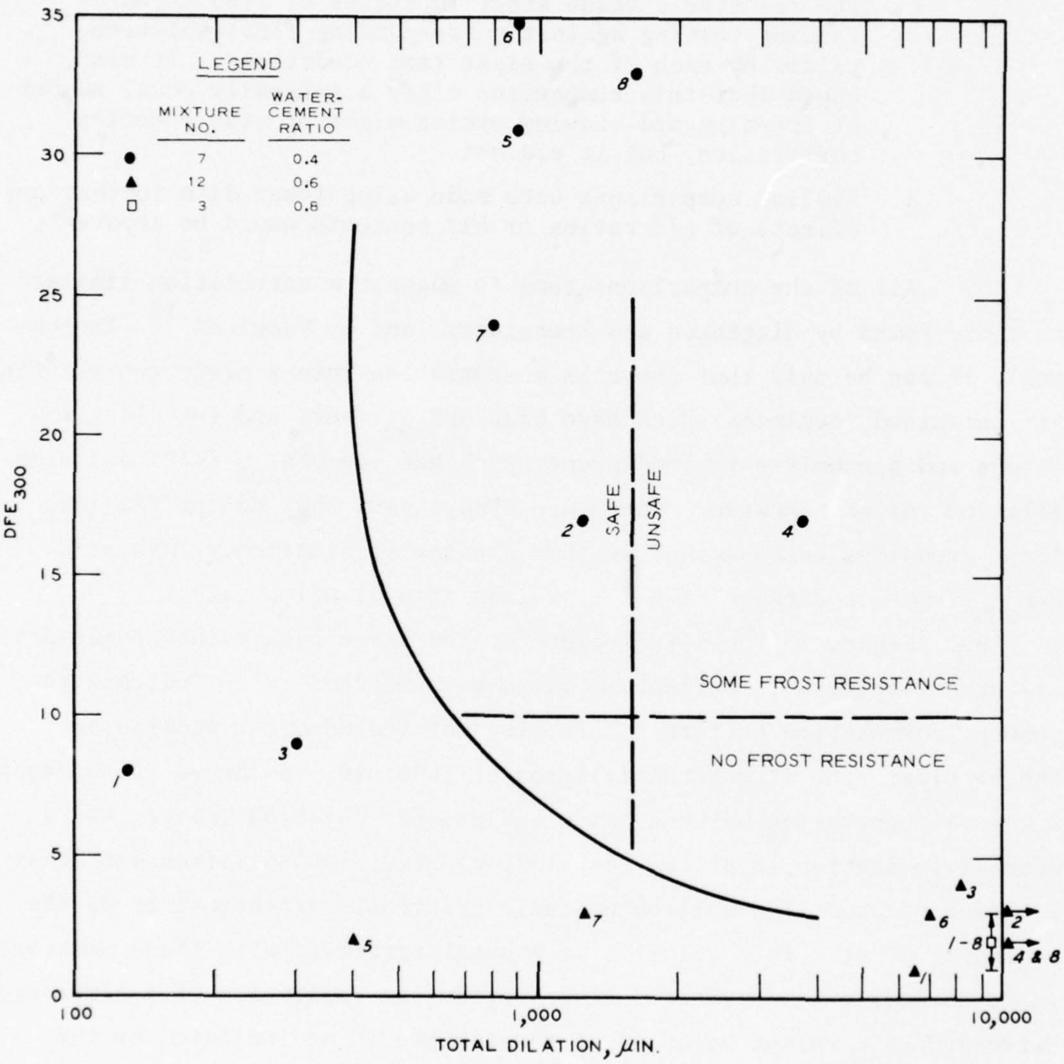


Figure 13. $DFE_{300}$ versus total dilation for three nonair-entrained mortar mixtures (24 specimens)

0.4 w/c ratio

65. The air-entrained mixtures (4, 1, 6) all had average $DFE_{300}$ values $\geq$83 and strength >4000 psi, so no significant trends were detectable. The strength and $DFE_{300}$ values for nonair-entrained mixture 7 both tended to increase with greater age.

0.6 w/c ratio

66. All the air-entrained mixtures (5, 10, 8) had strengths $\geq$2400 psi and average $DFE_{300}$ values >60 with some improvement with greater air contents; no other significant variation of strength with $DFE_{300}$ was apparent.

0.8 w/c ratio

67. Both the strength and $DFE_{300}$ data varied together by increasing air contents and by age (to 20-1/2 months) for the air-entrained mixtures (9, 2, 11), but there was no such trend for the specimens treated by cyclic pressure. Between 20-1/2 months and 28 months, the $DFE_{300}$ values had decreased and the strength values remained essentially constant. No reason for this behavior is readily apparent.

68. For the nine air-entrained mortar mixtures, the 0.4-w/c ratio group had a minimum strength of >4000 psi and a minimum $DFE_{300}$ of 83, the 0.6-w/c ratio group had minimum strength >2400 psi and $DFE_{300}$ >60, while the 0.8-w/c ratio group showed no such separation. In general, the strength and $DFE_{300}$ both increase with decreasing w/c ratio values, so that all of the 0.6-w/c ratio air-entrained group are frost resistant (i.e., $DFE_{300}$ >60).

## Discussion

69. There is a general lack of significant effect of the cyclic pressure treatment on test specimens having a range of w/c ratios and air contents. This is strong evidence that the development of a state of critical saturation which when followed by freezing caused the frost damage to concrete at Eisenhower Lock[1] was not contributed to by the cyclic variation in water pressure in that concrete due to filling and emptying of the lock.

70. The measurement of tendency of concrete to dilate on freezing has been found in these tests, as previously found by Powers,[5] to be a sensitive indication of the frost resistance of a specimen at the time of test.

71. It has been assumed for many years that some concretes are immune to frost action. Such concretes are those that are made with nonfrost-susceptible aggregates and a proper air-void system and cured to an appropriate degree of maturity so as to reduce the fractional volume of freezable water on saturation to limits that can be accommodated by elastic volume change and by the air-void system. Such concrete is characterized by no significant reduction in mechanical integrity after hundreds or thousands of cycles of freezing and thawing under conditions in which saturation is attained and maintained either in nature or in the laboratory accelerated freezing-and-thawing test. Such concrete is typically described as having a $DFE_{300}$ of 80 or more. Such concrete would be expected not to show critical dilation no matter how long it was allowed to soak in water prior to being tested for dilation. It has been suggested that concrete of this sort is properly referred to as "immune to frost action." However, it has also been suggested that, since the immunity of such concrete depends in part on the maintenance of the air-void system, if an environmental mechanism were to be encountered which filled the air voids with water, such concrete would lose its immunity and become critically dilatant and hence frost susceptible. The work reported here indicates that the cyclic pressure exposure used is not an effective environmental mechanism of this sort. Vacuum saturation has been reported to be such a mechanism; but no vacuum saturation followed by freezing has as yet been reported in an actual environmental concrete exposure in service. It is therefore correct, as is done in ASTM C 671, to place the emphasis in dilation testing on whether a specimen is protected for the period of time that it is estimated will be needed for the actual structure in the field (i.e., "the period of interest"). Such information would be useful since Wuerpel[14] has pointed out that there was no basis for expressing the results of laboratory freezing-and-thawing tests as number of freezing-and-thawing cycles in nature at a particular locality.

72. Comparisons of the transitory dilation during a single test with the permanent length-change during that test or with the cumulative length-changes from repeated dilation tests suggest that the transitory value may be used. The determination of permanent change during a test requires comparison of length values at the same temperature during cooling and warming, which involves more effort than the measurement of the transitory value.

73. It is believed that concrete can be made with adequate assurance that it will be frost resistant. Careful advance consideration of environmental factors should permit the proper selection of materials and a proper w/c ratio and air content. Testing of the selected mixture for resistance to freezing and thawing will screen out frost-susceptible aggregates.

## PART V: CONCLUSIONS

74. Based on the majority of the laboratory cyclic pressure data and especially on those data pertaining to combinations most like those in the lock itself, the cyclic pressure changes resulting from changing water levels during lockages at Eisenhower Lock do not appear to have had a significant effect in inducing a greater degree of saturation of that concrete than would have been achieved without such effects.

75. The concrete mixture that simulated Eisenhower Lock concrete with the large aggregate removed was found to be frost resistant when it is adequately mature.

76. There is a direct increase in the frost resistance of mortar and concrete as the w/c ratio is lowered. A nonair-entrained mixture with 0.4 w/c ratio may be frost resistant to about minus 6°F if the aggregates are durable, and the needed period of frost immunity is not very long.

77. Air entrainment is needed regardless of how low the w/c ratio may be, at least within the range of w/c ratios investigated in this study.

78. The air content of air-entrained concrete required for frost resistance increases as the w/c ratio is increased. Seven percent air is needed in 0.4-w/c ratio mortars. However, about 9 percent seems to be needed in 0.8-w/c ratio mortars. These values are consistent with the air content percentages given in paragraph 4-2c of EM 1110-2-2000 and specified in paragraph 9.4 of Guide Specification CE 1401.01, and no changes thereto are necessary.

79. FW content as measured in this study is not a sensitive index to characterize frost resistance of concrete.

80. The beneficial effect of increased maturity (i.e., decreased FW content) on frost resistance of portland cement mortars and concretes is most pronounced with w/c ratios greater than 0.6. At 0.6 and lower w/c ratios, 14 days of moist curing will provide almost as much frost resistance as 28 days of moist curing.

81. Dilation testing provides a sensitive measure of frost resistance of concrete or mortar at the time of test. It will also indicate the time when a previously frost-resistant specimen may begin to lose and when it has lost its frost resistance, as the concrete becomes critically saturated under conditions in which either the fractional volume of FW is excessive or the air-void bubble-spacing factor is deficient or both.

82. Simultaneous measurement of dilation and FW by the methods used in this study is not recommended since the FW data have not proven useful.

83. The method given in ASTM C 671[4] for interpreting dilation data should be modified for some mixtures as indicated in this report. Pending possible changes in published standard methods for interpretation, the discussion within this report is considered pertinent when unusual dilation performance is detected.

84. The dilation data have shown that a $DFE_{300}$ value in the range of 11 $\pm$ 1 indicates some frost resistance while a $DFE_{300}$ value of 3 or less indicates no frost resistance. Therefore, such values indicate differences in levels of frost resistance. However, such differences are of no known practical significance.

85. Mixture 7 demonstrated that a frost-resistant, noncritically saturated mortar (and presumably concrete) specimen may become critically saturated and lose its frost resistance without access to additional water if the temperature alone is lowered far enough. A similar effect might occur if a temperature in the freezing range were maintained steadily for some period of time. This change is believed to occur as water moves from gel pores to larger pores or as water freezes in progressively smaller pores with decreasing temperature or by a combination of each as the temperature is decreased in the freezing range.

86. Standard laboratory freezing-and-thawing tests remain the most appropriate method for evaluating the suitability of potential concrete aggregates (paragraph 2-2d(4) of EM 1110-2-2000).

87. Use of the dilation test would seem appropriate to determine whether a sample of concrete or mortar is frost resistant at the time of test or to measure the period of frost immunity; the latter being the

stated purpose of ASTM C 671-74T. This being the case, use of the dilation test will typically be limited to concrete containing aggregates of marginal frost resistance and to climates where the concrete may be expected to be exposed to freezing conditions at early ages.

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Table 1

Test Data on Portland Cement RC-602

| Chemical Data | Amounts, % |
|---|---|
| $SiO_2$ | 21.6 |
| $Al_2O_3$ | 5.7 |
| $Fe_2O_3$ | 4.5 |
| CaO | 62.8 |
| MgO | 0.7 |
| $SO_3$ | 2.0 |
| Loss on ignition | 1.8 |
| Alkalies - total as $Na_2O$ | 0.34 |
| Insoluble residue | 0.14 |
| $C_3A$ | 7.4 |

| Physical Data | |
|---|---|
| Specific surface, $cm^2/g$ | 3255 |
| Air content, % | 6.3 |
| Compressive strength, psi | |
| 3 days | 1920 |
| 7 days | 2585 |
| False set* | 56.6 |
| Autoclave expansion, % | 0.02 |
| Initial set, hr/min | 3:30 |
| Final set, hr/min | 5:35 |

* Ratio of final penetration to initial penetration expressed as percent.

Table 2

Test Data - Aggregates

| Property | Coarse CRD-G-34(3) | Fine CRD-MS-17(9) |
|---|---|---|
| Bulk specific gravity, saturated surface dry | 2.79 | 2.66 |
| Absorption, % | 0.7 | 1.6 |
| Grading, sieve: | Cumulative Percent Passing | |
| 3/4 in. | 100 | -- |
| 1/2 in. | 95 | -- |
| 3/8 in. | 61 | -- |
| No. 4 | 7 | 100 |
| No. 8 | -- | 86 |
| No. 16 | -- | 64 |
| No. 30 | -- | 35 |
| No. 50 | -- | 19 |
| No. 100 | -- | 12 |
| Minus No. 100 | -- | 9 |
| Fineness modulus | -- | 2.84 |
| Approximate mineralogical composition | 86% dolomite, 10% quartz,* 4% feldspars | 85% calcite 13% dolomite 2% other |
| Rock type | dolomite | dolomitic limestone |

* Acid-insoluble residue is 13.8%; in addition to the quartz and feldspars, there are small amounts of pyrite, clay-mica, and possibly anhydrite.

Table 3

Mixture Data

| No. | Water-Cement Ratio | Air Content, % Intended | Air Content, % Actual | Slump, in. | Cement Content, lb/yd$^3$ | Casting Date |
|---|---|---|---|---|---|---|
| **Mortars*** | | | | | | |
| 7 | 0.4 | none | 2.5 | 3-3/4 | 1100 | 15 Dec 70 |
| 4 | 0.4 | 7 | 7.0 | 3-3/4 | 1025 | 25 Aug 70 |
| 1 | 0.4 | 9 | 9.5 | 3-3/4 | 996 | 19 May 70 |
| 6 | 0.4 | 11 | 11.4 | 3-1/2 | 959 | 25 Aug 70 |
| 12 | 0.6 | none | 3.4 | 3-1/2 | 686 | 9 Mar 71 |
| 5 | 0.6 | 7 | 6.6 | 3-1/2 | 611 | 25 Aug 70 |
| 10 | 0.6 | 9 | 8.6 | 3-1/4 | 583 | 9 Mar 71 |
| 8 | 0.6 | 11 | 10.8 | 3-1/4 | 555 | 15 Dec 70 |
| 3 | 0.8 | none | 3.3 | 3-1/4 | 517 | 19 May 70 |
| 9 | 0.8 | 7 | 7.0 | 3-1/4 | 470 | 15 Dec 70 |
| 2 | 0.8 | 9 | 8.6 | 3-1/2 | 442 | 19 May 70 |
| 11 | 0.8 | 11 | 10.7 | 3-1/4 | 414 | 9 Mar 71 |
| **Concrete**** | | | | | | |
| Round 1 | 0.49 | 6 | 5.7 | 2-1/2 | 592 | 30 Jun 70 |
| Round 2 | | | 5.7 | 2-1/2 | | 22 Sep 70 |
| Round 3 | | | 5.5 | 2-1/2 | | 27 Jun 71 |

* Made with RC-602 and CRD-MS-17(9).
** Made with RC-602, CRD-G-34(3), and CRD-MS-17(9).

Table 4

Summary of Freezing-and-Thawing Data - Phase 6

| | $DFE_{300}$ (a) (b) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Mortar | 14-Day Age | 28-Day Age | 20-1/2-Month Age | 28-Month Age | 14-Day Age +4000ΔP (c) | 28-Day Age +4000ΔP (c) | 20-1/2-Month Age +4000ΔP (c) | 28-Month Age +9800ΔP (d) |
| **0.4 w/c ratio** | | | | | | | | |
| 7M, 2.5% air | 8 | 9 | 31 | 24 | 17 | 17 | 39 | 33 |
| 4M, 7.0% air | 85 | 87 | 88 | 92 | 86 (e) | 86 | 92 | 92 (e) |
| 1M, 9.5% air | 89 | 85 | 86 (e) | 86 | 86 | 87 | 91 | 89 (e) |
| 6M, 11.4% air | 85 | 83 | 85 | 92 | 86 | 88 | 90 | 88 |
| **0.6 w/c ratio** | | | | | | | | |
| 12M, 3.4% air | 1 | 4 | 2 | 3 | 3 | 2 | 3 | 2 |
| 5M, 6.6% air | 71 | 70 (e) | 66 | 70 (e) | 67 | 68 | 68 | 82 (e) |
| 10M, 8.6% air | 80 | 82 | 77 | 67 | 67 | 72 (e) | 61 (e) | 74 |
| 8M, 10.8% air | 86 | 83 | 84 (e) | 77 | 75 | 74 | 77 | 74 |
| **0.8 w/c ratio** | | | | | | | | |
| 3M, 3.3% air | 3 | 3 | 2 | 1 | 3 | 1 | 2 | 1 |
| 9M, 7.0% air | 12 | 33 | 69 | 30 | 39 | 59 | 45 | 34 |
| 2M, 8.6% air | 31 | 67 | 72 | 66 (e) | 45 | 64 (e) | 69 | 34 |
| 11M, 10.7% air | 66 | 72 | 68 | 49 | 67 | 63 | 48 | 69 |
| **Concrete** | | | | | | | | |
| **0.49 w/c ratio, ~6% air** | | | | | | | | |
| 1 C Round 1 | 57 | 76 | 72 | 80 | 70 | 71 | 79 | 76 |
| 2 C Round 2 | 65 | 75 | 81 | 83 | 61 | 62 | 80 | 78 |
| 3 C Round 3 | 89 | 78 | 83 | 84 | 63 | 67 | 82 | 78 |
| Average of 9 | 70 | 76 | 79 | 82 | 65 | 67 | 80 | 77 |

(a) Each value is an average for three beams unless indicated otherwise by (e).
(b) CRD-C 20.[2]
(c) Water pressure on the specimens was alternated between 14 and 31 psi hourly for a total of 4000 times to simulate a short navigation season.
(d) Specimens had 4000 ΔP, then 4 months in fog room, and then additional 5800 ΔP to simulate two navigation seasons.
(e) Bad values not included (Table 5).

Table 5

Individual Data from Freezing-and-Thawing Tests, $DFE_{300}$ (a)

| Condition (b) | Beam | Mortars, 0.4 Water-Cement Ratio, Mixture 7 | Mixture 4 | Mixture 1 | Mixture 6 | 0.6 Water-Cement Ratio, Mixture 12 | Mixture 5 | Mixture 10 | Mixture 8 | 0.8 Water-Cement Ratio, Mixture 3 | Mixture 9 | Mixture 2 | Mixture 11 | Concrete, Round 1 | Round 2 | Round 3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 14 days | 1 | 8 | 87 | 89 | 91 | 1 | 69 | 80 | 87 | 3 | 10 | 29 | 67 | 54 | 69 | 92 |
| | 2 | 8 | 84 | 89 | 81 | 1 | 67 | 80 | 84 | 3 | 13 | 36 | 67 | 48 | 64 | 87 |
| | 3 | 7 | 84 | 89 | 84 | 1 | 76 | 80 | 88 | 3 | 12 | 27 | 63 | 69 | 62 | 88 |
| 14 days + ΔP | 4 | 15 | 86 | 85 | 85 | 3 | 64 | 71 | 75 | 3 | 31 | 28 | 58 | 70 | 59 | 66 |
| | 5 | 16 | 85 | 87 | 87 | 3 | 69 | 60 | 76 | 3 | 51 | 44 | 72 | 68 | 60 | 64 |
| | 6 | 19 | 54(c) | 85 | 85 | 3 | 68 | 71 | 73 | 3 | 35 | 62 | 72 | 72 | 65 | 60 |
| 28 days | 7 | 10 | 87 | 85 | 78 | 3 | 71 | 83 | 85 | 3 | 29 | 64 | 72 | 77 | 76 | 80 |
| | 8 | 9 | 87 | 86 | 85 | 4 | 45(c) | 81 | 80 | 3 | 27 | 70 | 72 | 78 | 71 | 76 |
| | 9 | 7 | 86 | 85 | 85 | 4 | 69 | 82 | 85 | 4 | 43 | 66 | 72 | 73 | 78 | 78 |
| 28 days + ΔP | 10 | 18 | 84 | 86 | 87 | 2 | 65 | 29(c) | 75 | 1 | 61 | 63 | 59 | 70 | 63 | 66 |
| | 11 | 17 | 88 | 89 | 89 | 1 | 69 | 30(c) | 73 | 1 | 62 | 33(c) | 61 | 70 | 61 | 66 |
| | 12 | 16 | 86 | 87 | 89 | 2 | 70 | 72 | 75 | 1 | 55 | 65 | 68 | 73 | 62 | 69 |
| 20-1/2 months | 13 | 30 | 88 | 68(c) | 83 | 2 | 64 | 77 | 51(c) | 2 | 70 | 69 | 66 | 68 | 80 | 84 |
| | 14 | 33 | 86 | 85 | 86 | 2 | 66 | 77 | 83 | 2 | 71 | 73 | 69 | 79 | 82 | 84 |
| | 15 | 29 | 90 | 88 | 87 | 2 | 69 | 77 | 84 | 2 | 67 | 75 | 70 | 68 | 80 | 82 |
| 20-1/2 months + ΔP | 16 | 33 | 94 | 92 | 90 | 3 | 67 | 33(c) | 66 | 2 | 40 | 67 | 38 | 80 | 83 | 84 |
| | 17 | 42 | 88 | 90 | 89 | 3 | 68 | 24(c) | 84 | 2 | 35 | 70 | 63 | 81 | 80 | 79 |
| | 18 | 43 | 94 | 92 | 90 | 3 | 69 | 61 | 80 | 2 | 59 | 69 | 43 | 77 | 76 | 82 |
| 28 months | 19 | 22 | 90 | 82 | 93 | 3 | 73 | 63 | 77 | 1 | 32 | 68 | 47 | 77 | 80 | 84 |
| | 20 | 25 | 94 | 88 | 91 | 3 | 67 | 73 | 80 | 1 | 34 | 63 | 60 | 83 | 85 | 84 |
| | 21 | 26 | 92 | 88 | 91 | 3 | 46(c) | 64 | 73 | 1 | 25 | 31(c) | 40 | 81 | 85 | 83 |
| 28 months + ΔP | 22 | 31 | 94 | 90 | 91 | 2 | 21(c) | 75 | 69 | 1 | 30 | 32 | 66 | 74 | 77 | 77 |
| | 23 | 36 | 91 | 88 | 84 | 2 | 82 | 75 | 76 | 1 | 31 | 26 | 70 | 75 | 80 | 79 |
| | 24 | 31 | 52(c) | 34(c) | 90 | 2 | 23(c) | 73 | 78 | 1 | 42 | 45 | 70 | 80 | 76 | 77 |

(a) CRD-C 20.[2]
(b) ΔP denotes the cyclic pressure treatment described in the text.
(c) These values were not used in calculating the averages shown in Table 4.

Table 6

Phase 6 - Compressive Strength, psi(a)

| Mortar(b) | 14-Day Age | 28-Day Age | 20-1/2-Month Age | 28-Month Age | 14-Day Age +4000ΔP(c) | 28-Day Age +4000ΔP(c) | 20-1/2 Month-Age +4000ΔP(c) | 28-Month Age + 9800ΔP (d) |
|---|---|---|---|---|---|---|---|---|
| 0.4 w/c ratio | | | | | | | | |
| 7M, 2.5% air | 8640 | 9320 | 14,280 | 14,210 | 11,660 | 12,660 | 13,640 | 14,620 |
| 4M, 7.0% air | 6250 | 7480 | 10,600 | 11,480 | 9,140 | 9,820 | 10,440 | 11,220 |
| 1M, 9.5% air | 5160 | 6120 | 9,980(e) | 10,240 | 8,700 | 8,580 | 9,720 | 9,860 |
| 6M, 11.4% air | 4320 | 5110 | 7,450 | 8,240 | 6,440 | 6,470 | 7,520 | 8,220 |
| 0.6 w/c ratio | | | | | | | | |
| 12M, 3.4% air | 3610 | 4500 | 7,360 | 7,180 | 6,950 | 6,790 | 7,510 | 7,150 |
| 5M, 6.6% air | 3500 | 4220 | 6,620 | 6,600 | 5,780 | 5,980 | 5,900 | 6,650 |
| 10M, 8.6% air | 2740 | 3440 | 5,950 | 5,880 | 5,490 | 5,430 | 5,980 | 5,880 |
| 8M, 10.8% air | 2420 | 2890 | 4,860 | 4,770 | 4,290 | 4,350 | 4,890 | 4,700 |
| 0.8 w/c ratio | | | | | | | | |
| 3M, 3.3% air | 1780 | 2250 | 3,840(e) | 3,810 | 3,420 | 3,550 | 3,760 | 3,620 |
| 9M, 7.0% air | 1660 | 2060 | 3,850 | 3,920 | 3,290 | 3,300 | 3,770 | 3,850 |
| 2M, 8.6% air | 1590 | 1920 | 3,290(e) | 3,350 | 2,990 | 3,250(f) | 3,210 | 3,320 |
| 11M, 10.7% air | 1420 | 1780 | 3,280 | 3,180 | 3,000 | 3,020 | 3,180 | 3,150 |
| Concrete(g) | | | | | | | | |
| 0.4 w/c ratio | | | | | | | | |
| Round 1, ~6% air | 3620 | 4120 | 6,520 | 6,710 | 5,980 | 5,900 | 6,760 | 6,760 |
| Round 2, ~6% air | 3380 | 4120 | 6,600 | 6,540 | 5,790 | 6,220 | 6,690 | 6,940 |
| Round 3, ~6% air | 3620 | 4530 | 6,990 | 7,400 | 6,170 | 6,500 | 7,560 | 6,430 |
| Average of 6 | 3540 | 4260 | 6,700 | 6,880 | 5,980 | 6,210 | 7,000 | 6,710 |

(a) CRD-C 227.[2]
(b) Each strength value is the average of two 2- by 2- by 2-in. mortar cubes except for (f).
(c) Water pressure on the specimens was alternated between 14 and 31 psi hourly for a total of 4000 times to simulate a short navigation season.
(d) Specimens had 4000 ΔP, then 4 months in fog room, and then additional 5800 ΔP to simulate two navigation seasons.
(e) Tested at 18-1/4-month age by mistake.
(f) Single value since one cube was no good.
(g) Each strength value is the average of two 6- by 12-in. cylinders.

Table 7

Summary of Phase 6 Dilation Tests of Four Mortar Mixtures with 0.4 Water-Cement Ratio (a)(b)(c)

| Test Cycle | 14-Day Age | 14-Day Age + 4000 ΔP | 28-Day Age | 28-Day Age + 4000 ΔP | 20-1/2-Month Age | 20-1/2-Month Age + 4000 ΔP | 28-Month Age | 28-Month Age + 9800 ΔP |
|---|---|---|---|---|---|---|---|---|
| | | | | Mixture 7 - 2.5% Air | | | | |
| 1 | 1100(d) | -- | -- | 500/400/1500(d) | 150/200/900 | 400/500/900 | 850/200/800(e) | 100/850/1600 |
| 2 | -- | 100/100/1850 | 100/150 | -- | (f) | (f) | (f) | (f) |
| 3 | -- | -- | 100/500 | -- | | | | |
| 4 | 750 | 150/750 | 200/200 | 320/1100 | | | | |
| 5 | 800 | 450/750 | 150/250 | -- | | | | |
| 6 | 200/400 | -- | 300/250 | -- | | | | |
| 7 | 180/500 | -- | 300/250 | -- | | | | |
| 8 | 130/100 | -- | -- | 400/750 | | | | |
| 9 | -- | 650/1100 | -- | 660/3700 | | | | |
| 10 | -- | 400/1250 | -- | 350/1050 | | | | |
| | | | | Mixture 4 - 7.0% Air | | | | |
| 1 | 150 | 250/500 | None | 500/200 | None | 75/300 | 100 | 100/300 |
| 2 | -- | 400 | None | 300 | None | (f) | (f) | (f) |
| 3 | None | 100 | -- | 300 | None | | | |
| 4 | None | 140 | 100 | 475 | 145 | | | |
| 5 | 100 | 200 | -- | -- | 40 | | | |
| 6 | 125 | -- | -- | -- | None | | | |
| 7 | -- | -- | -- | -- | (f) | | | |
| 8 | -- | -- | -- | 530 | | | | |
| 9 | -- | 285 | -- | 450 | | | | |
| 10 | 200 | 470 | 200 | 615 | | | | |

(Continued)

(a) Expressed as total microinches per cycle.
(b) ΔP refers to an hourly alternation in water pressure between 14 and 31 psi for number of times indicated.
(c) Dash indicates malfunction.
(d) A single value indicates a single dilation; multiple values indicate additional dilations.
(e) Ran two consecutive cycles by mistake. There was no detectable effect of this.
(f) Stopped after one cycle or at point indicated.

Table 7 (Concluded)

| Test Cycle | 14-Day Age | 14-Day Age + 4000 ΔP | 28-Day Age | 28-Day Age + 4000 ΔP | 20-1/2-Month Age | 20-1/2-Month Age + 4000 ΔP | 28-Month Age | 28-Month Age + 9800 ΔP |
|---|---|---|---|---|---|---|---|---|
| | | | | Mixture 1 - 9.5% Air | | | | |
| 1 | -- | -- | -- | -- | None | None | None | 625(g) |
| 2 | -- | 400 | None | -- | None | (f) | (f) | (f) |
| 3 | None | -- | -- | -- | 50 | | | |
| 4 | None | -- | None | 200 | 50 | | | |
| 5 | -- | -- | None | -- | None | | | |
| 6 | None | -- | None | 200 | None | | | |
| 7 | -- | 300 | None | 300 | None | | | |
| 8 | -- | 525 | None | 200 | None | | | |
| 9 | 100 | None | 100 | 380 | None | | | |
| 10 | 100 | 205 | 100 | -- | 100 | | | |
| | | | | Mixture 6 - 11.4% Air | | | | |
| 1 | None | 200 | None | 700 | None | 110 | 50 | 100 |
| 2 | -- | 200 | -- | 200 | None | (f) | (f) | (f) |
| 3 | None | 300 | None | 300 | None | | | |
| 4 | None | 145 | -- | 180 | None | | | |
| 5 | 100 | 315 | -- | -- | 85 | | | |
| 6 | -- | -- | -- | -- | None | | | |
| 7 | -- | -- | -- | -- | (f) | | | |
| 8 | -- | -- | -- | 315 | | | | |
| 9 | -- | 390 | -- | 195 | | | | |
| 10 | 300 | 290 | 200 | 335 | | | | |

(g) Beam may have been damaged in handling.

Table 8

Summary of Phase 6 Dilation Tests of Four Mortar Mixtures with 0.6 Water-Cement Ratio (a)(b)(c)

| Test Cycle | 14-Day Age | 14-Day Age + 4000 ΔP | 28-Day Age | 28-Day Age + 4000 ΔP | 20-1/2-Month Age | 20-1/2-Month Age + 4000 ΔP | 28-Month Age | 28-Month Age + 9800 ΔP |
|---|---|---|---|---|---|---|---|---|
| | | | | Mixture 12 - 3.4% Air | | | | |
| 1 | 1250(d) | -- | 50/1400 | -- | 150/200/400 | 7000(e) | 1250/1125 | 14,500(e) |
| 2 | 1550/900 | -- | 50/1200 | -- | (e) | 6250/1100(f) | (e) | 15,500(f) |
| 3 | 800/200/400/700(d) | -- | -- | 35,500(g) | | | | |
| 4 | -- | 17,280 | -- | 19,500 | | | | |
| 5 | -- | 20,800 | -- | 19,360 | | | | |
| 6 | -- | 18,800 | 5400 | 20,400 | | | | |
| 7 | 1750/1400 | 23,800 | -- | 21,400 | | | | |
| 8 | -- | 24,400 | 7600 | 19,000 | | | | |
| 9 | 5860 | 24,800 | 8200 | 22,000 | | | | |
| 10 | 6590 | 28,000 | -- | 20,400 | | | | |
| 11 | None(f) | | | | | | | |
| | | | | Mixture 5 - 6.6% Air | | | | |
| 1 | 50 | 1000/350 | None | 300/550 | 220 | 355 | 200 | 250 |
| 2 | -- | -- | None | 250 | 300 | (e) | (e) | (e) |
| 3 | 100 | 165 | None | 400 | 320 | | | |
| 4 | -- | 195 | 100 | 430 | 450 | | | |
| 5 | 300 | 300/150 | -- | -- | 410 | | | |
| 6 | 500/1400 | -- | -- | -- | 450 | | | |
| 7 | -- | -- | -- | -- | (e) | | | |
| 8 | -- | -- | -- | 805 | | | | |
| 9 | -- | 615 | -- | 500/1000 | | | | |
| 10 | 200/750 | 412 | 300 | 715 | | | | |

(Continued)

(a) Expressed as total microinches per cycle.
(b) ΔP refers to an hourly alternation in water pressure between 14 and 31 psi for number of times indicated.
(c) Dash indicates malfunction.
(d) A single value indicates a single dilation; multiple values indicate additional dilations.
(e) Stopped after one test or at point indicated.
(f) Tested again at 4-yr age.
(g) Recorded near -50°F; the dilation was 18,000 for the temperature (-10° to -20°F) where subsequent cycles were recorded.
(h) The second dilation was recorded at -40°F.

Table 8 (Concluded)

| Test Cycle | 14-Day Age | 14-Day Age + 4000 ΔP | 28-Day Age | 28-Day Age + 4000 ΔP | 20-1/2-Month Age | 20-1/2-Month Age + 4000 ΔP | 28-Month Age | 28-Month Age + 9800 ΔP |
|---|---|---|---|---|---|---|---|---|
| | | | | Mixture 10 - 8.6% Air | | | | |
| 1 | None | -- | 200 | -- | 50 | 350 | 50 | 200 |
| 2 | 195 | -- | None | -- | (e) | (e) | (e) | (e) |
| 3 | 95 | -- | -- | 120/2100(h) | | | | |
| 4 | -- | None | -- | 255 | | | | |
| 5 | -- | 145 | -- | 250 | | | | |
| 6 | -- | 255 | 150 | 200/400/250 | | | | |
| 7 | None | 255 | -- | 420 | | | | |
| 8 | None | 425 | 200 | 500 | | | | |
| 9 | 325 | 365 | 290 | 395 | | | | |
| 10 | 65 | 225 | -- | 160 | | | | |
| | | | | Mixture 8 - 10.8% Air | | | | |
| 1 | None | -- | -- | 260 | 115 | 300 | 100 | 500 |
| 2 | -- | 115 | None | -- | (e) | (e) | (e) | (e) |
| 3 | None | -- | 200 | 80 | | | | |
| 4 | 200 | 150 | 200 | 105 | | | | |
| 5 | 200 | 235 | 200 | -- | | | | |
| 6 | 330 | -- | 145 | -- | | | | |
| 7 | 410 | -- | 400 | -- | | | | |
| 8 | 400 | -- | -- | 170/350 | | | | |
| 9 | -- | 505 | -- | 85 | | | | |
| 10 | -- | 675 | -- | 345 | | | | |

Table 9

Summary of Phase 6 Dilation Tests of Four Mortar Mixtures with 0.8 Water-Cement Ratio (a)(b)(c)

| Test Cycle | 14-Day Age | 14-Day Age + 4000 ΔP | 28-Day Age | 28-Day Age + 4000 ΔP | 20-1/2-Month Age | 20-1/2-Month Age + 4000 ΔP | 28-Month Age | 28-Month Age + 9800 ΔP |
|---|---|---|---|---|---|---|---|---|
| | | | | Mixture 3 - 3.3% Air | | | | |
| 1 | -- | -- | -- | -- | 4,220 | 14,000 | 9850 | 26,000(d) |
| 2 | -- | 24,500 | 1500 | -- | 3,120 | (d) | (d) | 32,800(e) |
| 3 | 1050 | -- | (d) | -- | 5,350 | | | |
| 4 | (d) | -- | | -- | 7,900 | | | |
| 5 | | -- | | -- | 9,000 | | | |
| 6 | | -- | | -- | 10,700 | | | |
| 7 | | >8,500(f) | | >9,200(f) | 12,400 | | | |
| 8 | | >9,700(f) | | >9,700(f) | 13,900 | | | |
| 9 | | -- | | -- | 13,800 | | | |
| 10 | | -- | | -- | 16,000 | | | |
| | | | | Mixture 9 - 7.0% Air | | | | |
| 1 | 200(g) | -- | -- | 300/150/1850 | 455/100 | 150/100/750 | 200(h) | 400/500 |
| 2 | -- | 1000/1000 | None/300(g) | -- | 235 | Skipped | (d) | Skipped |
| 3 | None | -- | None/100 | 120/400 | Skipped | -- | | -- |
| 4 | 300 | 1200/550 | 100/100 | 290 | Skipped | Skipped | | Skipped |
| 5 | 150 | 1600/600 | 200 | -- | 355 | 420 | | 1800 |
| 6 | 270 | -- | 185 | -- | Skipped | Skipped | | Skipped |
| 7 | 630 | -- | 200 | -- | 150/1000 | 925 | | 1750 |
| 8 | 675 | -- | -- | 150 | Skipped | Skipped | | Skipped |
| 9 | -- | 7400 | -- | 450 | 870 | 1650/100/550 | | 1600(d) |
| 10 | -- | 26,000 | -- | 440 | Skipped | 2100/1200(i) | | 500/2200/500(i) |

(Continued)

(a) Expressed as total microinches per cycle.
(b) ΔP refers to an hourly alternation in water pressure between 14 and 31 psi for number of times indicated.
(c) Dash indicates malfunction.
(d) Stopped after one cycle or at point indicated.
(e) Tested again at ~5-yr age.
(f) Off scale.
(g) A single value indicates a single dilation; multiple values indicate additional dilations.
(h) Ran two consecutive cycles by mistake. There was no detectable effect of this.
(i) Tested again at 4+ yr.

Table 9 (Concluded)

| Test Cycle | 14-Day Age | 14-Day Age + 4000 ΔP | 28-Day Age | 28-Day Age + 4000 ΔP | 20-1/2-Month Age | 20-1/2-Month Age + 4000 ΔP | 28-Month Age | 28-Month Age + 9800 ΔP |
|---|---|---|---|---|---|---|---|---|
| | | | | Mixture 2 - 8.6% Air | | | | |
| 1 | -- | -- | -- | -- | 100 | 450 | 160 | 450 |
| 2 | -- | 150 | 100 | -- | 160 | (d) | (d) | (d) |
| 3 | None | -- | -- | -- | 100 | | | |
| 4 | 425 | -- | 100 | 300 | 200 | | | |
| 5 | -- | -- | 300 | -- | 400 | | | |
| 6 | 100 | -- | 150 | 200 | 200 | | | |
| 7 | -- | 600 | 100 | 700 | 1000 | | | |
| 8 | -- | 500 | -- | 270 | 800 | | | |
| 9 | 225 | 400 | 175 | 400 | 950 | | | |
| 10 | 400 | 700 | 200 | -- | 975 | | | |
| | | | | Mixture 11 - 10.7% Air | | | | |
| 1 | 270 | -- | 100 | -- | 100 | 300 | 200 | 150 |
| 2 | 185 | -- | 70 | -- | (d) | (d) | (d) | (d) |
| 3 | 285 | -- | -- | 395/1850 | | | | |
| 4 | -- | 395 | -- | 75 | | | | |
| 5 | -- | 620 | -- | 275 | | | | |
| 6 | 445 | 1120 | 390 | 60 | | | | |
| 7 | 390 | 625 | -- | 260 | | | | |
| 8 | -- | 1085/100 | 700 | 105 | | | | |
| 9 | 335 | 550 | 400 | 55 | | | | |
| 10 | 370 | 650 | -- | 260 | | | | |

Table 10

Summary of Phase 6 Dilation Tests of Three Rounds of One Concrete Mixture (a)(b)(c)

| Test | 14-Day Age | | | 14-Day Age + 4000 ΔP | | | 28-Day Age | | | 28-Day Age + 4000 ΔP | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cycle | Round 1 | Round 2 | Round 3 | Round 1 | Round 2 | Round 3 | Round 1 | Round 2 | Round 3 | Round 1 | Round 2 | Round 3 |
| 1 | -- | None | 250 | 500(d) | 200/300 | 100/500 | 150 | 50 | None | -- | 350/250 | 150/400 |
| 2 | -- | 200 | 300 | -- | 300/50 | 200 | 300 | 200 | None | 50 | 350 | 200 |
| 3 | 175 | None | None | 300 | 200/100 | -- | -- | -- | 270 | 100/100 | -- | -- |
| 4 | -- | -- | 510 | 150 | -- | -- | 30 | None | 540 | None | -- | -- |
| 5 | None | 200 | 315 | 200 | -- | -- | 50 | 400 | -- | 100 | -- | -- |
| 6 | 200 | -- | -- | 400 | -- | 200/250 | 50 | -- | -- | -- | 100/100 | 100/100 |
| 7 | -- | -- | -- | 200/50(d) | 500/100 | 450 | None | 300 | -- | 150 | -- | 150/100 |
| 8 | 300 | -- | -- | 260/50 | -- | 300/50 | -- | 300 | 175 | -- | 300/200 | 230 |
| 9 | -- | 200 | 345 | -- | 300/100 | 100/100 | 200 | 500 | 155 | -- | 300/50 | 200/200 |
| 10 | -- | 250 | -- | -- | 170 | 350 | None | 550 | 280/100 | -- | -- | 50/150 |

| Test | 20-1/2-Month Age | | | 20-1/2-Month Age + 4000 ΔP | | | 28-Month Age | | | 28-Month Age + 9800 ΔP | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cycle | Round 1 | Round 2 | Round 3 | Round 1 | Round 2 | Round 3 | Round 1 | Round 2 | Round 3 | Round 1 | Round 2 | Round 3 |
| 1 | 520 | 120 | 90 | 175 | 200/150 | 100 | 100 | 150 | 100 | 300/50 | 100/200 | 150/100 |
| 2 | 50 | 180 | (e) | (e) | (e) | (e) | (e) | (e) | (e) | (e) | (e) | (e) |
| 3 | 50 | 200 | | | | | | | | | | |
| 4 | 180 | (e) | | | | | | | | | | |
| 5 | 250 | | | | | | | | | | | |
| 6 | 280 | | | | | | | | | | | |
| 7 | 200 | | | | | | | | | | | |
| 8 | 125 | | | | | | | | | | | |
| 9 | 100 | | | | | | | | | | | |
| 10 | -- | | | | | | | | | | | |

(a) Expressed as total microinches per cycle.
(b) ΔP refers to an hourly alternation in water pressure between 14 and 31 psi for number of times indicated.
(c) Dash indicates malfunction.
(d) A single value indicates a single dilation; multiple values indicate additional dilations.
(e) Stopped after one cycle or at point indicated.

Table 11

Freezable Water in Three Nonair-Entrained Mortar Mixtures at 20 and 10°F

| Mixture No. | Water-Cement Ratio | Air Content, % | Water Frozen at 20°F and at 10°F, g: 14-Day Age 20°F | 14-Day Age 10°F | 28-Day Age 20°F | 28-Day Age 10°F | 20-1/2-Month Age (a) 20°F | 20-1/2-Month Age (a) 10°F | 28-Month Age 20°F | 28-Month Age 10°F |
|---|---|---|---|---|---|---|---|---|---|---|
| 7 | 0.4 | 2.5 | 13 | 46 | 29 | 72 | 20 | 75 | 5 | 25 |
| 12 | 0.6 | 3.4 | 240 | 359 | 106 | 206 | 210 | 320 | 144 | 275 |
| 3 | 0.8 | 3.3 | 425 | 500 | (b) | (b) | 315 | 410 | 300 | 370 |
| | | | 14-Day Age +ΔP(c) | | 28-Day Age +ΔP(c) | | 20-1/2-Month Age + ΔP (c) | | 28-Month Age + ΔP (d) | |
| 7 | 0.4 | 2.5 | 24 | 50 | 19 | 42 | (b) | (b) | 2 | 45 |
| 12 | 0.6 | 3.4 | 155 | 250 | 144 | 217 | 230/200(e) | 340/390(e) | (b)/240(e) | (b)/370(e) |
| 3 | 0.8 | 3.3 | 380 | 500 | (b) | (b) | 360 | 430 | (b)/520(f) | 340/610(f) |

(a) During the first 21 months of testing, data were averaged for number of cycles tested. Thereafter, each specimen was tested for one cycle only. The validity of averaging these data is shown on the next table.
(b) No data or bad data.
(c) ΔP means there were 4000 cyclic changes in water pressure between 14 and 31 psi (97 to 214 kPa) at hourly intervals.
(d) ΔP in this case consists of the above, then 4 months soaking followed by 5800 cyclic ΔP.
(e) Retested at 4-yr age.
(f) Retested at 5-yr age.

Table 12

Freezable Water Content of Mortar at 0°F During First Test Cycle

| Mixture No. | Air Content, % | Amount of Water Frozen at 0°F During First Test Cycle for Conditions Shown, g: 14-Day Age | 28-Day Age | 20-1/2-Month Age | 28-Month Age | 14-Day Age + ΔP(a) | 28-Day Age + ΔP(a) | 20-1/2-Month Age + ΔP(a) | 28-Month Age + ΔP(b) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 0.4 Water-Cement Ratio | | | | | |
| 7 | 2.5 | nd(c) | nd | 140 | 70 | nd | 85 | nd | 105 |
| 4 | 7.0 | 200 | nd | 90 | 350 | nd | nd | 350 | 225 |
| 1 | 9.5 | 130 | nd | 115 | 170 | 180 | nd | 200 | 500 |
| 6 | 11.4 | nd | nd | 155 | 220 | nd | nd | 190 | 620 |
| | | | | 0.6 Water-Cement Ratio | | | | | |
| 12 | 3.4 | nd | 320 | 380 | 325 | nd | nd | 420 | 1310 |
| 5 | 6.6 | 375 | nd | 380 | 270 | nd | nd | 410 | 610 |
| 10 | 8.6 | nd | 240 | 900 | 505 | nd | nd | 620 | 500 |
| 8 | 10.8 | nd | nd | 340 | 590 | nd | 485 | 550 | 575 |
| | | | | 0.8 Water-Cement Ratio | | | | | |
| 3 | 3.3 | nd | nd | 365 | 420 | nd | nd | 470 | 400 |
| 9 | 7.0 | nd | nd | 340 | 540 | nd | 900 | 610 | 510 |
| 2 | 8.6 | 440 | nd | 380 | 490 | nd | nd | 595 | 570 |
| 11 | 10.7 | nd | 485 | 500 | 565 | nd | nd | 830 | 665 |

(a) ΔP means there were 4000 cyclic changes in water pressure between 14 and 31 psi (97 to 214 kPa) at hourly intervals.
(b) ΔP in this case consists of the above, then 4 months soaking followed by another 5800 ΔP.
(c) No data or bad data.

Table 13

Freezable Water and Dilation of Mortar Specimen 3M5* by Test Cycle

| Test Cycle | Freezable Water at 20°F, g | Freezable Water at 10°F, g | Total Dilation, μin. |
|---|---|---|---|
| 1 | 180 | 320 | 4,220 |
| 2 | 370 | 495 | 3,120 |
| 3 | 265 | 420 | 5,350 |
| 4 | 330 | 415 | 7,900 |
| 5 | 400 | 520 | 9,000 |
| 6 | 355 | 460 | 10,700 |
| 7 | 350 | 405 | 12,400 |
| 8 | 295 | 360 | 13,900 |
| 9 | 325 | 375 | 13,800 |
| 10 | 275 | 320 | 16,000 |
| Average | 315 | 409 | not calculated |
| Standard deviation, g** | 63 | 68 | not calculated |

* Specimen had been continuously soaked in limewater for 2 months when testing began. Mortar had 0.8 w/c ratio and contained 3.3 percent air.

** Standard deviation = $\sqrt{\Sigma(d^2)/n-1}$ .

Table 14

Air Contents and Relative Saturation of 13 Cylinders

| Cylinders | Air Content of Fresh Mortar or Concrete, % (a) | Data on Cylinders: Air Content, % (b) | Data on Cylinders: Duration of Test, days | Relative Saturation, % (c) |
|---|---|---|---|---|
| 1M3, 28 days old | 9.5 | 6.4 | 13 | 33 |
| 1M2, 14 days + ΔP | | 8.4 | 57 | 11 |
| 2M1, 14 days old | 8.6 | 7.7 | 2 | 10 |
| 2M3, 28 days old | | 7.0 | 2 | 19 |
| 2M2, 14 days + ΔP | | 2.2 | 8 | 75 |
| 3M1, 14 days old | 3.3 | 1.7 | 3 | 48 |
| 3M3, 28 days old | | 3.3 | 2 | 0 |
| 3M2, 14 days + ΔP | | 1.6 | 11 | 51 |
| 3M4, 28 days + ΔP | | 0.8 | 7 | 75 |
| 1C1, 14 days old | 5.7 | 4.3 | 6 | 25 |
| 1C3, 28 days old | | 4.2 | 13 | 26 |
| 1C2, 14 days + ΔP | | 2.8 | 41 | 50 |
| 4M1, 14 days old | 7.0 | 6.6 | 45 | 6 |

(a) CRD-C 41.[2]
(b) CRD-C 83;[2] however, no heating was used.
(c) Calculated as the ratio of filled space (air plastic - air hardened) x 56 cc to available space (air plastic) x 56 cc. Each 6- by 12-in. cylinder has a volume of ~5600 cc. Therefore, each percent of this volume is 56 cc.

Table 15

Weight Gain of 12 Mortars Due to Cyclic Pressure Treatment, Percent of Original Weight (a)

| Specimen | 0.4 Water-Cement Ratio | | | | 0.6 Water-Cement Ratio | | | | 0.8 Water-Cement Ratio | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mixture 7 2.5% Air | Mixture 4 7.0% Air | Mixture 1 9.5% Air | Mixture 6 11.4% Air | Mixture 12 3.4% Air | Mixture 5 6.6% Air | Mixture 10 8.6% Air | Mixture 8 10.8% Air | Mixture 3 3.3% Air | Mixture 9 7.0% Air | Mixture 2 8.6% Air | Mixture 11 10.7% Air |
| Condition 2 (14 days) | | | | | | | | | | | | |
| Cylinders | 0.4 | 0.4 | 0.9 | 1.0 | 2.0 | 1.2 | 2.0 | 2.2 | 1.0 | 2.1 | 2.4 | 2.8 |
| Beams(b) | 0.2 | 0.5 | 0.8 | 1.0 | 1.7 | 1.0 | 1.7 | 2.0 | 0.8 | 1.4 | 1.8 | 1.8 |
| Condition 4 (28 days) | | | | | | | | | | | | |
| Cylinders | 0.4 | 0.4 | 0.8 | 0.9 | 1.7 | 1.1 | 1.7 | 1.7 | 1.2 | 1.8 | 2.1 | 2.8 |
| Beams(b) | 0.3 | 0.5 | 0.7 | 1.0 | 1.6 | 1.4 | 1.6 | 1.4 | 0.9 | 1.3 | 1.4 | 2.0 |
| Condition 6 (20-1/2 months) | | | | | | | | | | | | |
| Cylinders | 0.1 | nd(c) | 0.4 | nd | nd | nd | nd | 0.9 | 0.8 | 1.0 | 1.6 | nd |
| Beams(b) | 0.1 | 0.1 | 0.4 | 0.5 | 0.8 | 0.3 | 0.8 | 0.8 | 0.6 | 1.1 | 1.2 | 1.2 |
| Condition 8 (18-1/2 months) | | | | | | | | | | | | |
| Cylinders | 0.2 | nd | nd | nd | nd | nd | nd | 1.5 | nd | 1.4 | nd | nd |
| Beams(b) | 0.2 | 0.4 | 0.6 | 0.3 | 0.8 | 0.4 | 0.8 | 1.0 | 0.6 | 1.2 | 1.1 | 1.4 |
| Condition 8 (28 months) | | | | | | | | | | | | |
| Cylinders | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd |
| Beams(b) | trace | 0.1 | 0.3 | 0.1 | trace | 0.2 | trace | 0.2 | 0.5 | 0.3 | 0.3 | 0.2 |

(a) Gains due to pressure.

(b) Usually the average of four specimens.

(c) Not determined.

Table 16

Weight Gain of Concrete Due to Cyclic Pressure Treatment, Percent of Original Weight

| Specimens | Concrete, 0.49 w/c Ratio | | | |
| --- | --- | --- | --- | --- |
| | Round 1 | Round 2 | Round 3 | Average |
| Condition 2 (14 days) | | | | |
| Cylinders | 0.7 | 1.2 | 0.9 | 0.9 |
| Beams | 0.6 | 0.7 | 0.6 | 0.6 |
| Condition 4 (28 days) | | | | |
| Cylinders | 0.6 | 0.8 | 0.7 | 0.7 |
| Beams | 0.5 | 0.5 | 0.3 | 0.4 |
| Condition 6 (20-1/2 months) | | | | |
| Cylinders | 0.3 | 0.2 | 0.4 | 0.3 |
| Beams | 0.3 | none | 0.3 | 0.2 |
| Condition 8 (18-1/2 months) | | | | |
| Cylinders | 0.4 | 0.4 | 0.4 | 0.4 |
| Beams | 0.5 | 0.3 | 0.3 | 0.4 |
| Condition 8 (28 months) | | | | |
| Cylinders | 0.1 | 0.3 | none | 0.1 |
| Beams | 0.3 | 0.3 | none | 0.2 |

Table 17

Weight Gain During Three Years Moist Storage, Percent of Original Weight*

| | Weight Gain |
|---|---|
| Mortar, 0.4 w/c ratio | |
| Mixture 7 (2.5% air) | 0.5 |
| Mixture 4 (7.0% air) | 1.1 |
| Mixture 1 (9.5% air) | 1.2 |
| Mixture 6 (11.4% air) | 1.6 |
| Mortar, 0.6 w/c ratio | |
| Mixture 12 (3.4% air) | 0.3 |
| Mixture 5 (6.6% air) | 0.9 |
| Mixture 10 (8.6% air) | 0.5 |
| Mixture 8 (10.8% air) | 1.1 |
| Mortar, 0.8 w/c ratio | |
| Mixture 3 (3.3% air) | 0.6 |
| Mixture 9 (7.0% air) | 0.7 |
| Mixture 2 (8.6% air) | 1.1 |
| Mixture 11 (10.7% air) | 0.8 |
| Concrete, 0.49 w/c ratio | |
| Round 1 | 0.8 |
| Round 2 | 0.6 |
| Round 3 | 0.8 |
| Average | 0.7 |

* Based on weights of 6- by 12-in. control cylinders that were measured several times over a 3-yr span.

Table 18

Saturation Increases of Mortar Cylinders Due to Different Types of Pressure, Percent*

| Type of Treatment | Increase in Saturation, % | | |
|---|---|---|---|
| | Mixture 7 | Mixture 8 | Mixture 9 |
| 4000 cycles of pressure between 14-31 psi | 0.37 | 2.24 | 2.06 |
| Constant pressure of 31 psi for same time as above | 0.25 | 2.60 | 2.07 |
| Constant pressure of 14 psi for same time as above | 0.14 | 1.60 | 1.62 |
| Nominal air content, % | 2.5 | 10.8 | 7.0 |
| Water-cement ratio | 0.4 | 0.6 | 0.8 |

* Based on changes in weight of one 6- by 12-in. mortar cylinder per condition. All gains are due solely to pressure since the gain due to hydration was removed by calculation.

Table 19

Long-Term Weight-Change Data of Mortar and Concrete Cylinders (a)(b)

| 0.4 w/c Ratio | Mortar | Weight Change 4000 ΔP (c) | Weight Change with Extra ΔP: Weight | Weight Change with Extra ΔP: ΔP (d) | Fog Room Weight Change After ΔP: Weight | Fog Room Weight Change After ΔP: Days |
|---|---|---|---|---|---|---|
| Increasing | 7M | +85 | +28 | ~9,000 | zero | 53 |
| Air | 4M | +85 | +85 | ~14,000 | not determined | |
| Content | 1M | +170 | +57 | ~11,000 | zero | 119 |
| | 6M | +170 | +113 | ~14,000 | not determined | |
| 0.6 w/c Ratio | 12M | +142 | zero | ~7,000 | zero | 53 |
| | 5M | +170 | +57 | ~14,000 | not determined | |
| | 10M | +227 | +28 | ~3,000 | -28 | 155 |
| | 8M | +312 | +57 | ~5,000 | zero | 155 |
| 0.8 w/c Ratio | 3M | not determined | | | | |
| | 9M | +284 | -28 | ~6,000 | -28 | 119 |
| | 2M | +312 | zero | ~11,000 | zero | 119 |
| | 11M | +369 | zero | ~4,000 | -28 | 119 |
| Concrete | | +142 | zero | ~4000-9000 | zero | 101-155 |

(a) Weights are in grams. The values for 1M and 2M are for single ~13.6-kg cylinders; those for the concrete are the average for five ~13.6-kg cylinders. All other values are the average for a pair of ~13.6-kg cylinders.

(b) ΔP means an hourly alternation of pressure between 14 and 31 psi. There are 8760 ΔP per year (24 x 365).

(c) Cyclic pressure treatment was started when specimens were 14 and 28 days old.

(d) Additional cyclic pressure treatment was started when the specimens were about 6 months old and immediately after the first 4000 ΔP were completed.

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Investigation of frost resistance of mortar and concrete, by Alan D. Buck. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1976.

1 v. (various pagings) illus. 27 cm. (U. S. Waterways Experiment Station. Technical report C-76-4)

Prepared for Office, Chief of Engineers, U. S. Army. Washington, D. C.

Includes bibliography.

1. Concrete tests. 2. Eisenhower Lock. 3. Frost resistant concrete. 4. Mortars. I. U. S. Army. Corps of Engineers. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Technical report C-76-4)

TA7.W34 no.C-76-4